Towards Automated Formal Analysis of Model Transformation Specifications

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Abstract

In Model-Driven Engineering, model transformation is a key model management operation, used to translate models between notations. Model transformation can be used for many engineering activities, for instance as a preliminary to merging models from different metamodels, or to generate codes from diagrammatic models. A mapping model needs to be developed (the transformation specification) to represent relations between concepts from the metamodels. The evaluation of the mapping model creates new challenges, for both conventional verification and validation, and also in guaranteeing that models generated by applying the transformation specification to source models still retain the intention of the initial transformation requirements. Most model transformation creates and evaluates a transformation specification in an ad-hoc manner. The specifications are usually unstructured, and the quality of the transformations can only be assessed when the transformations are used. Analysis is not systematically applied even when the transformations are in use, so there is no way to determine whether the transformations are correct and consistent. This thesis addresses the problem of systematic creation and analysis of model transformation, via a facility for planning and designing model transformations which have conceptual-level properties that are tractable to formal analysis. We proposed a framework that provides steps to systematically build a model transformation specification, a visual notation for specifying model transformation and a template-based approach for producing a formal specification that is not just structure-equivalent but also amenable to formal analysis. The framework allows evaluation of syntactic and semantic correctness of generated models, metamodel coverage, and semantic correctness of the transformations themselves, with the help of snapshot analysis using patterns.

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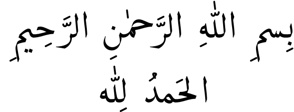

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Author's Declaration

I hereby declare that the contents of this thesis are the result of my own original contribution, except where otherwise stated. The following material, presented in this thesis, has been previously published:

- *Model Transformation Specification for Automated Formal Verification.* Asmiza Abdul Sani, Fiona A. C. Polack and Richard F. Paige. The 5th Malaysian Software Engineering Conference. IEEE. 2011. Awarded Best Paper.
- *Generating Formal Model Transformation Using a Template-based Approach.* Asmiza Abdul Sani, Fiona A. C. Polack and Richard F. Paige. The 3rd York Doctoral Symposium. 2010.
- *Developing Model Transformation Specification for Automated Formal Analysis through a Template Based Approach.* Asmiza Abdul Sani. Presented at the doctoral symposium at Formal Methods 2011, Limerick, Ireland.
- *Trans-DV: A Framework for Developing and Formally Verifying Model Transformation Specifications.* Asmiza Abdul Sani, Fiona A. C. Polack and Richard F. Paige. The 4rd York Doctoral Symposium. Poster presentation. 2011.

The thesis work was conducted under the supervision of Dr. Fiona A. C. Polack and Prof. Richard Paige at Department of Computer Science, University of York. This work has not previously been presented for an award at this, or any other, University.

Chapter 1

Introduction

How do we produce a reliable model transformation in Model-Driven Engineering (MDE)? That is, model transformations that are able to produce a final product according to the transformation requirements? The question of how to obtain a valid outcome from software development is not new, nor it is specifically an MDE problem. It has been discussed since the term "Software Engineering" was introduced in the North Atlantic Treaty Organisation (NATO) Software Engineering conference in October 1968 in an effort to cope with the so-called "Software Crisis". It was then that the idea of *defining a software engineering paradigm* was discussed in-depth to improve methodologies and tools with the hope of solving the essential problems in software development [Wir08].

After four decades, the quest to find *silver bullets* [FPB87] to solve all software development difficulties is far from over. The emergence and acceptance of MDE as a valid and productive software engineering approach has presented us with a new set of challenges related to obtaining products that satisfy our reliability and functional requirements by the end of development.

1.1 Introducing MDE

MDE is a software engineering paradigm that promotes models as first class engineering artefacts, and uses model transformation to produce the final (executable, deliverable) artefacts. MDE is based on using models and abstractions defining relations between elements in the problem domain. Such models and abstractions

are eventually mapped to an implementation (which may be executable code, or a simulation, or a description that can be used for further analysis). As such, MDE emphasizes developing models and transformations, as opposed to conventional writing of program code, to produce the final product. Models in MDE describe features of the domain, while transformations contain mapping instructions that manipulate these models, to generate output artefact in various forms, including: (1) *fully* or *partially* working code, or (2) other kinds of models, specifications or reports. There are many different kinds of transformations, include model-to-model, model-to-text, and update-in-place (discussed in Chapter 2); this thesis focuses on model-to-model transformations where the source and target languages differ (we discuss these restrictions later).

1.2 Model transformation development

The MDE approach for developing software is based on the application of modelling languages that have a defining structure (such as a metamodel) and automated tools for constructing and manipulating models (such as a means for executing model transformations)[1]. Works by Guelfi et al. [GP04] who proposed a framework named FIDJI and Küster et al. [KRH05] who proposed a systematic approach to develop systems, are examples of MDE development processes that are based on the use of transformations.

The key components in executing model transformations are *metamodels*, *models*, *transformation specifications* and *transformation implementations*. The development of model transformations begins with the specification and analysis of models and metamodels, then the specification and analysis of model transformation; the latter includes the elicitation and specification of *transformation requirements*. The works of both Guelfi et al. [GP04] and Küster et al. [KRH05] works focus on identifying model transformation features and testing of model transformations, but do not present a systematic process to develop model transformations from requirements.

[1]Lies, Damned Lies and UML2Java: http://blog.jot.fm/2013/01/25/lies-damned-lies-and-uml2java/

1.3 Analysis in MDE

MDE, like any other software development approach, needs mechanisms that can be used to ensure that the final engineering product includes all required features at an acceptable level of quality. The common approaches in mainstream software engineering – following life cycles such as waterfall, prototyping, and spiral variations – see software engineers conducting analysis activities in explicit phases, very often analysis in a form of testing is performed after a version of an executable is completed [Som07].

Analysis activity such as validation and verification is a significant problem in MDE, particularly because each component (models, metamodels, operations like transformations) requires analysis for ensuring their fitness; in particular, such components have to be *correct* and *well-formed*.

Transformations are a critical component of MDE. To ensure a fit final product, engineers have to make certain that transformations are capable of transforming a valid source model into a valid target model according to a set of transformation requirements. This includes ensuring that the transformation produces a syntactically conforming target model, and the intended semantics is preserved.

Several analysis techniques for model transformation have been presented in the literature. These include *testing* [MBT06; KAER07], *formal reasoning and proof* [Poe08; ABK07], *model checking* [BCR06] and *simulation* [ABK07]. Baudry et al. [BDTM+06] claims that generating effective test cases for transformations is considered difficult. Examples of testing approaches include mutation testing [MBT06] and code coverage testing [KAER07].

Testing is one of the most common approaches to validation and verification in MDE, partly because development of model transformations is often implementation oriented, and as such developers tend to adopt conventional approaches to analysis of code. But as testing depends on implementation, faults discovered at this stage could originate from many different sources, including the models and metamodels, and it may be difficult to identify the exact source (or sources) of faults or failures. Moreover, changes that originate in the different MDE components (e.g., models and metamodels) can introduce more faults and failures in

the implementation. As such, it may be desirable to try to catch faults earlier, in the design stages of model transformations.

One of the alternative approaches to analysis in software engineering is the use of formal methods. These techniques use mathematical logic descriptions as the basis of software specification and analysis [Spi92]. Although formal methods have been proven to be an effective analysis technique in certain domains and certain projects, software engineers often seem to avoid using them unless it is necessary to spend effort to ensure precise measurement [Hal90]. In the context of model transformation, despite the complexity of MDE components with respect to their interdependencies, formal methods have not been applied widely for model transformation analysis.

In general, analysis of model transformation is hard because it includes several components with complex interdependencies (e.g., instantiation, usage, generation) of different types. When using formal methods to analyse transformations, the resulting specifications that are used can be very large and complex, requiring significant mathematical skills to both formulate and use.

1.4 Motivation for research

In current applications of MDE, model transformation development is commonly handled in an ad-hoc manner, without much consideration for planning, designing and analysis of the model transformation specification [GdLK+10]. In conventional software engineering such as object-oriented development, the construction of executable or downstream artefacts are often well documented, using modelling languages such as the Unified Modelling Language (UML)[1].

The lack of representations that clearly specify the model transformation components and their features, makes it difficult to support analysis of model transformations at a conceptual level. Furthermore, established model transformation analysis techniques are predominantly focused on testing, and as briefly mentioned, having shortcomings, particularly their incompleteness (as is the case with all testing techniques) and the late identification of faults that could create

[1] UML: http://www.uml.org/

other inconsistencies across MDE components. Therefore, we aim to address correctness and how well-formed the model transformations are from the beginning of development. Ideally, we want to benefit from the rigorous and mathematical analysis capabilities provided by formal methods.

The motivation of this research is two fold: one is to create a systematic means to conceptually design model transformation specifications; the second is to do so in such a way that effective formal analysis of model transformation specifications can be performed. Several attempts have been proposed to address these issues individually. For example, in a literature presented by Siikarla et al. [SLSS08] showed that a model transformation could be produced by following an incremental approach to development. In an article by Bettin [Bet03], a compact language that contains a specialised concrete syntax for specifying model transformation was proposed, while Poernomo [Poe08] showed how formal methods can be used to specify and analyse model transformations. However, this previous work does not provide a framework that covers the design process of model transformations (including the design of the models and metamodels that the transformation depends on) in such a way that enables formal analysis.

1.5 Proposed approach

The thesis focuses on finding the solutions to these problems:

1. How can we systematically and effectively specify a model transformation? To this end we propose a number of visual modelling languages that enable the specification and eventual analysis of model transformations

2. How can we formally analyse model transformation effectively using practical approaches? (*Practical* in this sense refers to the ease of application of formal methods (we define this more precisely in the sequel)). To this end we propose a process for engineering transformations, as well as a set of *templates* that can be used for constructing model transformations that are more easily amenable to formal analysis.

To solve these problems, we aim to create a framework that has: (1) a systematic process that supports the development of model transformations; (2) a clear and comprehensible modelling language for representing model transformations; (3) templates for generating formal specifications of model transformations, thus enabling reasoning; and finally (4) practical formal methods for providing effective analysis and feedback.

We choose a visual modelling language for easy and clear comprehension of the modelling decisions (similar concept as UML). Our visual models support automated generation of formal specifications via instantiations of templates for analysis, adopting the approach proposed by Amálio in [Am7].

The *process* for our approach includes the following stages: (1) elicitation of model transformation requirements; (2) defining metamodels for the transformation; (3) analysis of the metamodels to enable later analysis; (4) specifying the model transformation; and (5) analysis of the model transformation specification. The mechanisms that allow us to do this are a set of visual modelling languages for representing model transformations and their components. The modelling languages we propose have been inspired by Guerra et al. [GdLK+12], who provide a family of languages for model transformation engineering.

The modelling languages we propose include constructs for: (1) documenting model transformation requirements; (2) specifying metamodels and model transformations; and (3) representations of model and model transformation instances. The modelling languages are also used to instantiate templates to produce formal specification.

The templates are the mechanism that addresses the problem of requiring significant mathematical expertise when using formal methods for analysis. The instantiation of templates by modelling language aims to hide the formalism from the transformation engineers. The use of templates for generating formal specification was inspired by Amálio's thesis [Am7], who created a formal template catalogue that can produce *correct-by-construction* instantiations of Z specifications.

The formal method chosen to provide an effective analysis and feedback contains features of the so-called *practical formal methods* defined by Heitmeyer

[Hei98]. In this sense, an *effective analysis* is a method that provides an automatic analysis of formal specification and also provides clear and comprehensible feedback that identifies the origin of error.

1.6 Research hypothesis

This research revolves around the hypothesis below, highlighting the significant terms that it embodies.

> *In ensuring that a* ***model transformation specification*** *is* ***precise****, we need a framework that provides (1) a set of* ***processes*** *for model transformation specification development, (2)* ***visual languages*** *that enable specifying model transformations using diagrammatic notations, and (3)* ***templates*** *for producing model transformation specifications that are tractable and amenable to* ***effective formal analysis****.*

1.7 Research objectives and contribution of thesis

The objectives of this thesis are:

1. To define development processes for constructing model transformation specifications.
2. To devise modelling languages for specifying model transformation development artefacts.
3. To create a formal template catalogue, which corresponds to the modelling languages, and which can be applied to produce model transformation specifications amenable to formal analysis.
4. To provide an automated formal analysis of model transformation specifications where engineers have to interact to a limited degree with the formalism itself.

Ultimately, based on the objectives, the thesis aim to produce a framework that provides the following:

- A process for model transformation specification development that focuses on discovering the essential features and components of a model transformation.
- A visual modelling language for representing model transformation specifications and their components.
- A catalogue of formal templates for producing formal specifications of model transformations that are tractable and amenable to effective formal analysis.

1.8 Research methodology

This research takes the approach of *qualitative research*. Qualitative research is defined as "*research devoted to developing an understanding of human system*"[SR04]. In the context of this research, the *human system* refers to MDE engineers developing model transformations.

To answer our research questions and to address our hypothesis, we perform three main activities: (1) domain reviews, (2) framework definition, and (3) application, as depicted in Figure 1.1.

In domain review, we aim to understand what is a model transformation, and what is its application environment. We also reviewed the current trends on analysis of model transformation. Based on this domain review and analysis, we define our framework. This includes identifying the processes and components required to develop and formally analyse model transformation specifications. We then demonstrate our framework by applying it to a case study, a class-to-relational-database model transformation. In this activity, we produce artefacts that allow model transformation specifications to be represented, through structured steps of eliciting requirements, defining a metamodel, and thereafter specifying the transformation. We then formally analyse these artefacts via the application of templates that generate formal specifications.

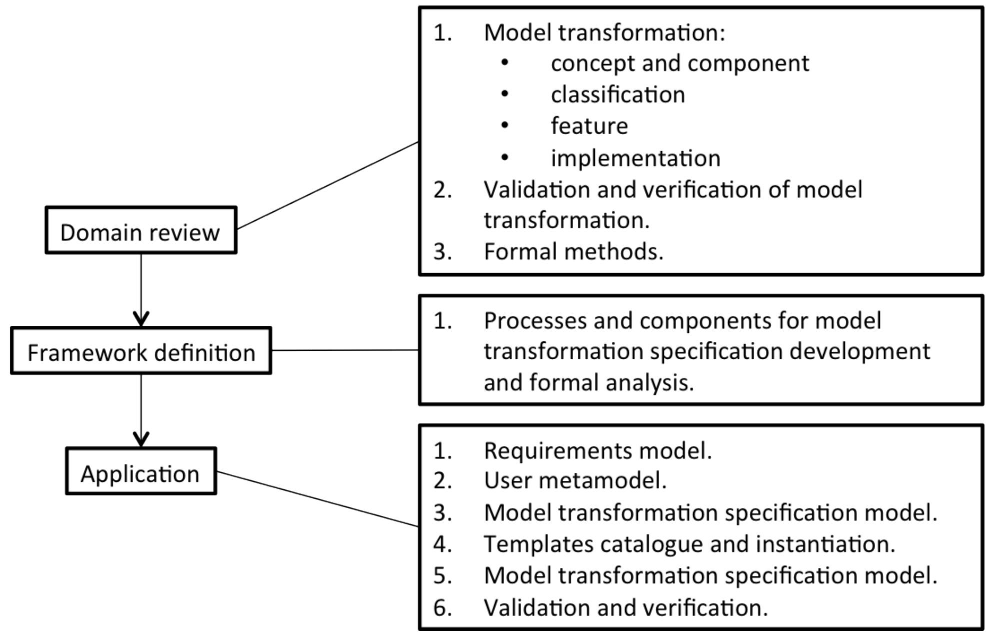


Figure 1.1: Research methodology

1.8.1 Research overview

To give an overview of the research, Figure 1.2 outlines the steps and their outcomes.

1.9 Thesis Structure

The thesis contains the following chapters:

Chapter 2 - Literature review on MDE. We present a domain review of MDE, model transformation and their context. This also describes the state-of-the-art in model transformation analysis techniques.

Chapter 3 - Literature review on formal analysis. We review current formal methods approaches to analysis, particularly for their application in the context of model transformation.

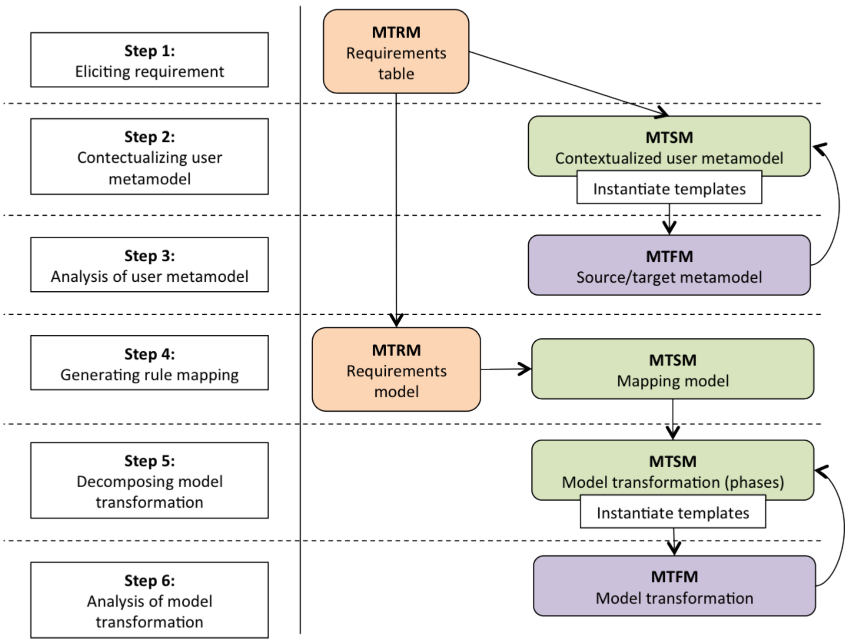


Figure 1.2: Overview of the proposed framework

Chapter 4 - Framework for specification and formal analysis of model transformation. We define our framework to model transformation specification development and formal analysis. We describe the processes and components involved.

Chapter 5 - Eliciting model transformation requirements and contextualizing metamodel. The process of specifying model transformation starts with the identification of model transformation requirements. We present several views used for eliciting model transformation requirements. One of these views will assist in defining a contextualized metamodel for model transformation; this is effectively a configuration process by which a general-purpose metamodel is tailored for the purposes of analysis and formal reasoning.

Chapter 6 - Analysing metamodel. Once we have established a contextualized metamodel, we can formally analyse the metamodel for correctness and how well it is formed by instantiating templates that map the metamodel into a formal specification.

Chapter 7 - Specifying and analysing model transformation. We show how to specify model transformations that use the contextualized metamodel as the source and target model. A requirements model is produced from the requirements view; it is then used to generate a rule mapping model. Model transformation phases are identified and the specification uses the rule defined in the rule mapping model. The specification is then used to analyse model transformation provided via template instantiations that produce formal specifications.

Chapter 8 - Applying and evaluating the TSP framework. To evaluate the capability of our framework, we apply it to specify and analyse the class to relational database model transformation.

Chapter 9 - Conclusion. To wrap up our work, we recap the approach. We highlight the features of our framework and point out the advantages as well as its limitations. We also discuss future work.

Chapter 2

Literature review on MDE

To understand how model transformation can be integrated with formal methods for an automated analysis, we will review two major domains; (1) Model Driven Engineering (MDE), which we will be covering in this chapter and, (2) formal methods, presented in Chapter 3.

Model-Driven Engineering (MDE) is a software engineering approach that uses *models*, *metamodels* and *transformations* as the key engineering artefacts. Not only are the components different between MDE and conventional software development, the processes used for producing the final product are also dissimilar.

This chapter consist of two parts: (1) defines the relevant technologies that underlie MDE; and (2) presents the challenges of analysis of model transformation, in parallel to understanding what is required for validation and verification in the context of MDE. In Chapter 3, we present a review of formal methods and formal analysis for model transformation. Besides getting to terms with the domain of this research, the outcomes of Chapter 2 and 3 determine the features of our framework for specifying and analysing the model transformation presented in Chapter 4.

This chapter contains the following main sections. Section 2.1 introduces MDE and defines *what is a model* in the context of this research (Section 2.2). This is followed by Section 2.3 and Section 2.4, where we review two significant components of MDE; (1) metamodels, and (2) model transformations, respectively. We describe two engineering approaches that define a development process

for model transformation in Section 2.5, followed by the model transformation language definition, and scenarios of model transformation in Section 2.6 and 2.7. We end the first part of this chapter with a brief introduction to MDE standards and tools in Section 2.8. In the second part, we highlight the challenge regarding analysis of model transformation implementation, in the context of MDE (Section 2.10). The analysis will take on three perspectives: (1) model in Section 2.11; (2) metamodel in Section 2.12; and (3) model transformation in Section 2.13. At the end of the chapter (Section 2.16), we describe some of the challenges in MDE with regards to the objective of the thesis.

2.1 Model Driven Engineering

Model-Driven Engineering (MDE) is a model centric software engineering approach to developing systems. It promotes the notion of a model, as its first class engineering entity and the basis of producing the final product. According to Bézivin [BBJ07], MDE provides the common and minimal set of fundamental principles, *representation* and *conformance*, as depicted in Figure 2.1. This illustrates that a model in MDE is conforming to a metamodel, and is used to represent a system.

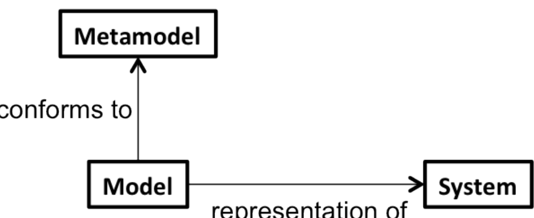


Figure 2.1: Basic relations of *representation* and *conformance* in MDE [BBJ07]

These concepts aim to improve the productivity in both *short* and *long-term efforts* in software development [AK03]. Short-term productivity refers to the effort of making primary artefacts capable of producing executable functionalities, for example, a visual model with details to generate working code. Long-term productivity addresses the capability of those primary artefacts to adapt with

changes over time and situation, which includes: (1) technical knowledge of development personnel; (2) changing of system requirements; (3) development tools dependency; and (4) platform independent deployment [AK03].

To realize these potential productivity improvements, MDE introduces three key concepts: (1) model; (2) metamodel; and (3) model transformation. In the following sections, we define each of these more precisely.

2.2 Model

Models have long proven useful in engineering as a tool for representation. Such representations are an abstraction of the subject matter. The Oxford Dictionary defines model as:

> ***noun 1*** *a three-dimensional representation of a person or thing, typically on a smaller scale.* ***2*** *(in sculpture) a figure made in clay or wax which is then reproduced in a more durable material.* ***3*** *something used as an example.* ***4*** *a simplified mathematical description of a system or process, used to assist calculations and predictions.* ***5*** *an excellent example of a quality.* ***6*** *a person employed to display clothes by wearing them.* ***7*** *a person employed to pose for an artist.* ***8*** *a particular design or version of a product.* [CS05]

Based on this definition, it is difficult to define what form models take, but it is clear that a model can be identified according to the domain that it is being applied to. In science, models play an important role in representing a particular scientific theory. Bohr's model of the atom, the evolutionary model in social sciences, equilibrium models of markets in economics and the double-helix model of DNA, are some of the many well-known domains that use a model as a mean to represent real-world features in context [FH09].

In software engineering, building models has become an essential activity, particularly at the early stage of software development. Ludewig [Lud03], suggests that software models can be *descriptive*, *prescriptive* or *transient*. A model is descriptive if it *mirrors* the original object. If the model can be used as a *specification* of an object to be built, then it is a prescriptive model. A transient

model is when a *modification* is imposed on a descriptive model, which in turn becomes a prescriptive model, to create a new object. Jackson [Jac95] also describes the definition of models by Ackoff [Ack62], as an *analogic* model, where a model should be more than just a description: a model "embodies a *simulation* of the real thing" [Jac95]. Figure 2.2, gives Jackson's definition of the meaning of model in software engineering, showing the relationship between a machine and its domain. In this case, the *machine* is assumed to be any type of software.

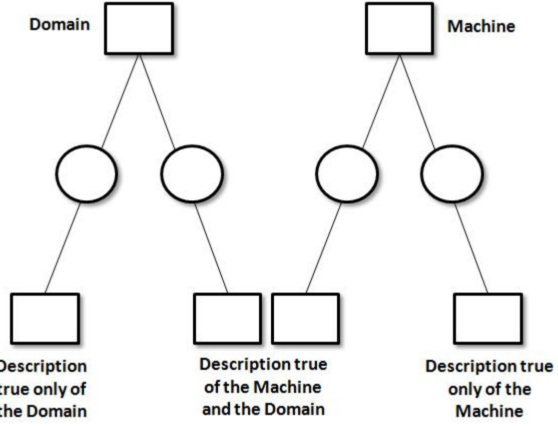


Figure 2.2: Jackson's definition of a model [Jac95]

The role of models in software engineering can be varied. As shown in Figure 2.3, a model plays a multi-faceted role. As suggested by Figure 2.3, MDE belongs to the model-centric spectrum.

The models in each approach for software engineering in Figure 2.3 are artefacts, *formulated in a modelling language* [Küh05]. Models are not just artefacts in the form of *diagrams*. A model can also take the form of a *code*, or a *mathematical specification*. These models can be used to represent aspects of a system during development. The purpose of a model is defined by its perspectives, which determines the details it produces of an aspect. In particular for MDE, models that reside in the same level of abstraction usually describe *views* of a system, while models at different level of abstraction describe the different *viewpoints* of a system.

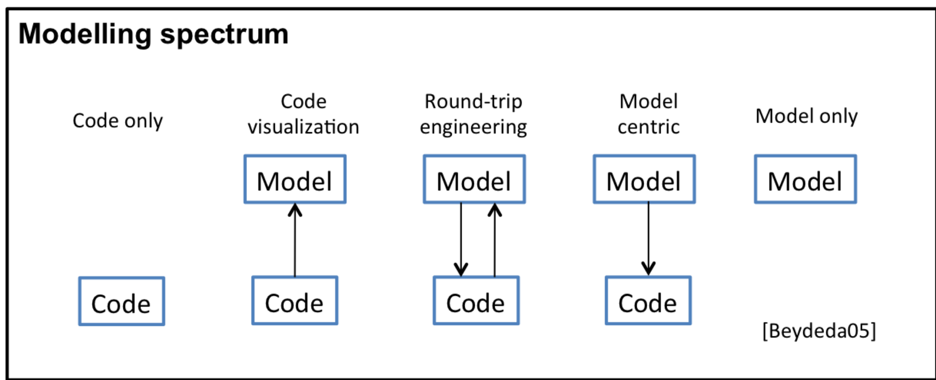


Figure 2.3: Spectrum of model use [BBG05]

There are various languages available in the literature to build a software model. One of the recognised languages for system modelling is the Unified Modelling Language (UML).

2.2.1 Unified Modelling Language

The Unified Modelling Language (UML) is a general-purpose object-based modelling language by Object Management Group (OMG)[1]. UML originated from three early-established object-oriented methods, Booch, OMT and OOSE [UML09]. The objective of UML diagrams is to provide standard *diagrammatic modelling language* that are flexible, to represent various kind of systems. UML aims to provide interoperable tool support for the language which includes analysis, design and implementation capabilities [UML09].

UML diagrams are expressed in a family of languages that can be used in representing various aspects of a system. Figure 2.4 shows the classification of UML diagrams. The diagrams can be classified into two: (1) structured; and (2) behavioural diagrams. Structured diagrams address a *static concern* of a system, including *architectural components*; while a behavioural diagram represents the *dynamic aspect* of a system, including state changes over time.

The current version UML is part of an effort to support Model Driven Architecture [UML09], another OMG framework, which is a particular instantiation of

[1]OMG website: http://www.omg.org/

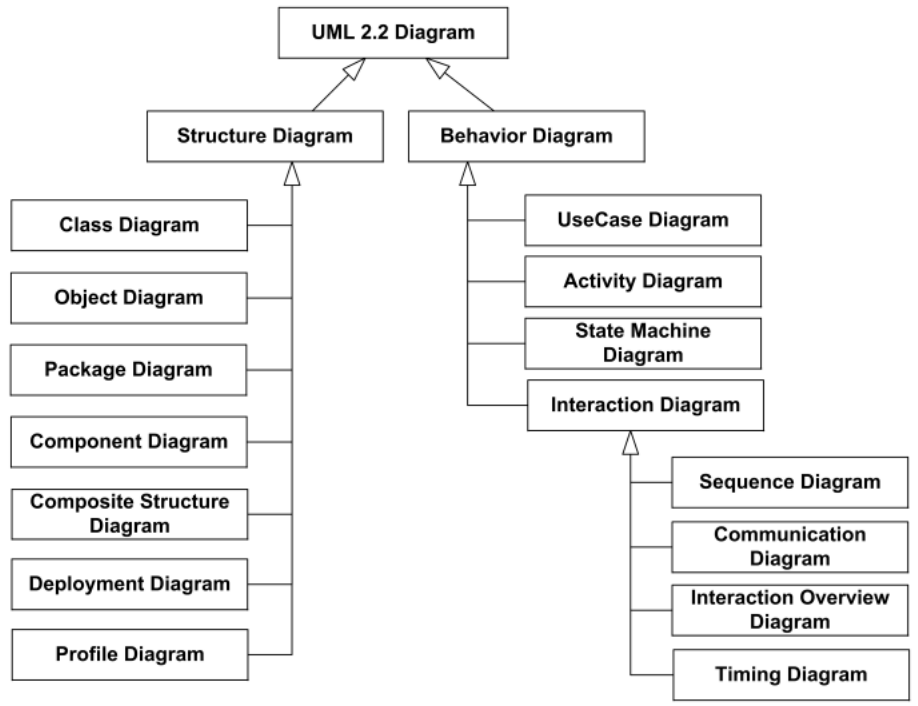


Figure 2.4: UML diagrams[1]

MDE.

UML is a general purpose modelling language. UML can be extended to include more details of a specific system. SysML [Sys] is an extension of UML for system engineering application. It reuses and modifies several UML diagrams and includes two additional diagrams; (1) requirement, and (2) parametric diagrams. SysML diagrams are shown in Figure 2.5.

SysML initially was an effort to customize UML to address the development of systems, but later, it was included by OMG as part of System Engineering RFP[3]. SysML is implemented as a UML profile that can be used to *specify*, *analyse*, *design*, *validate* and *verify* complex system development, which includes *hardware*, *software*, *information*, *processes*, *personnel* and *facilities* [Sys]. Apart from SysML unifying common methods used to developed systems, one of the features, the *requirement diagram* formalizes the representation of requirements,

[3]UML for Systems Engineering RFP: http://syseng.omg.org/UML_for_SE_RFP.htm

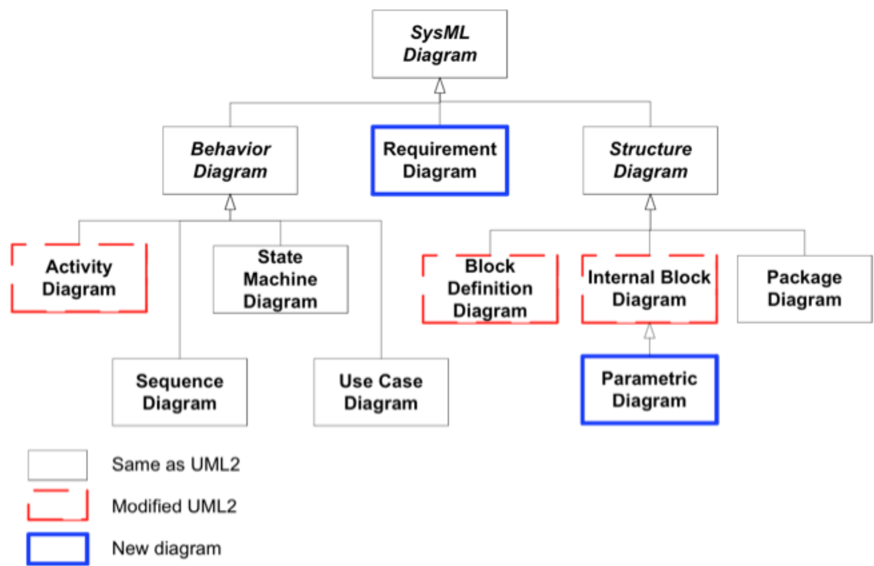


Figure 2.5: SysML diagrams[2]

which defines functional and non-functional features, and shows the model elements that fulfil these requirements. This allows analysis to find insufficiencies in the requirements.

2.2.2 Remarks

In a model transformation, a model is read by the transformation engine to produce another model. Partly to ensure the reliability of a model transformation to produce a valid product. A model provided as input has to be valid in terms of its syntax and semantics. Therefore, analysis for models used in a model transformation contribute towards a correct model transformation. Further discussion of this issue is presented in Section 2.11.

SysML allows requirements to be represented formally. In particular to our research, we want to have a formal representation of model transformation requirements, which allows a defined model transformation specification to be developed on top of the requirements. Therefore, we adopted SysML to define our model transformation requirements.

In MDE, models are often a user defined model that is developed using a *Domain Specific Modelling Language (DSML)*. A DSML is a language that defines a concrete syntax. In the next section, we are going to see how a metamodel is used to give a formal definition to model.

2.3 Metamodel

Metamodels play a significant role in MDE. A metamodel is *a model*, but of special kind, used to describe the syntax and semantics of another model. To give a non-technical analogy, a metamodel is to a model, as a dictionary and thesaurus are to a spoken language, such as English. Dictionaries and thesauri (metamodels) are used to describe the meaning of words and how the words are used in a sentence to form communication (model). Figure 2.6, gives more technical analogy: a metamodel is to a model as an EBNF is to a programming language [sDz09].

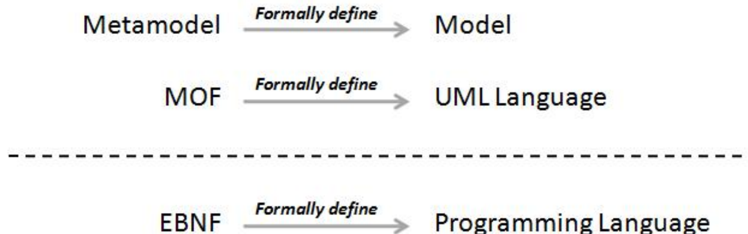


Figure 2.6: Metamodel to model and a similar non-modelling example (derived from [sDz09])

A metamodel can be used to create a Domain Specific Modeling Language (DSML). The syntax of a metamodel represents three key elements: (1) semantic domain; (2) abstract syntax; and (3) concrete syntax. The semantic domain identifies the features and meaning of real world objects that need to be modelled. These details are then realized as abstract syntax that contain elements, relations and condition specifications via *semantic mappings*. The abstract syntax are used to provide the concrete syntax for modelling domain through *syntactic mapping*.

2.3.1 Metamodelling architecture

The usefulness of a metamodel lies in its capability to define the functionality of a model to represent a domain. A metamodel is significant in MDE as it introduces the means to *abstract* details, which enables required *refinements* to intermediate or final models to be made.

In a metamodelling architecture, there is a structure that defines the organization between abstract and concrete models. In many MDE developments, the *four-layer architecture* is used to provide the structure of models and metamodels. An example of the application of the four-layer architecture, illustrating a UML-based development, is depicted in Figure 2.7.

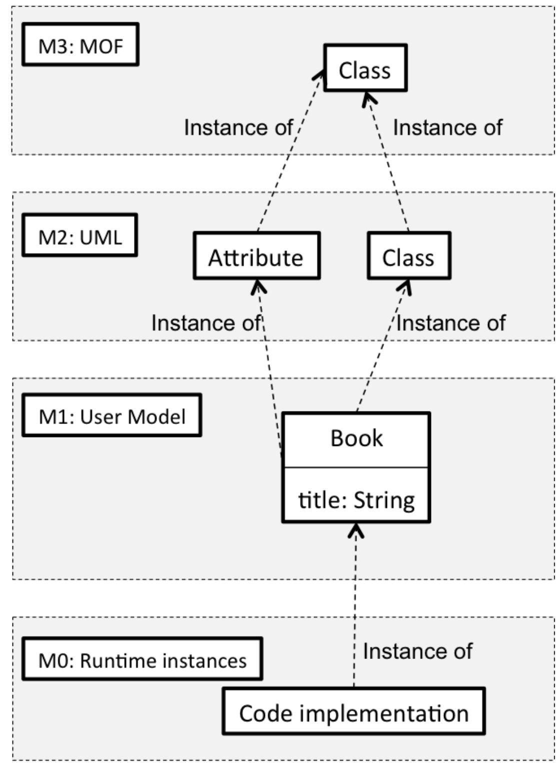


Figure 2.7: Four-layer architecture illustrated in terms of MOF and UML based on UML 2.2 Infrastructure Specification [UML09]

The models in each level (except the model in M3) is an instance to the model in the level above. M3 often resides the metamodel (MOF), while M2 is the model (UML model) that is used to *model* the system in M1 (User model), which reflects the runtime instances of the model in M0.

In the next part, we present two examples of metamodels (metametamodels), the (1) Meta Object Facility (MOF), and (2) Ecore.

2.3.2 Meta Object Facility (MOF)

.

An example of a well-known metamodel standard in the Meta Object Facility. It is a Domain Specific Language adopted by OMG to provide a framework for metadata[1]

The MOF metamodel defines notations for use by other models, often models within OMG standards. It also defines itself, and other metamodels. MOF supports the definition of the abstract syntax of object-oriented modelling languages.

MOF 2 [MOF11] is the current working version of MOF. It is made up of two packages, (1) Essential MOF (EMOF) and, (2) Complete MOF (CMOF) [MOF11]. EMOF provides the minimal construct for straightforward mapping between model and implementation, while more elaborate metamodeling requirements will be supported by the CMOF. Figure 2.8 gives an extract of the EMOF package that contains the elements for defining common constructs of object-oriented programming languages.

2.3.3 Ecore

The Ecore metamodel is the central component for Eclipse Modelling Framework (EMF) [2]. The EMF Ecore package contains properties that are used to describe metametamodels. Ecore is comparable to EMOF, as it has the capability to

[1]Metadata is "data about data". Metadata is a mechanism that enables a collection of data to be managed, manipulated or analysed into more meaningful information. Also, to enable development and interoperability of models and metadata driven systems [MOF11].

[2]EMF website: http://www.eclipse.org/modeling/emf/?project=emf

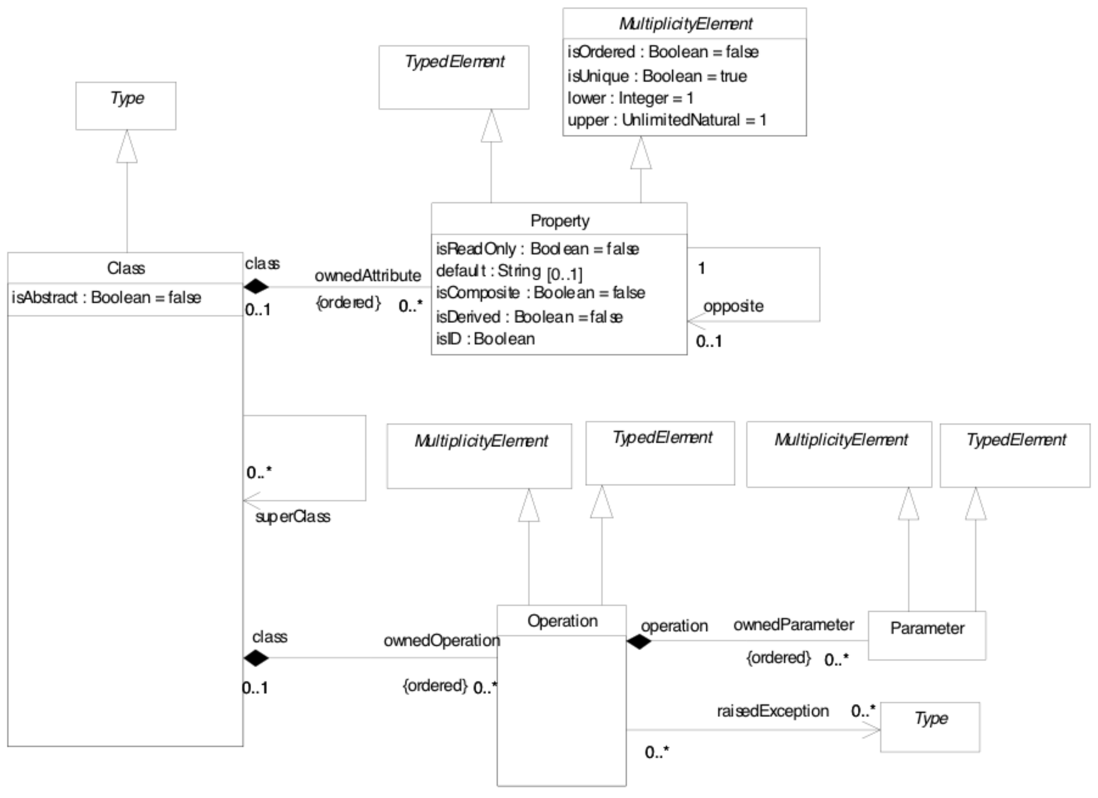


Figure 2.8: The Essential MOF (EMOF) classes [MOF11]

define common concepts of object-oriented programming language. Figure 2.9 shows the hierarchy of classes in the Ecore package.

2.3.4 Remarks

Metamodels achieve interoperability by providing common constructs for specifying modelling languages. MOF and Ecore are two standard metamodels (metametamodel) used for defining object-oriented modelling languages and implementation.

One issue for transformation is the characteristics of the metamodel that defines the model to be transformed. They can be a model with: (1) huge metamodel; (2) readily-available metamodel; and (3) non-existent metamodel.

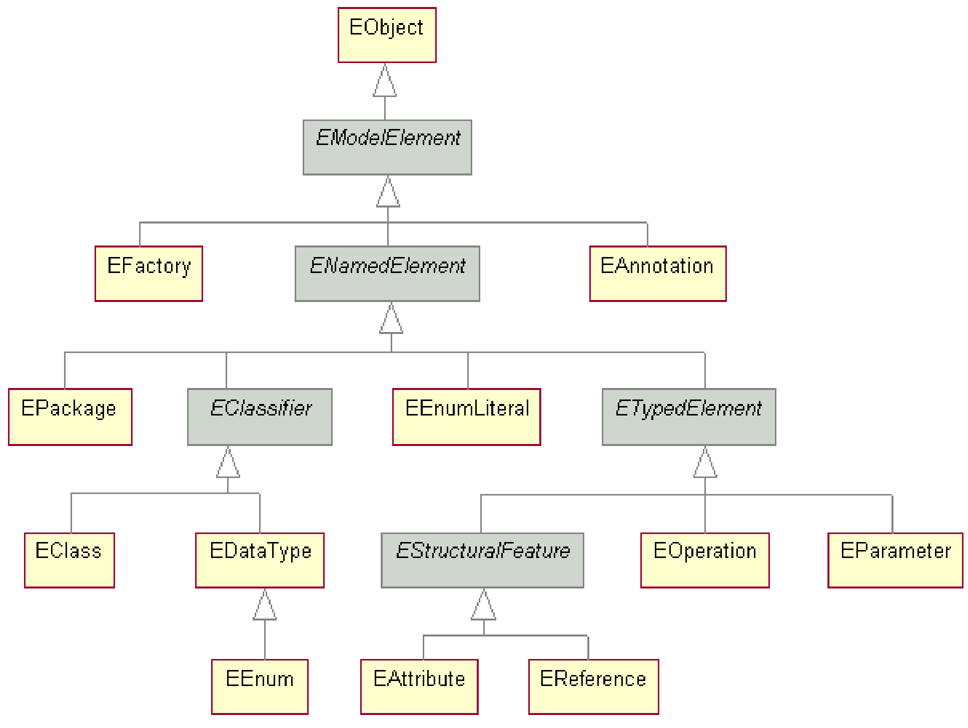


Figure 2.9: The Ecore classes[1]

Huge metamodel refers to a metamodel that defines multiple coverages of a model. And often, projects only use part of the metamodel to define the system. For example, the MOF that defines the UML has a huge set of metamodel elements, covering several perspectives of modelling, using multiple packages. Therefore, transformation of the UML model often accesses only parts of the UML metamodel.

Ordinarily, in using MDE, there are a number of alternatives available when considering languages for transformation. This is because there are many metamodels readily available, standardizing the concept of various application domains. For example, there is the Business Process Execution Language (BPEL) metamodel for business processes for the web, the Modelling and Analysis of Real Time and Embedded system (MARTE) metamodel, for real time and embedded application or Ant metamodel for Java builds. These metamodels and many more

can be accessed freely from metamodel zoo[1] where the metamodels are deposited in several formats such as EMF XMI (Ecore), KM3 and MDR XMI (MOF).

There are also some domain models that do not have a metamodel. To use a transformation, a metamodel needs to be constructed from the model, abstracting the syntax and semantics so that a mapping, either between two domains of different language, or between the abstract and concrete syntax, can be specified.

In terms of model transformation (model transformation is presented in Section 2.4) in MDE, there is at least one metamodel that defines the source model and the target model. The capability of a metamodel to provide a valid model for a valid transformation of the final product, has to be established. Therefore, performing analysis is required to ensure that the metamodel is fit for a model transformation. We discuss this further in Section 2.12.

At this point, we have seen the relations between a model and a metamodel. Now, we will show how models and metamodels play their part in a model transformation. The next section introduces the final components that motivates MDE, the model transformation.

2.4 Model transformation

The driver of MDE is *model transformation*. Model transformation is a mechanism that is used for managing changes to models automatically. The word *Transformation*, in the context of software engineering has been around since the emergence of second generation programming languages (2GLs). In the 1960s, transformation referred to the transforming of human-readable and human-written programs (or assembler, written in assembly language) into machine-readable forms, by a compiler. This is also known as *program transformation*. In the 1980s, came the idea of code generation, which introduced model transformation as an alternative approach to software production. The aim is to have models designed and transformed into executable code rather than having a programmer write a program.

[1] AtlanMod: http://www.emn.fr/z-info/atlanmod/index.php/Zoos

Model transformation in the context of MDE, refers to a process of executing a set of *transformation rules* to transform one or more source model (which acts as input) to produce one or more target models, as output [SK03; CH06]. Transformation rules specify how a model in the source language can be transformed into a model in the target language [KWB03]. In other words, transformation rules consist of *links that map between the source and the target models.*

Figure 2.10 shows the basic concepts of model transformation [CH06]. The *transformation engine* reads a *source model*, that conforms to a particular *meta-model*, and then executes the *transformation definition*, or specification that maps the relation between the *source* and *target meta-model*. The transformation engine then writes the *target model*.

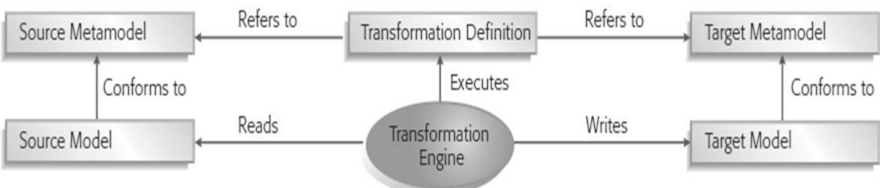


Figure 2.10: Basic concepts of model transformation [CH06]

To put model transformation in the perspective of metalevels, Figure 2.11 depicts how metamodels, models and transformations fit within the meta-level structure.

Developing model transformation in MDE requires a different development process, compared to conventional software engineering. This is due to a different set of artefacts being generated within the duration of the development. The following section discusses two approaches to developing model transformation.

2.5 Model transformation development process

The first model transformation process presented here, is the FIDJI methodology [GP04; GPR03]. It is an effort to create an engineering approach for product line development based on an *architectural framework*. Taking advantage of MDE

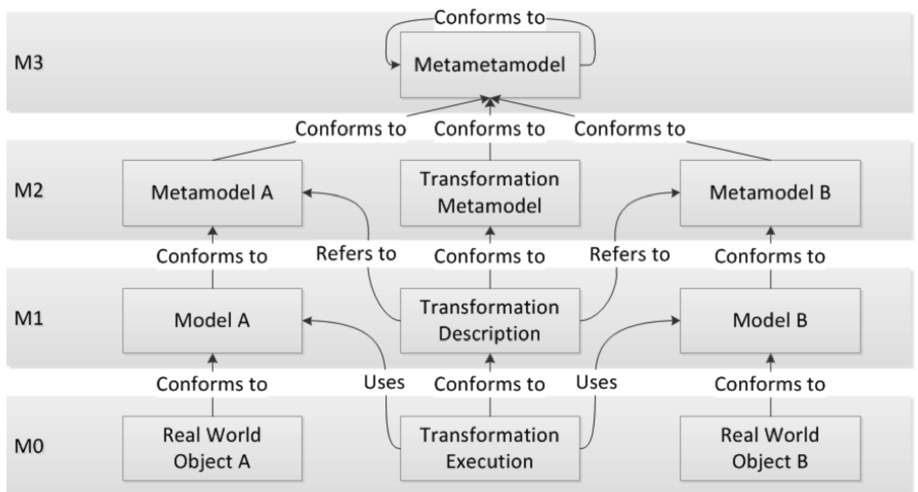


Figure 2.11: The metalevels of a model transformation [Bie10]

concepts that explicitly use *architectural engineering* and *model transformation*, the FIDJI methodology includes a process for developing model transformations.

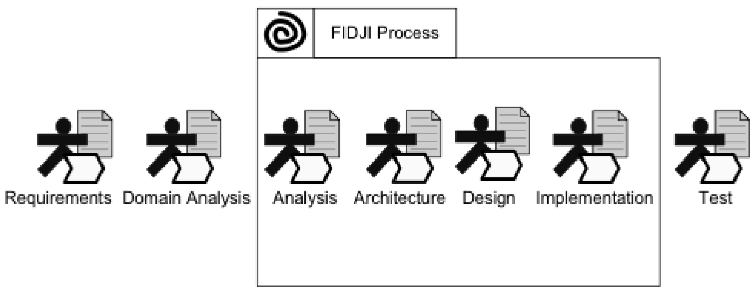


Figure 2.12: The FIDJI approach coverage [GP04]

Figure 2.12 shows the coverage of the FIDJI methodology in software development. It includes the *analysis*, *architecture*, *design* and *implementation modelling process*.

In the analysis phase, models are produced to provide a precise definition of system requirements. Analysis models represent sets of functions of a system using UML Use Case diagrams, and when necessary, using UML Class and Activity

diagrams.

Architectural modelling includes the production of three intermediate models: (1) a user experience diagram; (2) required transformations; and (3) architectural framework. A user experience diagram includes the interface and navigation structure details, partly generated from the analysis model. Required transformations are derived from the analysis model and the architectural framework. Architectural framework provided with the FIDJI approach includes; *abstraction classes* and an *enterprise component interface*.

In summary, UML models are used to design the system by instantiating the architectural framework profile. Design models are platform-independent models (PIMs), which will be transformed into platform-specific models (PSMs), and eventually, into the final code.

The FIDJI approach includes case tools that implement the JAFAR framework (J2EE Architectural FrAmewoRk), graph-based model transformation specification language[1], Visual Model Transformation (VMT) and a transformer (the UML Generic Model Transformer tool (MEDAL)) [GP04].

The second process for developing model transformation is presented in [KRH05]. The proposed process is based on a case study of business process model transformation. The process supports iterative and incremental production of model transformation related artefacts. The model transformation development process is shown in Figure 2.13.

The development process includes the following phases: (1) requirements; (2) analysis; (3) design; (4) implementation; and (5) testing. In the requirements phase, an analysis of requirements is performed informally, to identify the key requirements of model transformation.

In the design phase, a *high-level* and *low-level* design is produced based on the requirements. High-level design contains a set of rules, represented semi-formally using concrete syntax of models associated with the transformation. The rule defined in high-level design is used as an informal guide to discover possible cases of transformation. Rules are described based on *graph transformation*, they have a left and right side description, and contain *application conditions*, written in plain text.

[1]We define model transformation specification language further in Section 2.6.

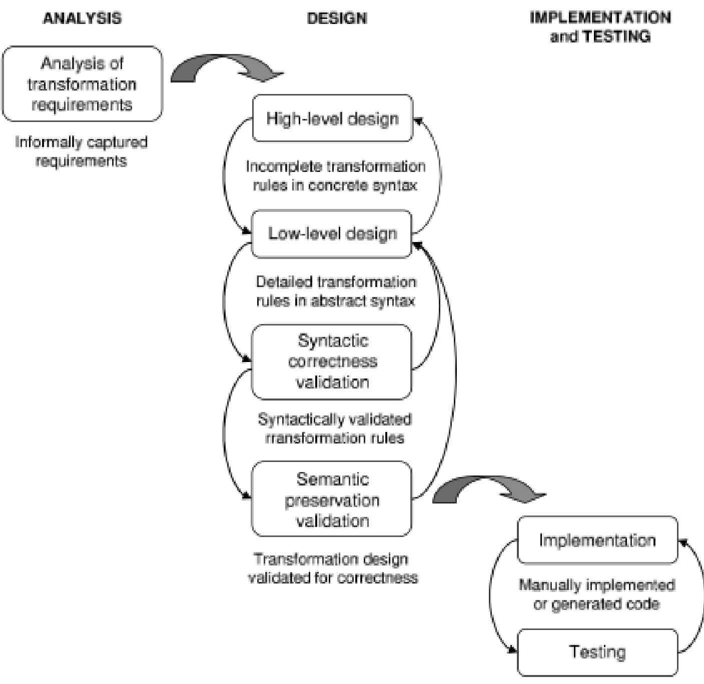


Figure 2.13: The model transformation development process [KRH05]

A low-level design is produced to refine rules in high-level design, using model transformation specification language. The language used is based on existing graph-based languages [MB03; Wil03; Mil02; CHM$^+$02; BNvK06]. The rule defined has a similar left and right side description in a form of *graphical patterns* using the UML Object diagram.

The implementations can be generated or manually produced based on the specified rule in the low-level design. Testing is performed to ensure the transformation satisfies the requirements.

2.5.1 Remarks

We have presented two approaches to software development that use model transformation. Both model transformation development processes share some characteristics; (1) specifies model transformation using a graph-based language, and

(2) implementation specific development, which uses UML models and UML-supported technology.

In terms of analysis of model transformation, both approaches support this feature differently. The analysis ensures that the transformation developed in the approach fulfils the requirements. The following describes the analysis methods by both approaches:

- The VMT used in FIDJI can be expressed in terms of graph transformation rules, which gives the language a formal semantics [SPGB03]. The *rule ordering* features in VMT enables model transformation to be defined in terms of chains of smaller transformations. Which therefore allows properties such as *termination* and *confluence* to be checked [SPGB03].

- Validation of *syntactic correctness* and *semantic preservation* is conducted manually in the low-level design through inspection of the specifications [KRH05]. Further testing is performed after implementation.

We present a more comprehensive review on model transformation analysis in Section 2.13.

In both of the model transformation development processes presented in this section, there were phases focusing on dealing with how a model transformation specification is produced to represent the rules required in a transformation. In the next section, we define what is a model transformation specification.

2.6 Model transformation specification

When we look again at the metalevel of model transformation in Figure 2.11, the transformation description (or transformation definition in Figure 2.10) can also be known as *model transformation specification*.

A model transformation specification is represented using a domain specific modelling language for defining model transformation. The language provides syntax and semantics specialised for defining transformation mappings between the source and target models. There are several model transformation specification languages, not only able to specify, but can also be executed by a transformation engine. To distinguish between an executable and a non-executable model

transformation specification language, a *model transformation language* refers to an executable model transformation specification.

Non-executable model transformation specification language shares the same classification as an executable model transformation language. An example of non-executable specification language includes, The Bidirectional Object Oriented Transformation Language (BOTL) [BM03], Visual Model Transformation (VMT) [SPGB03] and Extended UML Object Diagram [Mil02]. Model transformation specification language can be categorized into three major paradigms, (1) declarative, (2) imperative and, (3) hybrid model transformation language.

Declarative languages. Declarative model transformation specification languages describe what a transformation should do, without considering how it should be done. Examples of declarative model transformation language are Fujaba[1], Tefkat [LS06] and QVT-Relations [QVT08].

Imperative languages. Imperative model transformation specification languages can also be known as procedural or operational languages. Examples of imperative model transformation languages are MOLA [KCS05] and SiTRa [ABE+06].

Hybrid languages. Hybrid model transformation specification languages support both declarative and imperative features. Some examples of hybrid model transformation language are Epsilon Transformation Language (ETL)[2], Atlas Transformation Language (ATL) [JABK08] and Graph Rewriting and Transformation (GReAT)[3].

Czarnecki and Helson in [CH06] further define model transformation language into: (1) direct manipulation; (2) structure driven; (3) template-based; (4) relational; and (5) graph-based. As a result, model transformation languages can

[1]Fujaba: http://www.fujaba.de/

[2]Epsilon ransformation Language: http://www.eclipse.org/epsilon/

[3]GReAT: http://www.isis.vanderbilt.edu/tools/GReAT

belong to several categories, for example, QVT-Relation is a *declarative - relational* type, SiTRa is an *imperative - direct manipulation* type; and GReAT is a *hybrid - graph-based* type model transformation language.

Some of the languages are supported by a common platform. For example, Tefkat, ATL and ETL can be developed within the Eclipse Modelling Framework.

One of the objectives of this thesis is to use visual notation to represent model transformation specification. The following section discusses current graphical model transformation specification.

2.6.1 Graphical model transformation specification

Model transformation specification language can be textual or graphical. Currently, much of the language for model transformation is textual, while there are only a few graphical languages for model transformation. The most prominent are often based on graph languages such as Fujaba, GReAT and transML [GdLK+10]. This is due to the capability of these languages to use the formalism underlying graph theory to produce a well-formed transformation.

There are other graphical languages that are not based on graph theory. For example, MOLA [KCS05] defines model transformation using structured flowcharts, mimicking structured programming languages. [RM08] proposes a notation that has a similar definition to model weaving, providing concrete syntax and general well-formedness rules of a transformation. But their notation still requires a textual description for specifying the mappings and actions of a transformation.

Model transformation specification can described as different model transformation scenarios, as presented in the following section.

2.7 Model transformation scenarios

Model transformation can be categorized into several scenarios: (1) model-to-model (M2M); (2) model-to-text (M2T); (3) text-to-model (T2M); and (3) text-to-text (T2T) transformation. An M2M takes a model and transforms it into another model, perhaps a model at another level of abstraction (or sometimes

called a *refinement*) or a model at the same level of abstraction (for example UML Sequence Diagram to UML Statechart[1]). A M2T transformation produces text; a concrete example is code generation. Code can be in the form of, (1) programming language such as Java or C++[2], or (2) formal specification, such as UML to CSP [BN04]. A T2M transformation is concerned with parsing and the reverse engineering domain; while T2T transformation can be used for generating reports.

Other model transformation scenarios that are worth noting, are model synchronization, conformance checking and update-in-place [JK07]. Model synchronization allows any changes between two models to be made according to a predefined relation, while conformance checking enables two models to be compared, based on a set of relations without changing the models. Update-in-place transformation changes elements within the same model, for example, in model refactoring.

To define the scenarios in terms of their location in the four-layer architecture presented in Subsection 2.3.1, models taking part in a model transformation could reside in the same, or different level of abstraction. The models could share the same metamodel or they could come from different metamodels. The model transformation, according to the model locations and metamodels, can be distinguished into the following [MG06]:

- Endogenous
- Exogenous
- Vertical
- Horizontal

Figure 2.14 summarises the characteristics of these model transformations in the four-layer architecture. *Endogenous* and *exogenous transformation* involves transformation between models within the same level of abstraction; endogenous involves models of the same language, while exogenous involves models of different languages. Endogenous can also be dubbed as *rephrasing*, and exogenous as

[1]ATL transformation zoo: http://www.eclipse.org/atl/atlTransformations/

[2]Rational System Developer: http://www-01.ibm.com

translation [MG06]. An example of an endogenous transformation, is a transformation of UML Class to UML Profile[1]. For an exogenous transformation, there is an ATL translation from Ecore to KM3 model (EMF2KM3)[2]. Both endogenous and exogenous are types of *horizontal transformation*, because the same level of abstraction applies to the source and target models. Transformation between models that reside in a different level of abstraction, is called *vertical transformation*. An example of a vertical transformation, is the transformation of an Ecore model into Java code[3].

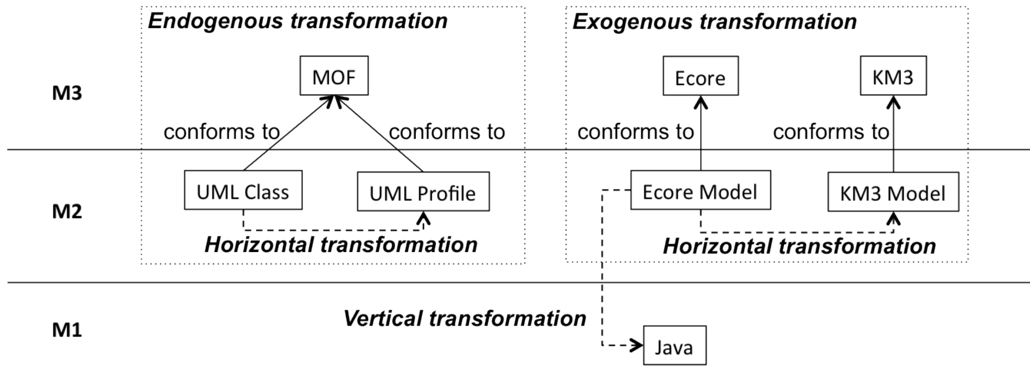


Figure 2.14: Examples of model transformation types

2.7.1 Remarks

Since the OMG QVT Request For Proposal [GGKH05], a variety of model transformation specifications have been proposed. Despite managing to introduce interoperability of models with concepts, such as abstraction with metamodels and model serialization technology, the variations in model transformation specifications have presented a new challenge, whereby any transformation specification explicitly needs to include platform specific details. When a chain of transformations is required, dealing with compatibility of languages between transformations could be an issue.

[1]Source: http://www.eclipse.org/atl/atlTransformations/UMLCD2UMLProfile

[2]Source: http://www.eclipse.org/atl/atlTransformations/EMF2KM3

[3]Source: http://www.eclipse.org/modeling/emf/?project=emf

Another issue is with regarding graphical model transformation specification languages that are often based on *graph theory*. Despite the fact that visual modelling provides a clearer representation, hence ease of comprehension, with a graph-based model, it introduces some level of complexity, partly due to the different concepts (eg. graph rewriting) as compared to common modelling language for programming. Instead, a non-graph-based model transformation language such as ETL, which resembles programming concepts, arguably, seems to be more accepted. This can be seen through a better tool support for non-graph-based language such as ETL. This allows a quick knowledge transfer for the developer when migrating to MDE.

In terms of analysis of model transformation specifications, there are two common approaches: (1) producing a mathematical-based model transformation specification and manually proving the properties; and (2) implementing an executable model transformation specification to enable tool supported analysis, such as *testing*. We describe analysis of model transformation specification further in Section 2.13.

At this point, we have established what is a model, metamodel and model transformation; and how these components play a part in implementing the MDE. In the final section on MDE, we briefly present several of the standards and tools that implement MDE.

2.8 MDE standards and tools

Model-Driven Architecture (MDA), a second framework adopted by Object Management Group (OMG) [MDA03], is a standardized instance of MDE. MDA highlights the concept of MDE by introducing the five key concepts of: (1) viewpoints; (2) Platform-Independent Model (PIM); (3) Computational Independent Model (CIM); (4) Platform-Specific Model (PSM); and (5) model transformation.

Model Integrated Computing (MIC) provided an implementation of MDE. MIC is created for complex, safety-critical systems [Dav02] and uses the Multigraph Architecture (MGA) framework[SK97]. MIC introduces the computational process of a system via integrated, multiple-view models that enable characteristics of a system, such as: (1) information processing; (2) physical architecture

features; and (3) operational features, to be captured. To provide a configurable modelling environment, MGA framework implements the Generic Modelling Environment, which provides a suite of tools for development [LMB+01].

Microsoft's Software Factory (SF)[1] is another example of MDE standards, which focuses on product line development [GSC+04]. SF has a component called the *software schema* that captures the domain knowledge of a product family. Software schema is defined as graph viewpoints that contain information for producing product members. Each viewpoint generates a model editor for building models that can be translated into, (1) executable code, or (2) specification of lower level of abstraction. A collection of patterns are derived from these, which are stored as software templates for when it is loaded into an IDE, such as Microsoft's Visual Studio. It is kept as a software factory to be used for developing product members.

2.9 Remarks

We have reviewed the key aspects of MDE; its key components, implementations and processes. The argued benefits of adopting MDE in performing software development can be summarized as the following:

Tool interoperability. Tool interoperability is concerned with allowing artefacts to be used in different tool platforms. Metamodel, model and model serialization technology allows model transformation artefacts to be performed on multiple platforms. For example, the MOF metamodel, can be used to define an object-oriented language such as UML, and XMI as a metadata interchange that enables a UML model to be used with different UML-based modelling tools.

Artefact reusability. The application of abstraction and refinement potentially allows artefacts to be reused in multiple settings. Artefacts such as a domain metamodel and a system model, could potentially be reused in different projects,

[1]MSDN Website - Visual Studio 2010: http://msdn.microsoft.com

provided they are compatible with the requirements.

In the second part of the chapter, we look specifically at how analysis of models, metamodels and transformations are done in the context of MDE.

2.10 Analysis in MDE

To recap, our motivation for this thesis is to accommodate the formal analysis of the model transformation specifications. The major challenges in implementing MDE, as presented in [FR07], can generally be classified as follows:

Modelling language challenges including those related to support for creating and using *problem-level abstractions*, or domain concepts, and for analysing models.

Separation of concerns challenges including the use of multiple, sometimes overlapping viewpoints, using possibly different languages.

Model manipulation and management challenges which focus on the capabilities of MDE tools to manage and manipulate MDE artefacts. For example, (1) defining, analysing, and using model transformations; (2) maintaining traceability links between model elements to support model evolution and round-trip engineering; (3) maintaining consistency between viewpoints; (4) tracking versions; and (5) using models during runtime.

A reliable implementation is one that adequately satisfies a set of requirements established early in the development. The reliability of an implementation of any software project depends on the fitness of artefacts produced during development. These artefacts can be analysed, either in a specific phase, i.e. after an integration or a version of implementation, or on individual artefacts after they have been produced. In the context of MDE, artefacts are strongly related; faults and errors may originate from the metamodel, model or the model transformation.

This outlines the needs for analysis of each of the artefacts in an effort to catch any anomalies at an individual phase of the development.

The analysis activity can be varied, depending on the types of artefact, but generally, it is in the form of *validation*, *verification* or *testing*. Here, we use Balci's definitions of validation, verification and testing, in the context of modelling and simulation [Bal98]:

> *"**Model Verification** is substantiating that the model is transformed from one form into another, as intended, with sufficient accuracy. [..] **Model Validation** is substantiating that the model, within its domain of applicability, behaves with satisfactory accuracy consistent with the modelling and simulation objectives. [..] **Model Testing** is ascertaining whether inaccuracies or errors exist in the model."*[Bal98]

We used these definitions to classify the validation, verification and testing in the context of MDE, due to the fact that it was formulated especially for modelling, simulation, and model transformation. To extend the our understanding of what needs to be done to ensure a fit model transformation, we have also classified the perspectives into three, (1) model analysis, (2) metamodel analysis, and (3) model transformation analysis.

2.11 Analysis of models

MDE relies on the concept of abstractions, defining the separation of concerns to describe a system. This is done using models to represent the different viewpoints in the domain. A precise model not only represents the intended system correctly, but also prepares a valid model to be used or generated in a transformation.

As defined early in the chapter, models in MDE can be in the form of a *diagram*, *code* or *mathematical specification*. The issue with analysing these models is no different to how they are analysed when used in other kinds of development. Models in MDE are used as an input, or generated as the output of a model transformation. Models needs to satisfy the *system requirements*. This

should not be confused with the *transformation requirements*; transformation requirements define the transformation features that enables models to satisfy the system requirements, to be used or generated by a model transformation.

Here, we focused on analysis of diagrammatic models. Diagrammatic models or *visual models* in MDE can be, but not necessarily, *object-oriented (OO)*. In terms of design analysis of an OO model, this can be generally categorized into: (1) understanding of the problem domain; (2) identifying the requirements; (3) including scalability and adaptability; and (4) encouraging reuse [CY91].

While through these processes, models should be sufficient to represent a valid instance, we may need to perform further analysis to ensure the well-formedness and correctness of models to represents the whole universe of instances.

To verify a model is accurate for all known instances, it must be validated that the model satisfies the system requirements, or tested to see if any anomalies exist in the model. In addition, two consistency aspects of models have to be evaluated, (1) static, and (2) dynamic features. In terms of static feature analysis, consistency refers to the well-formedness of *relations* between object classes, while dynamic features are concerned with *states* and *sequences of interactions* between object classes [RW03].

Diagrammatic notations such as UML have an auxiliary construct, the OCL [WK03], that helps further refine the well-formedness constraint on models using textual expressions. OCL incorporates rules and assertions, such as preconditions, postconditions and invariants in UML models [BC06], to precisely specify the semantics of objects. Due to this, various work has been done to perform analysis on UML models using OCL. In some this is done by translating them into formal, mathematical-based languages to allow them to be computed for analysis [BC06; CCGdL09; KFdB+05; ABGR10]. While some other analyses of UML models, are supported by tools[1], which provide an automated analysis of the consistency of models through constraint, for example, identifying any violation of constraint that results in an non-existent model or semantically incorrect model.

In the larger context of MDE, models are one of the components that contribute to production of the final product during transformations. Ensuring that

[1]Reational Software Architect: http://www.ibm.com/developerworks/rational/products/rsa/

models are a valid and sufficient representation of a domain, should eliminate the first source of faults and errors in a transformation.

Analysing a model in MDE includes making sure that it is conforming to its metamodels. In the next section, we presents the analysis of a metamodel, for providing the formal support for models, to produce a fit input and output model in a transformation.

2.12 Analysis of metamodels

A metamodel is a special kind of model that provides the syntax and semantics for another model. In MDE, metamodels contain elements and properties that define the input and output models of a transformation. These elements and properties are used in mapping the transformation relations between the source and target models.

Metamodels are defined in terms of *classes* and *relations*. Given that a metamodel is a kind of model, analysis to ensure the well-formedness of a metamodel can adopt a similar approach to the analysis of models [GPHS08]. Furthermore, the concepts of classes and relations in a metamodel, even though this is more on abstract levels, are the same as in a class model [GPHS08]. Therefore, it is appropriate that validation, verification and testing of a class model are applied to analysing a metamodel.

In general, when applied in the context of MDE, analysing a metamodel addresses the modelling language challenges that relate to the capturing of the problem domain. Establishing that a metamodel is well-formed, not only provides a valid input and output model for a transformation [VP03], but also includes ensuring, (1) the compatibility of metamodels to be used in a transformation[KAER07], and (2) sufficient elements for transformation [WKC06] due to the variations of conditions a metamodel can have.

In the next section, we presents the analysis of model transformation.

2.13 Analysis of model transformation

Analysing model transformation generally aims to address some of the challenges related to model manipulation and management tasks. We focus on analysing the model transformation specification to ensure that the transformation is capable of producing a correct final product. A model transformation engine executes rules that define the mapping between the source elements and target elements, that are defined using model transformation language. The analysis of model transformation is not complete without also analysing the artefacts used in a transformation. We have covered some methods of how models and metamodels can be analysed in the previous sections.

Model transformation analysis can be divided into *static* and *dynamic analysis* [SCD12]. Static analysis is when an analysis can be perform without executable implementations, while dynamic analysis needs some kind of executable implementation to enable the states of models to be observed [SCD12]. Model transformation analysis can be performed using several approaches, significant ones includes: (1) testing [Lam07; BFS+06; KAER07]; (2) formal methods [WKK+09; LLM+07; ABK07]; and (3) simulation [WKK+09; ABK07].

In terms of ensuring the reliability of model transformation as a whole, it requires techniques to measure the *properties* of a model transformation. Currently, there are various approaches to how a model transformation can be analysed. Each has a set of characteristics, which distinguishes its uses to evaluate different properties of a model transformation. The following defines the properties desired in a reliable implementation of model transformation [KAER07]:

- Metamodel coverage
- Syntactically correct model
- Semantically correct model
- Semantically correct transformation
- Confluence and termination

2.13.1 Metamodel coverage

Metamodel coverage refers to the coverage of model transformation to transform the source to the target model, according to desired transformation requirements [WKC06]. Metamodel coverage can also be called *syntactic completeness* [VP03].

This property is important, as any lack of coverage produces an *incomplete model*, which can be due to, (1) transformation not transforming elements, due to missing rules, or (2) transformation rules not being applied, due to missing or incompatible types of source element [KAER07].

The problem with a metamodel is that it has various forms (explained in Section 2.3). Performing an analysis for metamodel coverage ensures a metamodel is sufficient to be used with the transformation. Model transformation needs to ensure that every *case feature* [Küs04] of a metamodel is included in the transformation.

An example of a situation where a metamodel coverage analysis would be needed, is when the input model is only a subset of a bigger model. The metamodel should only include the subset of elements relating only to the input model. Or, if a set of elements have different configurations, a model transformation should be able to handle each configuration. To achieve complete coverage of a metamodel, a process called *contextualisation* can be performed. Details on contextualisation of a metamodel is presented in Chapter 5.

Related works on metamodel coverage include an approach proposed by Wang et al. [WKC06] that checks metamodel coverage by analysing details of *feature coverage*, *inheritance coverage* and *association coverage* from a Tefkat implementation.

2.13.2 Syntactically correct model

An input model for a model transformation has to be a valid instance of its metamodel. Likewise, the generated target model, after a model transformation has to conformed to its metamodel [VP03; KAER07]. The transformation model must also conform to its metamodel.

A model has to be syntactically correct for every instance of a model transformation. The result of a syntactically incorrect model violates the constraint

defined in the metamodel [KAER07]. This could happen when a transformation rule incorrectly updates a model [KAER07]. Lack of metamodel coverage, or a non-confluent transformation can also produce a syntactically incorrect model.

For example, when a transformation is applied to remove a whole-class in a composition, a model is syntactically correct if the part-class is also removed. To spot this error, a model can be inspected against a metamodel, possibly with tool support [KAER07].

2.13.3 Semantically correct model

A semantically correct model is required in a reliable transformation. The fault in this is subtle but undesirable as it can produce a model that conforms, syntactically, to the target metamodel, but not be semantically correct [KAER07; EE08].

This can happen when the wrong rule is applied to the source model [KAER07]. For example, a transformation of a class without a primary attribute could generate a table with an empty primary key column. This is syntactically conforming, but not semantically correct, as the primary key cannot be empty.

A fault in semantics of models can be identified with the help of tools that validate the model against the constraints specified in the metamodel[1]

2.13.4 Semantically correct transformation

A semantically correct transformation is a guarantee that a model transformation preserves the desired properties from metamodels and transformation requirements [KAER07]. A semantically correct transformation also includes a transformation that preserves the model semantics or produces a semantic equivalence model [Küs04; HKR^{+}10].

These properties are directly dependent on the syntactical and semantic correctness of transformation [KAER07]. The problem with semantic equivalence could also arise from different viewpoints that overlap when describing the common aspects of a system. Or, the *horizontal consistency* [EKHG01], and *vertical*

[1] Rational Software Architect: http://www.ibm.com/developerworks/rational/products/rsa/

consistency that relate to transformation features, such as refinement and behavioural properties [KAER07; EKHG01]. If a transformation is not capable of preserving the semantics, it will produce a semantically incorrect model.

An example of a semantically correct transformation is when a transformation factorizes a UML Class and OCL into a new model, it has to preserve the semantics of the original model [BM07]. This can be assured by evaluating the initial constraint against the new model [BM07].

To note, semantically correct transformation that produce a model conforming to its metamodel, is compulsory in a transformation. However, semantic preservation may not be the case in some transformations, for example, generating matrices for a UML Class diagram.

2.13.5 Confluence and termination

Confluence and termination are two properties that compliment each other. A confluence model transformation produces a unique, deterministic target model every time a transformation is applied to the same input model [VP03; Küs06; KAER07]. Non-confluence in a model transformation could also be caused when an intermediate model cannot be transformed any further, i.e. terminates unexpectedly [KAER07]. These properties are particularly important for a rule-based transformation [Küs04].

In a non-confluent transformation, the order during the application of rules in a transformation is not independent. A different application generates different output. [dLT04] presents an approach using the *critical pair analysis* to identify when a transformation is not confluent.

2.14 Tool support analysis of model transformation

In MDE, much of the validation, verification and testing of transformation properties have some kind of tool support. These tools are often specific to a model transformation language. The following are a few of the tool-supported solutions

to verification, validation and testing of model transformation provided by the literature.

For verification of model transformation, work by Wang [WKC06] defines properties and algorithms for verifying meta-model coverage of a Tefkat transformation specification on EMF tool. While Wimmer et al. [WKK+09] defines behavioural properties and a custom state space function to track and observe the origin of errors when transformation is using Transformation Nets (TNs) on Colored Petri Nets (CPN).

For validation of model transformation, Poernomo [Poe08] proposes a mathematical approach to writing model transformations, which enable proof checks of the well-formedness of the transformation using Constructive Type Theory (CTT). While Lengyel et al. [LLM+07] and Cabot et al. [CCGdL09] propose a way to validate model transformation by extracting the OCL invariants that constrain the model transformation.

For the testing of a model transformation, there are *Black-box* and *white-box* testing approaches. Black-box testing, or *functional testing* is concerned with verifying the functional requirements of the system, while the white-box testing, or *structural testing*, takes into account the details of the implementation structure of the system [Lam07]. Most literature on the challenges of applying testing to model transformation focuses on the issue of test case generation. For black-box, test cases can be generated from the input language metamodel [BFS+06] while for the white-box, test cases have to be based on the design and implementation of model transformation [KAER07].

2.15 Remarks

In the second part of the chapter we have presented the analysis in the context of MDE implementation. Analysis in MDE includes validation, verification and testing of models, metamodels and model transformations.

Generically, analysis in MDE can be categorized into two stages: (1) at model and metamodel; and (2) at model transformation development. The reason for this, is to enable most faults and errors to be detected and eliminated before the models and metamodels are used for model transformation. Analysis at model

and metamodel level is fairly common, using object-oriented analysis methods and tools. For model transformation, properties are proprietary for model transformation, therefore, approaches and tools are specific for handling the transformation.

Analysis of desired properties in a transformation is important to ensure a reliable model transformation implementation. In relation to this thesis, the analysis of model transformation has to include the checking of these properties, though compromises and limitations may arise, based on the capability of the chosen analysis approach.

Focusing on analysis of model transformation, the current situation seems to prefer an analysed implementation approach for testing for model transformation properties. This is expected, as model transformation development is often implementation oriented, therefore, analyses are more practical when there are executables.

One final observation of analysis of model transformation is that, based on the experience of the writer, only a few practical (ie. tool supported and easy comprehension approach) applications of formal methods are available for analysis of model transformation. Apart from formalism provided when model transformations are specified in graph-based languages, formal based analysis often requires a different set of skills and rigorous application to check for model transformation properties.

2.16 Chapter remarks

In relation to our objective of research, we would like to extend some of the challenges, and define the gaps we are addressing in this thesis.

2.16.1 Formally analysing relational model transformation at specification level

We presented two software engineering approaches [KRH05; GP04] that include the development of model transformation. Both cover the processes from identifying requirements to implementations, and provide some methods for manual

analysis at specification level, using graph-based language. Manual analysis, especially using mathematical-based methods, is rigorous and complex. Another preferred approach for non-graph-based model transformation languages, such as relational-based transformations, is testing implementation, which is often chosen as a method for checking model transformation properties [GV11]. There should be an approach that supports a practical formal analysis, with tool support, at the model transformation specification level for non-graph-based model transformation languages, particularly, for the relational type transformations.

2.16.2 Metamodel and transformation feature coverage

The variation of metamodel conditions for models, which can be huge, readily-available and non-existent, raise some issues that relate to providing sufficient coverage in a transformation. [WKC06] proposed a way for checking the metamodel and feature coverage via implementation. Finding problems during implementation could cause a change in a specification, which may produce inconsistencies in the existing specifications. Therefore, discovering insufficiencies at specification level can avoid problems during implementation.

2.16.3 Standard documentation of model transformation

Another problem with applying model transformation in MDE is the lack of formal documentation that specifies the features of artefacts, such as metamodel, model and model transformation. We need to have a framework that allows transformation engineers to plan, design and build a transformation that is reliable and satisfies the requirements, as well as documents their specifications.

2.17 Summary

This chapter has presented Model Driven Engineering, discussing its features, components and technological spaces. MDE has shown how a model can be the center of software development, and automation of development methods can be

made possible. Still, MDE poses challenges that need to be addressed, particularly in ensuring the consistency and well-formedness of models and transformation used in the development. We have presented several analysis issues in the context of MDE. The following chapter will discuss the topic of formal analysis for model transformation.

Chapter 3

Literature review on formal analysis

In Chapter 2, we presented MDE and reviewed its principles and technology, highlighting model transformation specification development and analysis.

This chapter extends the review to focus on the background to analysing model transformation using formal methods. Formal *mathematical-based* methods have been applied in the past in analysing model transformation. Though less mathematical approaches, like testing, have been more widely applied. Testing is necessary and applicable to implementation, but not specifications, as most of them are non-executable.

If we want to support early analysis, we need to use formal methods. To recap our research objectives, we aim to provide an approach to specifying and formally analysing model transformation specification on a conceptual level (before implementation). Most often, transformation engineers develop transformations and implement them intuitively; verification makes use of testing often unsystematically. We want to have a formal approach to validate and verify model transformation specifications before implementation. However, we need to do this while exposing less of the formalism to the transformation engineers.

In this chapter, we proceed with a review of how formal methods can be used to analyse model transformation, beginning with defining what is formal, in Section 3.1, followed by integration of formal methods in MDE, in Section 3.4.

Then, we outline the language requirements for identification of formal specification language for an effective analysis of model transformation, in Section 3.2. We identify potential formal specification languages for our framework in Section 3.3. We have selected and reviewed the formal specification languages in Section 3.5. Finally, we briefly present a formal template language in Section 3.6. We conclude our review of the chapter in Section 3.7.

3.1 Formal specification language

The underlying concept of formal specification language is mathematics. A formal specification language provides a mechanism to formally define properties without ambiguity. Spivey [Spi92] defines formal specification as the "*use of mathematical notation to describe in a precise way the properties which an information system must have, without unduly constraining the way in which these properties are achieved*". A formal specification can be used to represent design features of a system, which can be used at later stage of development for evolution, testing and maintenance [WD96]. A formal specification language can be interpreted by a machine, and thus, "*mechanize logical reasoning*" [MP93], based on a description of a problem domain. Logical reasoning uses the advantages of abstraction in defining concepts of a particular system domain via "mathematical data-types" [Spi92].

The formal specification languages can have various kinds of application. Some of the examples include: (1) formally defining system properties which can be analysed for consistency and well-formedness, for example, using languages such as Z notation [Am7; PG08]; (2) simulating model properties, for example, using Alloy [ABK07] and Maude [BCR06]; (3) describing behaviour through mathematical functions, for example, using the λ calculus [Poe08]; and (4) translating OCL constraint in a model into formal language, to allow it to be analysed [BM07].

3.2 Identifying formal specification language for effective formal analysis of model transformation

To incorporate formal analysis into analysing model transformation, a practical approach has to be defined to reduce the complexity of using a formal specification language.

Formal specification languages consist of a well-defined syntax and semantics. Most formal languages have specific logical representation capabilities that are targeted for generic application. To apply formal methods in the context of analysing model transformation, the formal specification language has to be able to represent model transformation concepts and properties.

Formal specification language can be classified into two types: (1) light-weight; and (2) heavy-duty [Hei98]. Light-weight techniques refers to the application of formal methods that do not require much mathematical knowledge or theorem proving skills (example, Alloy and Eiffle's Design by Contract). On the other hand, a heavy-duty technique needs someone with serious mathematical skills to concoct axioms and perform strategic formal proofs (such as, Z and PVS). To provide a practical approach to analysis of model transformation, formal specification language has to be easy to use, therefore is has to be light-weight, as well as appropriate.

[Hei98] defines a set of characteristics of practical formal methods. The following describes the characteristics (taken from [Hei98]).

Reduce the effort and expertise to apply formal methods. A practical formal analysis needs to have certain features: (1) be easy to use and understand notations, so that the application of formal methods can be more intuitive and natural; (2) automated analysis that eliminates the need for manual proofs; and (3) clear and understandable analysis feedback that points to the origins of error.

Tool suite. A practical formal method needs to have a tool supporting several analysis aspects. Usually, tools for formal specifications support only certain

logical methods. Formal analysis may require a multiple perspective coverage, therefore, a tool suite can include a consistency checker, simulator or theorem prover.

Integrate formal methods into a development process. Applying formal methods is not an isolated process to analyse software artefacts. Instead formal methods can be integrated into the current software development process, for example; in object-oriented development, formal methods should be used to formalise and reason about object-oriented models.

Provide simulation capabilities. Simulation provides a symbolic representation of the execution of a formal specification. Simulating a specification can demonstrate that the specification behaves as expected and can also be used to check for other properties of interest. Simulation is practical as it provides an automatic analysis of formal specifications.

3.2.1 Remarks

We have seen a set of criteria of practical formal methods. In the context of this thesis, we want to build on these criteria of practicality features by incorporating a *visual notation for model transformation*. Current visual model transformation languages that incorporate formal methods, still require rigorous application and are often implementation specific, such as graph-based model transformation specification [SCD12]. We aim to create a notation that captures model transformation features in a conceptual model, which is implementation independent and expresses enough detail to describe a transformation that can be used to perform analysis of model transformation properties. In terms of tool capability, we also need to be able to do consistency checking, to check if a model is type-checked and well-formed.

We need to find practical formal methods that can support an effective model transformation specification and analysis. In the next section, we look at potential

formal methods that are not just practical, but capable of representing model transformations and their properties.

3.3 Potential language and tools

Much formalism applied to model transformation is based on the application of graph theory [ALS+12]. The reason for this is because of its compatibility with a well-establish formal analysis approach using language such as Petri Nets [Mur89] that can provide a sound analysis, with tool support.

Two other works on formalization of model transformation are presented in [Poe08] and [ABK07]. Both approaches treat model transformation as programs and represent them in terms of functions. [Poe08] suggests that a model transformation is a higher-order *typed functional program* and uses *type theory* to define model transformation features, which then can be used to produce a *lambda calculus* specification via *extraction*. [ABK07] defines mappings of transformation specifications and well-formedness rules into Alloy, and uses simulation to detect flaws in the specifications.

Inherently, MDE builds on the features of object-oriented programming, and model transformations are themselves models. Therefore, the formal methods that support object-oriented concepts, also have the potential to be used in this framework. Z [WD96] and B [Abr96] notations are both model-based formal specification languages that can be use to support the object-oriented concept. These languages have not been applied in the context of analysing model transformation.

3.3.1 Remarks

There are many formal languages that have the potential to be used to formally analyse model transformations. We require a practical formal specification language that can provide an effective formal analysis, without the complexity of heavy-duty formal methods, while supporting our pattern-based approach to analyse model transformations.

Looking at the languages we stated in this section, each of them has the capabilities and potential to support analysis of model transformation, but we need to find one suitable for our framework.

Petri Nets is a state based language that is useful to represent the dynamic aspect of a system. Specification with Petri Nets, particularly for analysis, requires engineers to really go into detail in defining each state within a system. This activity is extensive and could get out of bounds for analysis if applied for complex systems. Furthermore, mapping a state-based model to a relational model could create more challenges. For example, if we need to specify a relational-based transformation using Petri Nets, we have to make sure the well-formedness properties in the Petri Nets model are preserved in transformation model.

Looking at methods that have been applied to analyse model transformation, the type theory, they also require proofs. Also, the extraction mapping to lambda calculus gets complicated with more complex transformation [Poe08], which again, does not fulfil the requirements we need to provide a practical formal method.

Z and B both have a strong formal foundation and are flexible enough to be applied to analyse model transformation, but they are proof based and not fundamentally object-oriented. Z in particular, has several adaptations to object-oriented methodology. For example, Z has a language that extends to object-oriented concepts, called the Object-Z [Smi00], and ZOO [APS05] has an object-oriented approach for template-generated Z. One interesting fact about the ZOO approach [APS05] is that the Formal Template Language (FTL) allows Z to be generated from a UML Class diagram. However, an expert person with formal skills is still needed to understand and oversee the proof strategies of the specification. Here is where we get our inspiration to adopt FTL into our framework, but to address the expertise issues, we have to find a practical formal specification language.

Even though Z can be applied in the object-oriented context, for some characteristics, where we want to provide practical formal methods for analysing model transformation, they were missing. For example, a Z specification cannot be combined with another specification; the specification has to be concatenate, which also needs to consider the organization of Z schemas [DD93]. This could

be a problem in applying Z for analysing model transformation. Although it is possible to include metamodel and transformation specification in one model, it would be an issue when a correct metamodel specification is updated to include transformation mapping, where it might violate some of the existing proof. B is related to Z, but it has a better unit management that allows seamless *inclusions* of new specifications [DD93]. B is also more implementation oriented, which is attractive to be integrated in model transformation specification. Even though both Z and B have tool support, their notations use mathematical symbols which seem less intuitive to the engineers. Another reason why neither Z or B are the language we are looking for, is that they do not provide simulation capabilities.

Apart from these languages, other formal methods such as Eiffel Design by Contract (DbC) [Mey92] and SPARK Pro [1], which have some capabilities of a lightweight method, also have the potential to be used to analyse model transformation. DbC has an underlying object-oriented principle that should be able to address model transformation concepts, while SPARK Pro is a tool suite that provides proof automation, which could ease the complexity of using formal methods. Both implement *contracts* for ensuring correctness and do not have simulation capabilities.

Finally, there is Alloy for analysing model transformation. Alloy is a notation that uses natural language for its specifications (no unconventional symbols), which eases the construction and readability of the specification. Components of Alloy language substantiate object-oriented techniques [Jac12], therefore, ease of adaptation due to known, well-established concepts of software development and MDE. Alloy comes with a tool, the Alloy Analyzer[2] that executes Alloy specification for analysis that includes, *simulation* of system behaviour and consistency checking. We will present in a later chapter how instances producde from simulation can be used to detect *under-constraint* and *over-constraint*. In terms of modularity of specification between model transformation components, Alloy supports multiple specifications.

With these, we believe Alloy can provide the practical formal specification language we needed for our approach. Using FTL to link our modelling language

[1]SPARK Pro website: http://www.adacore.com/sparkpro/

[2]Alloy Analyzer: http://alloy.mit.edu/

to Alloy, could provide the needed practicality for formal analysis of model transformation specification. To note, [ABK07] works do not have a framework that specifically supports analysis of model transformation specification using patterns and templates. Even though [ABK07] claims that the limitation of using Alloy is scalability, our approach has managed to provide a solution to this issue.

3.4 Formal methods integration with MDE

Using a formal method for analysing a system requires engineers to be well versed with both the application domain and the formal language itself [Hal90; BH95]. Currently, application of formal methods with MDE involves deep knowledge of the formal language, some of the existing work has been discussed in the previous section.

Formal methods in MDE have been used to ensure that properties of models, metamodels, and model transformations hold. In Chapter 2, we have reviewed some of these properties and approaches, but here, we further highlight analysis that is enabled using formal methods.

The task of analysing model transformation using formal methods is usually tool and case specific. Depending on the model transformation implementation platform, formal analysis may be integrated or independently performed by other formal analysis tools. Work presented in [WKK+09], proposed an integrated framework, TROPIC, for verifying model transformation using a DSL called Transformation Nets (TNs). These are used to represent structural and behavioural properties of the transformation, which could be fully translated into Color Petri Nets (CPNs) for simulation and analysis. On the other hand, in [ABK07], Anastasakis et al. presented an application of model transformation analysis using the Alloy notation and the Alloy Analyzer tool, which is independent from any kind of implementation, but have issues with scalability and a lack of specific processes and documentation.

Faults and errors in model transformations can originate from various sources. For example, a semantic error in a transformation can manifest from a syntactically correct but semantically incorrect input model, which may be due to an imprecise specification of a metamodel. Current approaches to the analysis of

model transformation, intend to discover semantic errors by analysing the whole model transformation specification. Ideally some of the faults and errors can be eliminated, if the input model is validated and verified *before* it is used in a transformation. Analysing input and output models for transformation can be done independently, by applying formal analysis of models using formal notation such as UML to B [SB01; LCA04], UML to Alloy [ABGR10] and UML to Z [Am7] (tool by [Wil09]). However, to date, they have not been included as part of the analysis of model transformation.

3.5 Alloy

Alloy [Jac12] is a declarative, Z-based, first-order logic modelling language. It extracts Z's features that are essential for object modelling and creates a lightweight specification language that is less formal [Jac02]. The notations of Alloy use ASCII characters, therefore a basic text editor is sufficient for documenting Alloy specifications [Bar10]. Alloy's kernel has semantics that are expressive enough to cover complex properties, while still amenable to efficient analysis [Jac02].

There are two kinds of analysis supported in Alloy: (1) simulation, where model properties are visualized to demonstrate state and transition of the specification, detecting over-constraint if no instance are found; and (2) checking, where assertions are used to test the specification for any counter-example, which could be caused by the under-constraint of the specification [Jac02]. To date, Alloy has shown its capabilities for detecting anomalies in models of graph transformations [BS06], visual models [SyF05; Bar10] and architectural framework [JS00].

An Alloy specification represents the abstraction of the system in question, just like the UML but with a mathematical foundation. Alloy specification defines properties using the concept of *atoms* and *relations.* The atom concept is almost similar to the notion of classes in object-oriented. They are immutable and cannot be broken further. An atom's actions and behaviours are described via relations.

The Alloy model is amenable to automated analysis. The Alloy Analyzer is a tool to analyse Alloy specification by verifying consistency of model properties, simulating valid model invariants and checking for any counter-example, to show the existence of invalid instances of the model. Alloy Analyzer provides fully

automated analysis via SAT solvers. Alloy models are translated into boolean constraints that permit SAT to find satisfiable assignments for all variables. There are various SAT solvers available off-the-shelf, to be used with the Alloy Analyzer, for example Kodkod[1], a constraint solver for first order logic.

Alloy automated analysis create instances via its run command. To be able to generate at least one instance, the scope has to consider the minimal number of elements that creates a valid instance. It is recommended that the number or range of instances for each element (signatures) is individually defined for a more effective coverage by the scope. The default scope for Alloy Analyzer is 3, which stated the bounds of search for each signature instances at most 3, unless defined otherwise [Jac12]. The scope give finiteness to the number of instance to be discovered.

Listing 3.1 gives the skeleton of an Alloy model. *Signature* (`sig`) is a construct for defining atoms, and *field name* defines any relations that an atom could have. *Fact* (`fact`) declares the constraint of a model property that always holds. A *predicate* (`pred`) and *function* (`fun`) are additional facts, that have names and parameter constraints, which only hold for a certain condition. The different between predicate and function is such that, a predicate returns *true* or *false*, while a function can return a *value*. *Assertion* (`assert`) is a statement about model properties that are assumed to be valid, and they can be executed by selection using `check` statement, looking for any counter-example. The `run` statement looks for instances within a finite scope, as defined by the user.

```
1  //<comment
2  sig <name>{
3    <fieldName1>: <multiplicity> <fieldType1>,
4    <fieldName_n>: <multiplicity> <fieldType_n>
5  }
6  fact <name>{
7    <constrain1>
8    <constraint_n>
9  }
10 pred <name> [<parameter1>: <domain1>, <parameter_n>: <domain_n>]{
11   <constrain1>
12   <constraint_n>
```

[1] Kodkod: http://alloy.mit.edu/kodkod/index.html.

```
}
fun <name> [<parameter1>: <domain1>, <parameter_n>: <domain_n>]
    :<domain> {
  <body evaluate value in domain>
}
assert <name> {
  <constrain1>
  <constraint_n>
}
check <name> for <scopeSize> but <exception>
run {}
```

Listing 3.1: Alloy generic syntax

3.6 Formal Template Language

The Formal Template Language (FTL) is a template language developed in [APS05], for the GeFoRME approach to formal verification of UML Class and State diagrams using ZOO. There is an example of another use of FTL in [WS10] for formalizing a relational model into Z. FTL is used to represent formal templates, which are instantiated to give a specification that is correct by construction, provided the underlying model is consistent. Although the initial purpose of creating FTL is for producing Z, the language is general enough to be used for any language [APS05]. In the context of this thesis, FTL is used to formalize a specification model into Alloy specification, as presented in Chapter 6, 7 and 8.

The FTL abstract mechanism uses the concept of *variables* to allow varying values to be included at any point in a sentence structure. During instantiation, the variables are substituted with the value in context. FTL consists of four main constructs [APS05]:

Text The static part of a target language, that is always true at every instantiation, is provided by the text.

Place-holder Allows variables to be substituted during template instantiation. The variable is represented by the place-holder, enclosed within $\ll$ and $\gg$.

List Specifies a list term that comprises of text and parameters and possibly another list, denoted within $[\![$ and $]\!]$. When using a place-holder within the list, the variable is an *indexed variable*.

Choice Provides selection of instantiation. Choices in FTL have two types; optional, denoted within $(\!($ and $)\!)^?$ and multiple, denoted $(\!($ and $)\!)$ with $\|$ in between selections. Optional indicates that an instantiation may be performed, while multiple requires that at least one instantiation has to be selected.

An example of how FTL works, given an *informal template* of Z schema, is as follows [WS10]:

$$Name \mathrel{\widehat=} \left[\, declaration \mid predicates \,\right]$$

Here, *Name*, *declaration* and *predicates* are variables that can be included as appropriately required. This informal template description can be represented formally using FTL as follows:

$$\ll Name \gg \mathrel{\widehat=} \left[[\![\ll declaration \gg]\!] \mid [\![\ll declaration \gg]\!] \right]$$

The ZOO approach has been implemented in the AUtoZ tools which automate the instantiations of the ZOO templates [Wil09]. The capabilities of AUtoZ include [Wil09] , (1) template translation, (2) template instantiation, and (3) theorem proving. The tool is implemented as an Eclipse plug-in[1] and uses Epsilon components[2] and the Epsilon Generation Language (EGL)[3]. EGL is a model-to-text language that allows transformation of serial models into textual artefacts.

[1]Eclipse: http://www.eclipse.org/

[2]Epsilon: http://www.eclipse.org/epsilon/

[3]Epsilon Generation Language: http://www.eclipse.org/epsilon/doc/egl/

3.7 Chapter remarks

To recap, our research aim to specify and formally analyse model transformation specifications. We have established that currently, development of model transformations are often ad-hoc, and most analysis techniques are either at implementation level using the testing approach. Or, using graph-based methods for model transformation definition and analysis at specification level.

We have also established that we need to include analysis of models and metamodels, to capture any faults that could manifest from an incorrect specification of models and metamodels, before they ared used to specify model transformations.

Currently, we do not have a standard documentation of model transformation that enables model transformation specifications to be planned and conceptually designed for implementation. Therefore, we need to have a family of modelling languages for these purposes.

The modelling language for model transformation must be tractable and amenable to formal analysis. Our selected formal specification language to be used must be practical (Alloy), and in extension to this, we integrate a visual notation, provided by the modelling language. The notations instantiate formal templates (FTL) that represent patterns of model transformation, mechanizing the production of formal model transformation specification, which can be used to simulate (Alloy Analyzer) to analyse model transformation specifications.

3.8 Summary

This chapter has presented the related issues to formal methods and how they have been applied to analyse model transformation. Even though formal methods appear not to be the favourite choice for this, due to their rigorous application, they have displayed promising techniques for establishing all the correct properties for generating a high quality final MDE product. We have highlighted the approach we are going to use in our framework. In the following chapter, we introduce the framework for specifying and formally analysing model transformation specifications.

Chapter 4

Framework for specification and formal analysis of model transformation

We have established a level of understanding of our research domain, the MDE and formal analysis in Chapter 2 and Chapter 3. Based on the reviews, we claim that there has not yet been established a systematic way of specifying and formally analysing model transformation specification using a pattern and template-based approach. We propose to address this by a framework, called the TSpecProber, that supports the process of developing a reliable and well-formed model transformation specification. This chapter introduces the concepts and components of our proposed framework.

We begin the chapter with the introduction to the framework (Section 4.1 and 4.2), followed by the presentation of the components in Section 4.3. Then we introduce the processes for specifying and analysing model transformation in Section 4.4. In Section 4.7 onwards, we describe the details of the key components in this framework. Finally, we present a scheme for tool supporting this framework in Section 4.9.

4.1 The TSpecProber Framework

The Oxford dictionary [CS05] defines the verb *probe* as to "*explore or examine (something), especially with the hands or an instrument*". Fittingly, for defining the purpose of our approach, we called our proposed framework, the TSpecProber (TSP) (formerly known an TranS-DV [SPP11]). TSP provides the infrastructure for transformation engineers to specify model transformation specification at a conceptual level, using an intuitive and compact graphical design notation for structural and behavioural features, which then can be *examined*, via formal analysis.

From the literature, we have agreed that just applying a formal method to analyse transformation has an unacceptable overhead in effort, due to its elaborate concepts, and it requires expertise. In the TSP framework, we address these issues by hiding the formalism via three key features: (1) a set of visual notation for conceptually specifying model transformation; (2) a practical formal specification language; and (3) use of formal templates that correspond to the notation. We further support the framework by providing a set of processes, specifically to develop model transformations that assist the transformation engineers' way of thinking about the design of the model transformation. This not only creates a methodical way of reasoning about the design decision, but also provides a convention for documentation of model transformation specification.

TSP is a facility for planning and designing model transformation specifications, using a diagrammatic modelling notation, that has the capability to instantiate a *correct-by-construction* formal template, which is used to generate the formal specification with analysis capability. By adapting the processes from conventional software engineering, TSP covers the process from eliciting requirements for transformation, to the design of a model transformation specification and its analysis.

4.2 TSP framework coverage

The TSP framework applies at the conceptual level where it focuses on having the right specification for an implementation. Figure 4.1 depicts the TSP framework

coverage for specifying and formally analysing model transformation. We introduce new models, defined in the next sections, that cover the specification and analysis of model transformation components. The TSP models can be extended to accommodate implementation based on the transformation engine, but this is a whole new challenge and we have suspended the research in this area for future work.

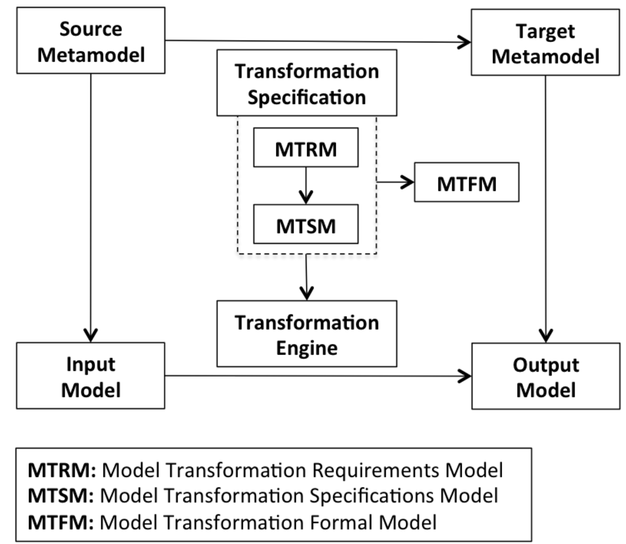


Figure 4.1: TSP framework coverage for model transformation

4.3 Components of TSP framework

The TSP is made up of several interrelated components for defining and formally analysing model transformation. The components can be divided into four main groups, the (1) requirements models; (2) specification models; (3) templates catalogue; and (4) formal specification models. TSP components are illustrated in Figure 4.2.

The following parts describe each of the TSP components.

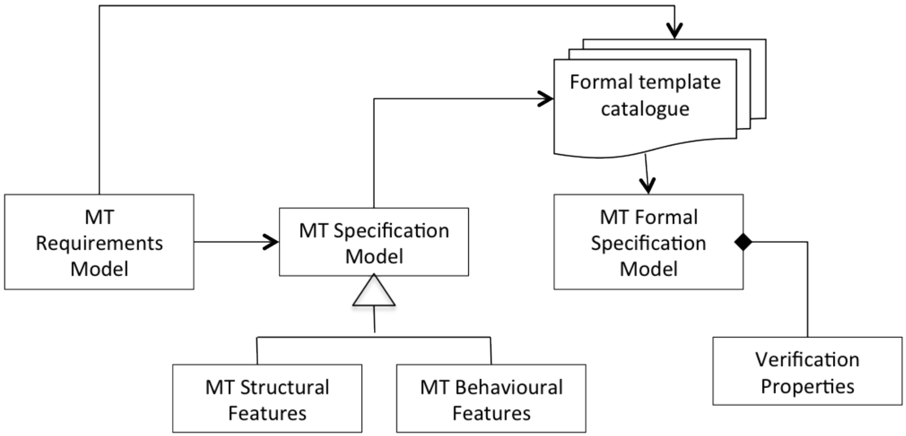


Figure 4.2: TSP components

4.3.1 Model Transformation Requirements Model

The TSP framework suggests that eliciting and documenting model transformation specification, features decisions which encourage transformation engineers to focus on requirements and the scope of a transformation. The Model Transformation Requirements Model (MTRM) defines additional views for eliciting the requirements of model transformation in extension to system requirements, therefore strategically aiding the process of discovering the requirements and formally defining of each of the elements required in a transformation.

The elicited requirement is presented in a form of a table. The requirements table is an informal model which records the features of a transformation, classified by views. The views represent aspects of a transformation specification, ie. domains, instances and transformation features.

We adopted using tables to represent our informal requirements model from SysML [Sys]. In fact, many requirements are documented in tabular form[1].

There are two consequent outcomes of the requirements tables, the (1) requirements model; and (2) the user metamodel. The requirements model contains a

[1]See: http://www.klariti.com/software-development-lifecycle-templates/functional-requirements-specification-template/

hierarchical, diagrammatic view of the model transformation requirements, giving the requirements a formal representation. These are used later for defining the the mapping model. These are presented in detail in Chapter 5.

4.3.2 Model Transformation Specification Model

The TSP provides a visual representation of a model transformation. There are three types of Model Transformation Specification Model (MTSM), the (1) user metamodels (source and target), (2) mapping models, and (3) transformation phases.

The user metamodels are *contextualised metamodels* of the source and target metamodel for the transformation under development, produced from the requirements tables. Contextualized, in this context, refers to a *meaningful* metamodel that includes only the elements needed for a transformation. Certain special relationships between elements have a formal definitions, allowing analysis of well-formedness and correctness. Contextualization optimizes the metamodel and thus, reduces complexity. Contextualization also allows user metamodels to be formally analysed for well-formedness and correctness. A metamodel in a transformation can have several forms: (1) huge metamodel; (2) readily-available metamodel; and (3) non-existent metamodel. The reason we need to create a user metamodel, is to prepare a sufficient metamodel for the transformation by: (1) extracting a subset of elements from huge metamodels; (2) ensuring the readily-available metamodels are appropriate for the transformation; and (3) producing a metamodel for a transformation. Producing a user metamodel is explained in Chapter 5 and analysing a user metamodel is presented in Chapter 6.

The mapping model is the result of extracting the required rules of a transformation from the requirements model. It defines the associating source and target elements to the rules of the transformation. Generating mapping is defined in Chapter 7.

The rules in the mapping model are used in defining the transformation phases. TSP defines the model transformation specification using phases to modularize model transformation specification, and at the same time encour-

aging scalability and re-usability. Phasing of model transformation specification is demonstrated in Chapter 7

4.3.3 Formal Template Catalogue

To hide the formalism from the transformation engineers, we adopted the template-based approach to produce a formal specification, which enables an automated formal analysis. The template catalogue contains formal templates to produce Alloy fragments instantiated by TSP models. Templates are defined using the FTL (see Section 3.6).

In Chapter 3, we have identified Alloy as a practical formal specification language that is appropriate to be integrated into TSP framework. Our template catalogue will be used for producing Alloy specifications.

The Alloy template catalogue can be classified into several parts; each of them has a specific focus, representing patterns of model transformation, and formally defining transformation specification, to enable effective simulation and verification of the specification using the Alloy model checker. The following describes the purpose of parts of Alloy templates catalogue:

Module Provides a header that links all related files (includes TSpecProber Alloy generics) and global conditions. An example of the content of generics, is the definition of multiplicity.

User metamodel Describes the structural and behavioural features of user metamodels. The user metamodel templates are divided into two parts, *class* and *relation.*

Model transformation specification model Defines the structural and behavioural features of transformation phases.

Model Instances Corresponds to the instance model patterns defined by the transformation engineers. There are two types of instance model template, one is for user metamodels, and the other extends to represent model transformation. This template is used to perform our pattern snapshot analysis.

4.3.4 Model Transformation Formal Specification Model

Each instantiation of a template creates parts of a Model Transformation Formal Specification Model (MTFM). There are three types of MTFM: (1) source and target user metamodel formal specifications; (2) model transformation formal specifications; and (3) instance source, target and model transformation formal specifications.

4.4 Process for model transformation specification development and analysis

The TSP aims to cover the whole process, from planning and designing, to implementing model transformations, while ensuring that most requirements are captured and anomalies are discovered early, before it becomes expensive to mend later in the development. The generic process for TSP is shown in Figure 4.3.

The processes in TSP support incremental development, where model transformation can be developed part-by-part. In contrast to [KRH05], which presents an incremental process for model transformation development between high-level and low-level model transformation specification, TSP model transformation development explicitly defines a stage where the metamodel definition is developed. Requirements elicitation iteratively identifies the prerequisite of the development of a model transformation, which determines the outcome in the subsequent steps; the defined metamodels, mapping organizations, rule composition and refinement. The analysis is a recurring process during the specification of these components. Ultimately, the specifications can be used for producing transformation implementations. The extension of TSP to implementation is not in the scope of this thesis, but the consideration has been included in defining the approach.

TSP provides steps for specifying and analysing model transformation. Figure 4.4 shows a detailed process of TSP in six steps, which includes the outcomes and relations of the TSP components.

Step 1: Eliciting Requirements - performs the process of identifying models, metamodels and transformation requirements. Here, transformation engineers

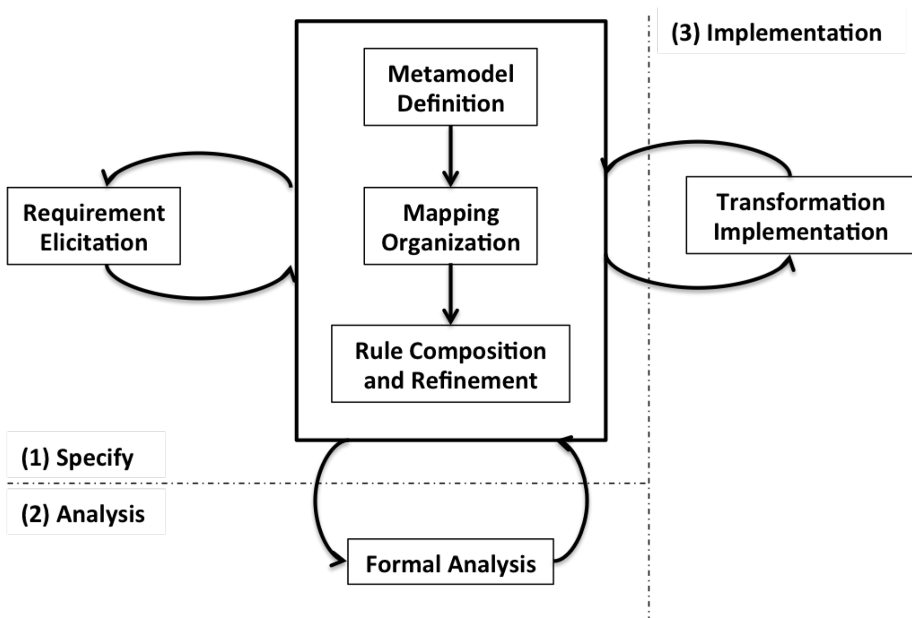


Figure 4.3: TSP abstract processes

create a requirements table that contains informal design decisions for model transformation components. These are presented in Chapter 5. **Outcomes:** Requirement tables.

Step 2: Contextualizing user metamodel - performs the process of discovering the minimal set of elements and their relations required for a transformation. This step allows transformation engineers to prepare the user metamodel for model transformation specification. The user metamodel includes predefined relation behavioural using stereotypes for variatios of *generalization* and *association*. Requirements tables are presented in Chapter 5. **Outcomes:** Source and target user metamodels.

Step 3: Analysis of the user metamodel - performs the process of applying the templates to produce a formal specification of the user source and target metamodel. It also analyses the specification by finding models and verifying the user metamodel using positive and negative pattern snapshots. These are presented

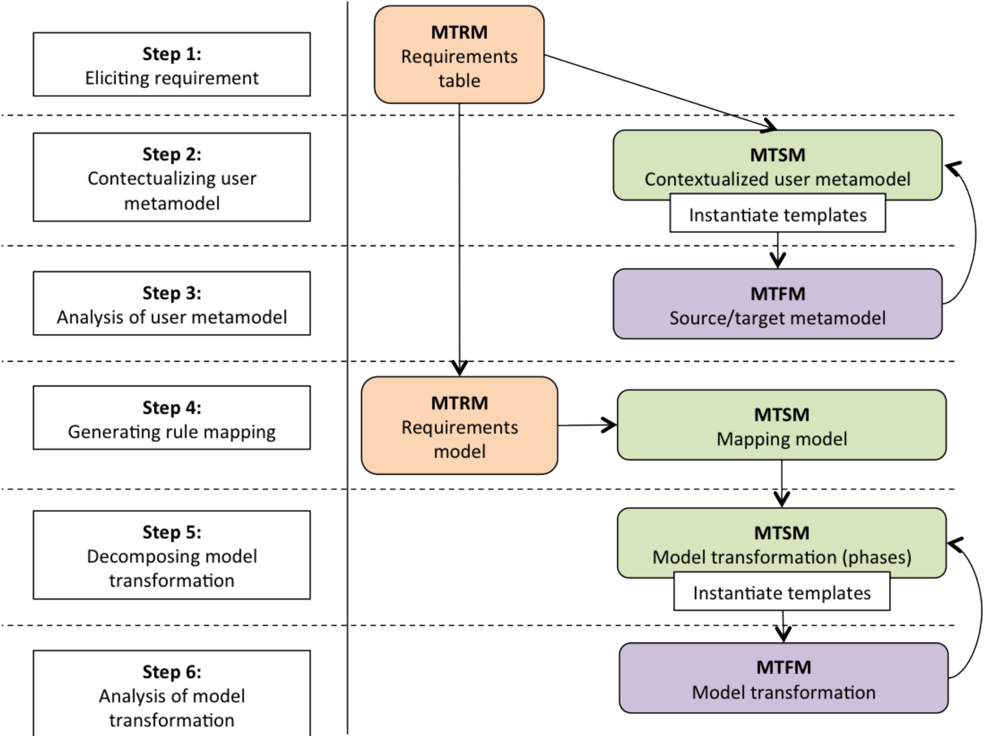


Figure 4.4: TSP steps and outcomes

in Chapter 6. **Outcomes:** Source and target user metamodel formal specifications, and source and target user metamodel instance model formal specifications.

Step 4: Generating rule mapping - performs the process of extracting rules from the requirements model to produce a rule mapping model. These are presented in Chapter 7. **Outcome:** Requirements model and rule mapping model.

Step 5: Decomposing model transformation - performs the process of breaking down model transformation into phases and refining model transformation components, to include structural and behavioural features. These are presented in Chapter 7. **Outcomes:** Model transformation specification.

Step 6: Analysis of model transformation - performs the process of applying templates to produce a formal specification of the model transformation

phases, and analyse the specification by verifying model transformation specifications using positive and negative pattern snapshots. These are presented in Chapter 7. **Outcomes:** Model transformation formal specifications and transformation instance model formal specifications.

4.5 Model structure

TSP framework produces three types of model: (1) an informal model for aiding design and analysis patterns; (2) a specification model for defining model transformation features; and (3) a formal specification for analysis of model transformation (Alloy model). TSP models are as depicted in Figure 4.5.

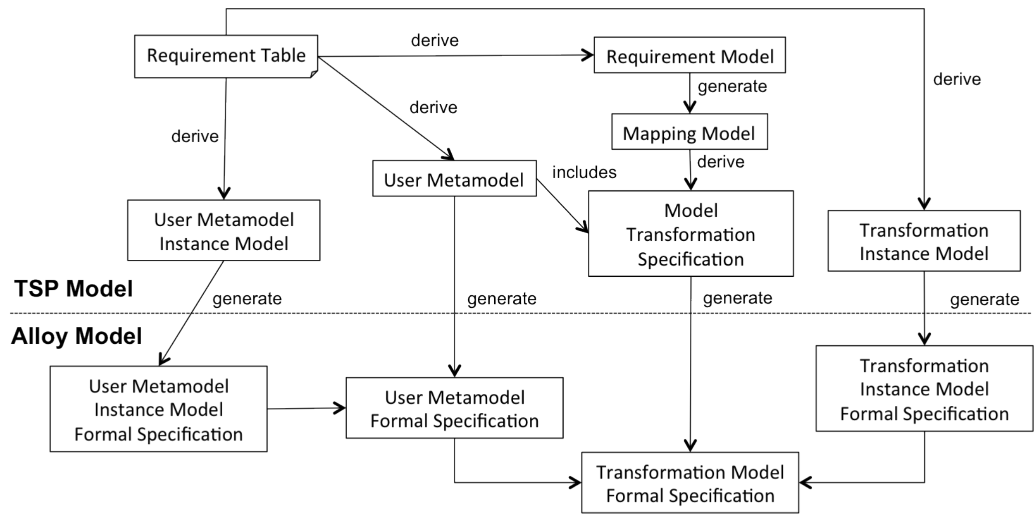


Figure 4.5: TSP model structure

A requirements table is an informal model that contains textual details on requirements for a transformation. The requirements table is used to derive the, (1) requirement model; (2) user metamodel; (3) user metamodel instance model; and (4) transformation instance model. The requirement model is used to generate mapping model. Model transformation specification is the result of decomposition and refinement of the mapping model. Decomposition and refinement applies to the user metamodels.

The templates are used to generate an Alloy model from the user metamodel and model transformation specification. To analyse the user metamodel, its instance model is formed, based on the requirements from the requirements table. The instance model (user metamodel instance model) is translated and used against the user metamodel formal specification. Similar to model transformation formal specification, a transformation instance model is derived from the requirements table, instantiates templates to generate formal specification and is used against model transformation formal specification for analysis.

4.6 Patterns for specifying and analysis of model transformation

One of the factors that enables TSP to accommodate the production of formal specifications, is identifying patterns for model transformations. There have been several works defining patterns for model transformation. One of the earliest works, Akehurst et al. in [AKP03], defines patterns of metamodel abstract, concrete and semantic syntaxes. Iacob et al. [ISH08], present several high-level rule transformation patterns, and Goldschmidt et al. [GU11] proposes patterns for managing bidirectional transformation changes using trace information.

These examples do not explicitly relate to analysis of model transformations, though they suggest an approach for creating better transformation specifications. In the TSP, patterns for model transformation are used to define the structural and behavioural features. Some of the patterns have attached conditions that define additional details such as *structural integrity*. Structural integrity enables structural features of model transformation to be correctly constrained. The constraint is automatically applied when patterns instantiate templates. For example, Figure 4.6 shows a reflexive association $\boldsymbol{r}$ for class $\boldsymbol{S}$ that is acyclic, and its integrity constraint.

Another kind of pattern applied in the TSP framework is the *positive* and *negative* pattern, for analysing TSP models using the *pattern snapshot analysis*. In [Am7], the positive and negative scenario is defined to perform the *snapshot analysis* to analyse the dynamic behaviour UML+Z model. An identical concept

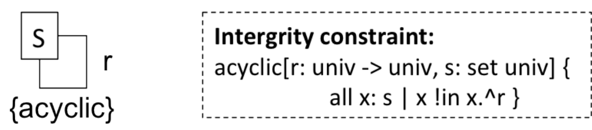


Figure 4.6: Acyclic reflexive association pattern with integrity constraint

is used in [GdLW+12], where positive and negative patterns are used as a *contract* for model transformation.

The snapshot analysis is a mechanism that creates *assertions* for analysing model transformation. This substitutes the need to manually write Alloy *assert expression* for checking TSP models.

4.7 Graphical notations for specifying model transformation

The TSP modelling language enables model transformation to be specified visually. It includes notations for graphically representing source and target metamodels and model transformation specifications. The language is designed to be supported by the templates in the Templates Catalogue. Modelling language instances instantiate templates that produce formal specifications that can be use for analysis.

The analysis adopts the concept of transML [GdLKP10] in defining positive and negative patterns for source, target and transformation models, which will be transformed into Alloy for verification. In TSP, these patterns instantiate a specific set of templates which can be used against the generated model transformation formal specifications.

Model transformation specification in TSP is conceptual, any platform specific implementation details are to be considered in extension to the process of generating implementation later. Therefore, the specification is focused on defining the essences of the transformation, which are the domain specifications and transformation features.

The TSP modelling language is part of the TSP framework. It corresponds to the steps for specifying and analysing model transformation specifications. Therefore, the design decisions made using this language are defined systematically, and it is possible that the defined model transformation specifications can be used to produce *correct-by-design* formal specifications.

4.7.1 Phasing

The TSP modelling language for model transformation adopts the phasing mechanism [CM09] to specify transformation. The main reason for this, is to address the issues with scalability of Alloy that needs more processing resources and time to analyse bigger models. Applying phases in our specification allows model transformation to be decomposed into smaller units, therefore allowing a more compact analysis of the transformation. More benefits that come with applying phasing are that it provides the facility to modularise model transformation which encourages reuse. Phasing used in this framework is discussed in detail in Chapter 7 Subsection 7.2.3.

4.8 Model transformation analysis with Alloy

In attempting to capture the relations in a model transformation system, we have to determine how these relations are to be defined and understand how they are interpreted in Alloy. Fundamentally, it bores down to how a first order logic is used to address complex relations, such as model transformation systems.

4.8.1 Model transformation representation in Alloy

When we formalize our user metamodel, the relations are between a set of elements. Applying first order logic is appropriate to represent the syntax and semantics of the domain. But when we need to extend the specification to include a mapping between the two sets of relations in the source and target user metamodel, we need to define a perspective on how a representation using first order logic can be made. Here, we define how we specify the model transformation in Alloy.

An example of a common transformation is depicted in Figure 4.7, where we have a specification that transforms **A** (that has a one-to-many relation, *ab*, to **B** of a domain), into **X** (that has a one-to-many relation, *xy*, to **Y** of another domain).

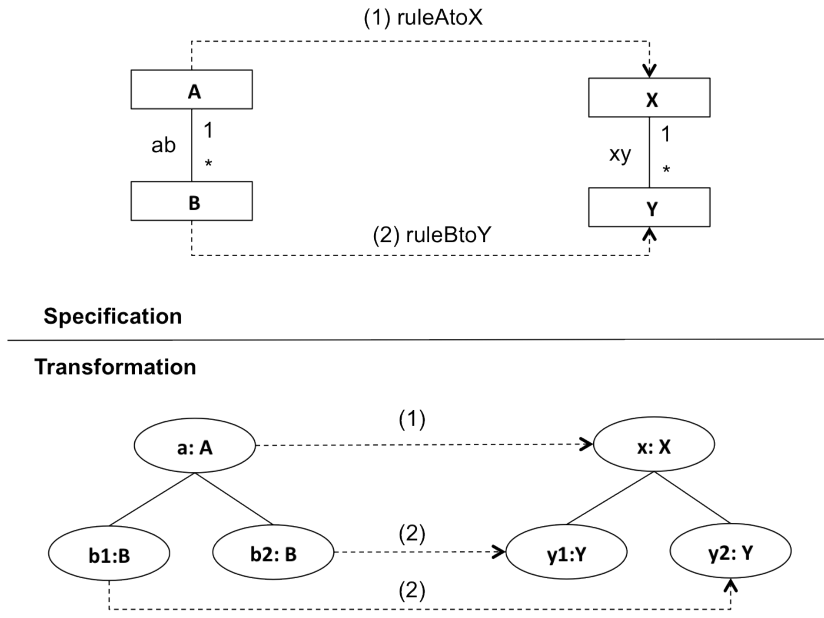


Figure 4.7: The relation between a specification and transformation

When executing the specification, a transformation engine performs traversal over the node of the source model and applies the rule to generate the target model. In Alloy, a formal specification that represents a similar transformation specification, each rule mapping reflects the relations of an instance of the source to another instance of a target element. Therefore, it does not apply the rule and generate the final target model as depicted in Figure 4.7. Instead, the instance generated presents the result of applying each rule once, for an instance of an element. This creates a series of possible instances based on one rule application. Figure 4.8 shows the possible instances generated from the specification.

The reason for defining the differences between the specification and the actual transformation is to show how we can use the specification for analysing the model transformation. The static analysis is based on an instance of singular

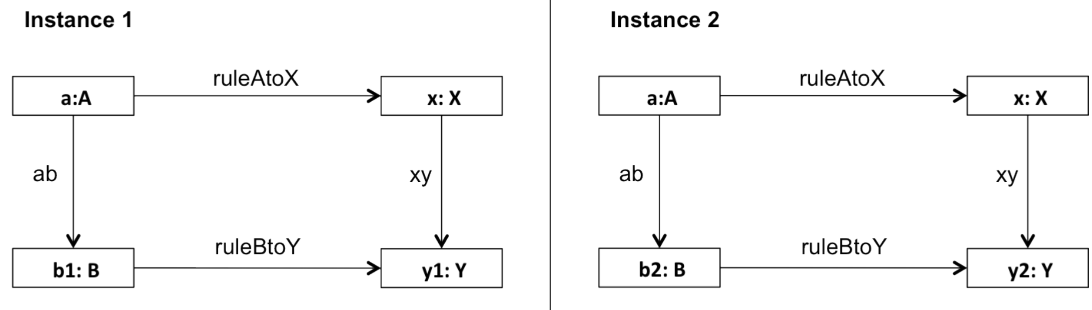


Figure 4.8: Two instances generated from specification of transformation in Figure 4.7

rule applications. With the static analysis, we can check the well-formedness of a specification in terms of model transformation's structural properties, such as ensuring *metamodel coverage*, a *syntactically and semantically correct model*, and a *semantically correct transformation*

To include dynamic analysis, we need to include functions and predicates that define the behaviour of instances using *pre-state* and *post-state conditions*. By having this, we can capture all instances, and possibly, perform queries about properties, such as *confluence* and *termination*.

4.9 TSP Tool Support

Having tool support allows transformation engineers to develop TSP models and automates the instantiation of templates for analysis. AUtoZ [Wil09] is a tool that implement the GeFoRME approach in [Am7]. AUtoZ provide an automatic instantiation of ZOO templates for analysing UML Class diagram.

For this thesis, we have developed an elementary prototype tool[1] , that allows the generation of an Alloy model from a TSP model to be mechanised (Figure 4.9). We build the tool on Eclipse, and use XML to represent and persist our TSP models. A Java program implements the instantiation rules provided by the

[1]TSP Tool can be downloaded at: https://sites.google.com/a/york.ac.uk/tspecprober/

templates to generate Alloy. A specific Java package will produce an Alloy model (MTFM artefacts) from a TSP model (depicted in Figure 4.5).

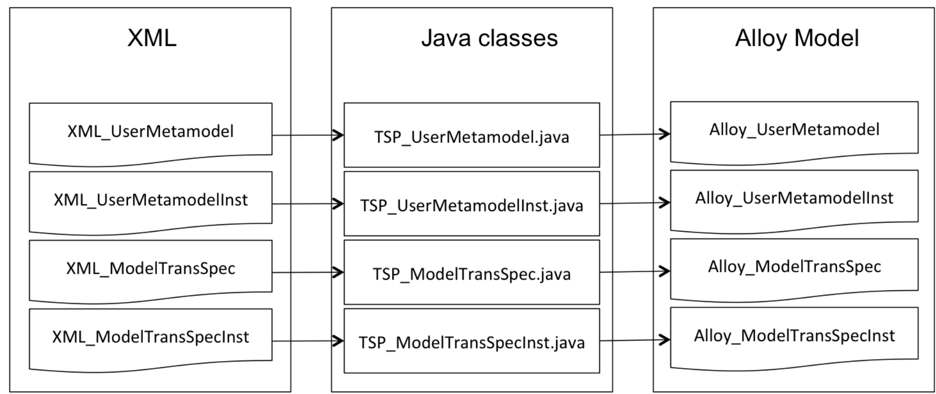


Figure 4.9: TSP tool prototype - elementary version

The following demonstrates how to generate an Alloy model from a TSP model. Figure 4.10 shows a TSP User Metamodel that define the structure of a book.

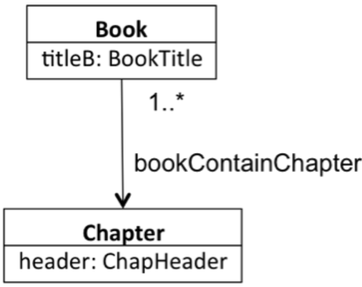


Figure 4.10: Example - TSP User Metamodel

The TSP tool is able to read a model to generate a formal (Alloy) model. The TSP tool takes in the XML representation of the model as an input to produce the equivalent Alloy using the rules provided by the template. Listing 4.1 is XML representing a TSP User Metamodel from Figure 4.10.

```
<user_metamodel name = "BookStructure" source = "True" target = "False" bidirectional = "True">
  <class_element ElmtName = "Book" abstract = "False">
    <attribute AttrName = "titleB" type = "BookTitle"></attribute>
    <association RoleName = "bookContainChapter" multOf = "one_to_many" ElmtName2 = "Chapter"> </association>
  </class_element>
  <class_element ElmtName = "Chapter" abstract = "False">
    <attribute AttrName = "chapHeader" type = "Header"></attribute>
  </class_element>
</user_metamodel>
```

Listing 4.1: XML representation of TSP User Metamodel (Figure 4.10)

Using the XML in Listing 4.1, the Java class *TSP_UserMetamodel* will generate the following Alloy model (Listing 4.2).

```
sig Book{
  titleB: one BookTitle,
  bookContainChapter: some Chapter
  }
fact MultiplicityBookChapter{
  bookContainChapter in Book one -> Chapter
  }
fact SingleValuetitle{
  AttrSingleValue[titleB, BookTitle]
  }

sig Chapter{
  header: one ChapHeader,
  numPages: int }
fact SingleValueheader{
  AttrSingleValue[header, ChapHeader]
  }

sig BookTitle{}
sig ChapHeader{}
```

Listing 4.2: Alloy model for TSP User Metamodel (Figure 4.10)

The main motivation for this elementary prototype is to maintain consistency of the generated Alloy models from TSP models in this thesis (we have yet to

implement tools that support templates explicitly). It provide a simple mechanisation that allows TSP model to created, loaded into the tool and generate its formal Alloy model. The TSP models in this thesis is manually translated into XML and their formal Alloy model is automatically generated by the tool.

In the current version of the tool, we excluded header template instantiation in the specification as we manually include the associated file . In the future, we aim to develop better tool support for TSP framework which provides a visual editor for TSP models, integrated Alloy Analyzer for analysis and formal template management facilities.

4.10 Summary

This chapter has presented the TSpecProber (TSP), a framework to support the specification and formal analysis of model transformation. It introduces concepts and components, and how they define a holistic method to specify platform independent model transformation specification, to a certain level of correctness, attainable before implementation. It includes a brief introduction to tool support for the framework. The following chapter presents the first step towards a well-formed model transformation specification; defining the requirements for a transformation.

Chapter 5

Eliciting model transformation requirements and contextualizing metamodel

In Chapter 4, we have briefly introduced the components of TSP framework. This chapter, we presents how those components work to provide an approach towards specifying and formally analysing model transformation specifications.

We are going deliver the framework in three parts: (1) eliciting requirements and contextualizing metamodels (Figure 4.4 Step 1 and 2) in this chapter; (2) formally analysing metamodels (Figure 4.4 Step 3) in Chapter 6; and (3) decomposing model transformation specifications (Figure 4.4 Step 4-6) in Chapter 7.

5.1 Elicit model transformation requirements

Like any software engineering, eliciting requirements plays an important role in defining the vision of a system. The requirements specification produced during elicitation includes the descriptions of *functional/non-functional requirements*, *user requirements*, *system requirements* and *interface requirements* [Som07]. The requirements are discovered and documented through *requirements engineering processes* that include *elicitation*, *analysis* and *validation* [Lau02].

Problems in any software development can often be traced back to elicitation issues [CK92]. In MDE particularly, requirements specifications have to be

interpreted further to define model transformations. Hence, any inadequacy in requirements specification is propagated, perhaps magnified, into the later stage of model transformation development and this may be expensive to fix.

In this step of the TSP framework, we aim to address the gap between the system requirements specification and the transformation requirements specification, to allow transformation engineers to have the right focus on defining features of the transformation.

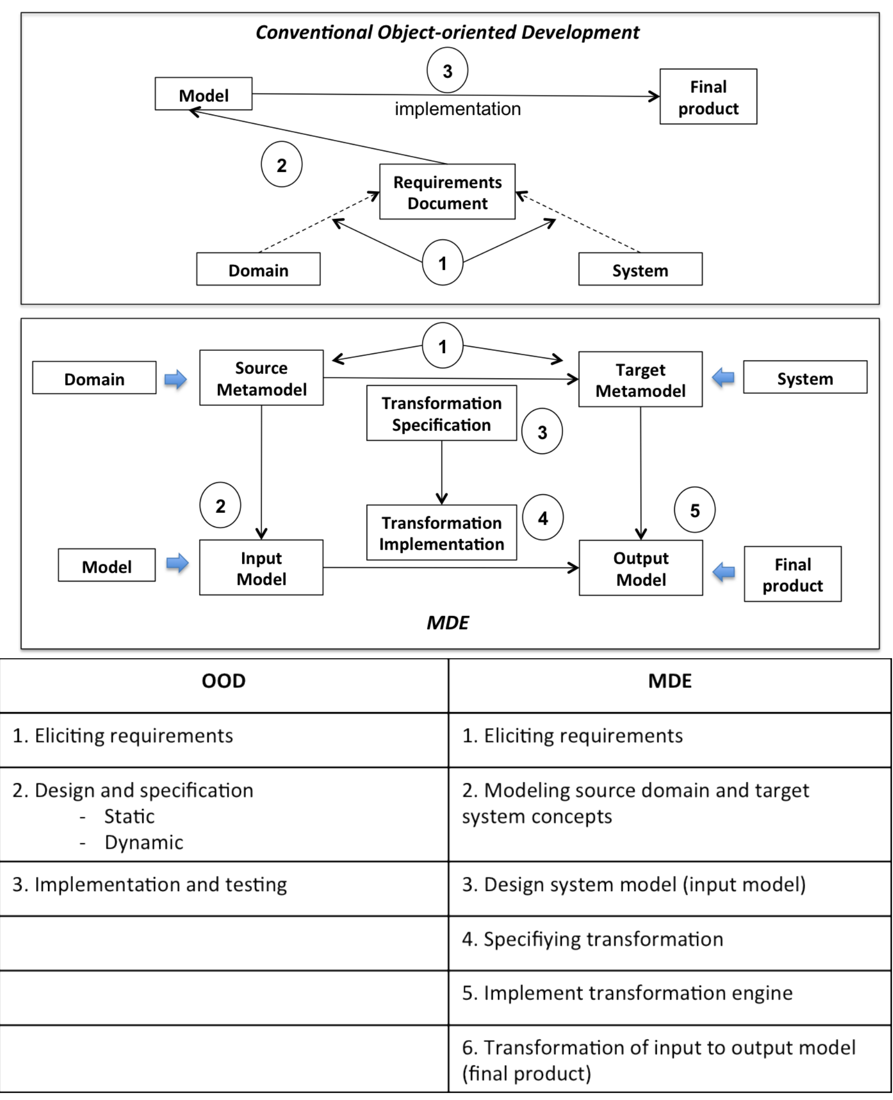
5.1.1 The rationale for eliciting model transformation requirements

Establishing a requirements specification does not only draw a clear picture of an ideal final product, but through the process itself, helps to clarify the feasibility of development. If we look at the current approach to the development process using model transformation [GP04; KRH05], there is a stage for defining system level requirements. However, as yet there is no comprehensive approach that facilitates the process of specifying requirements particularly for model transformation. In this case, we need to have an additional perspective to define requirements at model transformation level, based on the system requirements.

We select an example of a conventional object-oriented software development and compare it to an MDE development to clarify the rationale for eliciting model transformation. Figure 5.1 shows the difference between the two development approaches.

In conventional object-oriented development, requirements specifications are realized using models that include *static* and *dynamic* models. Then they are implemented by programming.

The difference in development using model transformation, is that the requirements specification does not include the requirements that define model transformation features. This is the gap, a *grey area*, between requirements specification and the requirements for model transformation components. Indeed in MDE, it is usually the case that transformation engineers intuitively interpret the requirements specification and implement ad-hoc model transformation.



OOD	MDE
1. Eliciting requirements	1. Eliciting requirements
2. Design and specification - Static - Dynamic	2. Modeling source domain and target system concepts
3. Implementation and testing	3. Design system model (input model)
	4. Specifiying transformation
	5. Implement transformation engine
	6. Transformation of input to output model (final product)

Figure 5.1: Comparison between conventional object-oriented and MDE development

To illustrate requirements specification issues, we extend the example which implements a system that produces a publication from a book[1]. Normally, we specify our requirements in the form as follows.

[1]See: http://www.eclipse.org/atl/atlTransformations/Book2Publication

Functional Requirements 1: *The system shall display the publication detail of a book, containing title and number of pages.*

The next step in object-oriented development is to model the system using static and dynamic models. Figure 5.2 shows a static and dynamic model of a system fragment that meets the requirement ***FR1*** in the form of a class diagram and an activity respectively.

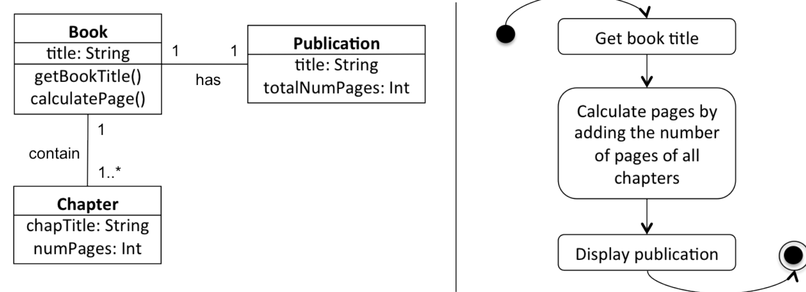


Figure 5.2: (Left) Class diagram (right) Activity diagram for display publication

These models are then implemented in a programming language, such as Java or C++.

In an MDE development, the models are different. We need to specify: (1) the source metamodel; (2) the target metamodel; and (3) the transformation rule. In this case, we have to extend the requirements to define these components. These are what we called the *model transformation requirements*, and can be defined as follows:

Source metamodel (Book)
Functional Requirements 1: *A book has one title and contains one or many chapter(s).*
Functional Requirements 2: *A chapter has a chapter heading and number of pages.*

Target metamodel (Publication)
Functional Requirements 1: *A publication has a title and total number of pages.*

Transformation rule (Book to Publication)
Functional Requirements 1: *For every book, a publication is generated. Condition: (1) Book title = publication title, (2) Publication total number of pages = Sum of all pages of chapters of a book .*

In MDE, the source and target metamodel are required by transformation engineers to implement model transformations. Sometimes, when the transformations are between generic models, we also need to specify the requirements at model level, which are called the *business rules.* For example, if we have a transformation of class model to a relational database model, we may need to include specialised constraints on the class model or relational model, perhaps, an instance of an account class cannot have a negative amount value.

We have shown why we need to have model transformation elicitations. To address the lack of formality in eliciting model transformation requirements, we provide a process for generating a *Model Transformation Requirements Model.* This consists of a set of requirements tables, informally representing different views required to developed model transformation components, which will then be use as a basis for: (1) contextualizing a user metamodel and its analysis; and (2) formally defining transformation requirements.

5.1.2 Model transformation requirements view

We have clarified the needs for eliciting model transformation requirements. Based on that, we define three model transformation views that allows the requirement of each model transformation components to be specified: (1) rule mappings, which define the top level transformation requirements; (2) source metamodel and target metamodel, both of which determine the required elements of a user metamodel; and (3) input model and output model, which specifically constrain transformation to valid input and output models.

To visualize the relationship between each view, Figure 5.3 shows their hierarchical dependency.

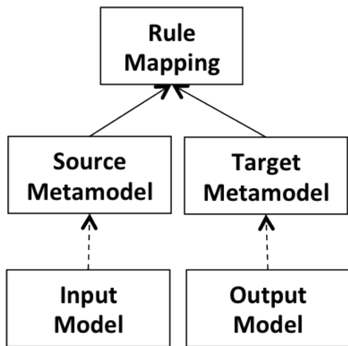


Figure 5.3: Views for model transformation requirements and their dependencies

The requirements for each view are informally specified in the form of tables. One of the reasons why we encourage initial elicitation to be specified in a form of a table, is to facilitate the thinking process. We want the details to be made explicit, especially the condition of the rules. This way, we assume that a transformation engineer will be made aware of the possibilities of structural and behavioural features, including constraints that apply to the rule. We will see later (in Chapter 7), in the requirements model, how requirements are formalised to provide enough details for specifying a transformation, but will not hold much information about the conditions. The link between the transformation requirements table and the transformation requirements model is linked via IDs that allow trace back to requirements table when needed.

The following section describe the views further.

5.1.3 Rule mapping requirements view

A rule specifies the relationship between the source and target metamodel elements. Rule mapping defines the rules for generating a target model from source model.

In this view, transformation engineers need to discover the main rules needed for a transformation and what are their related elements. The findings are informally documented in a table. The table for a rule mapping requirements view

consist of *requirements ID*, *description*, *condition* and *source ad target element*. The requirements ID column name each requirement with a unique ID, while the description column describes what the rule does. The condition columns state generic structural and behavioural details of the rules, while in the source and target element column, we define the elements that take part in the rule.

Using the previous *Book to Publication* example, the rule mapping requirement can be represented as listed in Table 5.1

Table 5.1: Rule mapping requirements view

ReqID	**Description**	**Condition**	**Source**	**Target**
T1.0	For every book, a publication is generated	(1) Book title = publication title (2) Publication total number of pages = Sum of all pages of chapters of a book	Book Chapter	Publication

5.1.3.1 Model transformation logic

The identification of rule mapping relates to how a transformation between the source and target models is to be performed. Conceptually, a model transformation does this via several goals in order to generate the final model. The goals define parts of metamodel elements that need to be created in order to create a whole target model. These parts represent a transformation logic within a model transformation.

Transformation logic depends on transformation engineers' design decisions to model a transformation. A model transformation for a similar source and target metamodel can have a variations of *transformation logic*. For example, in a class to relational database transformation, the transformation logic may define each class in a hierarchy to have an individual table connected by foreign keys, or, we can have a flattened hierarchy that generates a table [WKK+12]. Both transformation approaches maintain the meaning of source class hierarchy and target table structure.

This is an example of identification of *semantic equivalence* between two models. Relating different models of different paradigms creates an *impedance mismatch* problem [IBN+09]. To do this we need to decide on the *compatibility* that specifies the *common grounds* between the source and target model. Rules needs to be specified to address this, to preserve the semantics between the source and target model elements during transformation.

In the example of book to publication model transformation, the transformation logic is deterministic because books and publication have a small language that shares similar features.

5.1.4 Source/Target Metamodel requirements view

For each model transformation, there is a source and target metamodel. We have stated the various forms of a metamodel to be use in a transformation. The reason we need to specify the contextualization requirements for metamodels is to identify the required elements needed to produce the target model.

In the rule mapping requirements view (Table 5.1), we already identified the required source and target model elements for each rule. These are the elements that are compulsory to be available for a transformation that implements the rule. In the metamodel requirements view, we further define the characteristics of the elements.

The reason for this is that for an existing metamodel, elements may include attributes or relations to other elements that are not required by a transformation, eg. certain attributes in a class, or operations of the class may not be required for a certain transformation. It is also to identify elements or relations that may not be used in a transformation, but are required to define the elements, eg. an element inherits attributes from other elements.

Metamodel requirements view table contains five columns: (1) element; (2) description; (3) attribute; (4) relation; and (5) condition. The element, description and attribute columns defines the features, while the relation column identifies what relations the element is part of. In the condition column, any additional constraint is stated here. Table 5.2 shows the source metamodel elements, and Table 5.3 defines the target metamodel elements for model transformation

Table 5.2: Source metamodel requirements view

Element	Description	Attribute	Relation	Comment/ Condition
Book	Represent a book object	(1) Title: String	(1) has [1..*] Chapter	-
Chapter	Containing parts of a book	(1) Headings : String (2) Number of pages : Integer	(1) belongs to [1] Book	-

Table 5.3: Target metamodel requirements view

Element	Description	Attribute	Relation	Comment/ Condition
Publication	Represent a publication object	(1) Title : String	-	-
		(2) Number of pages : Integer	-	-

Details identified in this view will be used to produce a contextualized user metamodel, which we present later in Section 5.2.

5.1.5 Source/Target model requirements view

This view allows the transformation engineers to look at the input/output model of a transformation. These models are instances of metamodels. The requirements in this view relate to the *business rules*, specific to which the transformation is being applied. The requirements in this view specify an additional constraint that an input and output model have to incorporate, apart from con-

straints defined by the metamodel. The requirements table in this view contain columns: (1) requirement ID; (2) description; and (3) condition.

Our Book to Publication example is trivial, we will explain this further using a bigger example in Chapter 7.

5.1.6 Remarks

We have presented why and how to elicit model transformation requirements. Basically, in this step, we provide a systematic coverage for considering the possibilities of defining model transformation and its components. We have explained why eliciting model transformation requirements is needed and defined three views for specifying model transformation requirements.

In the rule mapping requirements view, while transformation engineers think about what rule is required in a transformation, implicitly, this suggests that the transformation engineers should consider the *concept semantics*. This relates to the deliberation of whether the source model can be mapped to the target model and how it can be done using *transformation logic*.

For example, features such as inheritance, which have many different semantics, and may not have support, should be given extra consideration during the specifying of model transformation. For metamodel concepts that are syntactically and semantically equivalent, such as support for inheritance, then the transformation between them is fairly straight forward. But for a model transformation where one language does not support inheritance, doing a systematic elicitation of the model transformation helps to identify additional details on the behaviour of the transformation. Take for instance, the class to relational database model transformation, where class diagrams have support for inheritance but the relational model does not directly have inheritance. Eliciting model transformation requirements helps engineers to think about all the possibilities for handling inheritance in the source model, and transforming to a conventional relationship with foreign keys.

5.2 Contextualizing user metamodel

When a metamodel is correctly defined and formally analysed, the first source of faults in a model transformation are eliminated, and there are fewer errors in the implementation. Therefore, in Step 2, contextualizing a user metamodel, we provide a process for specifying the source and target metamodel, in a way that is compact, well-formed and sufficient; and amenable to automated formal analysis. We use the term user metamodel to differentiate between between our contextualized metamodel and the original or existing metamodel. The resulting user metamodel for the source and target metamodel is part of the Model Transformation Specification Model.

Before we go further into detail about this step, we justify the decision to have a contextualized user metamodel and its advantages in the following section.

5.2.1 Preparing a contextualized user metamodel

Contextualization is the process of identifying the minimal set of elements required for a transformation. In TSP, the contextualization of the source and target user metamodel are specified using the TSP metamodelling language. The reason for using the TSP metamodelling language is to enable templates to be fully instantiated to produce a complete formal specification of the user metamodel. The formal specification is used for analysis to ensure the user metamodel is correct and well-formed.

Contextualization is useful to acquire and analyse the required metamodel for models with no existing metamodel for transformation. But the common case now, is that many models have an existing metamodel, provided by zoos such as the AtlanMod Zoo[1]. For an existing metamodel, it is difficult to check if the metamodel is sufficient for a transformation. Some existing metamodels such as the UML, contain a huge collection of elements, which makes formal analysis for correctness and well-formedness almost impossible.

Existing metamodels can be of benefit for contextualizing the user metamodel by using the user metamodel as a reference to identify the required features. For

[1] AtlanMod Zoo website http://www.emn.fr/z-info/atlanmod/index.php/Zoos

huge metamodels, the user metamodel can be use to extract the required elements. This is a similar case for readily available metamodels, where user metamodels can be used to detect if the metamodel contains the required elements. These extracting and detecting features would be much more useful if they were supported by a tool.

In the previous step, we have identified the elements by the source and target metamodel required for the transformation. In this step, we are contextualizing and formally analysing the source and target metamodel for a transformation. At the end of this step, we should have a source and target user metamodel that have the minimal set of elements and relations, whilst containing a *sufficient* set of elements and relations to support the model that take part in the transformation, and also to have them formally analysed for correctness and well-formedness.

5.2.2 TSP Metamodelling Language

A metamodelling language should contain the capabilities to model concepts of a domain. According to [GPHS08], basic modelling elements sufficient for representing various domains consist of four important meta-concepts, *class*, *attribute*, *association* and *association end*. Based on this, the TSP metamodelling language provides the abstract construct that uses a minimal set of elements to construct a contextualized user metamodel.

To ensure that our metamodel can support various implementation formats, we look at two common metamodels, Ecore and Meta Object Facility (MOF) [MOF06]. TSP metamodelling language only includes common features and eliminates unnecessary features that are often platform specific, e.g., classifiers in Ecore contain instance declarations for Eclipse.

TSP metamodelling language abstract syntax is defined in Figure 5.4. the concepts for TSP metamodelling language is based on MOF and Ecore constructs. Each of these constructs have mappings to Alloy produced by the templates. The mapping is given in Table 6.1 in Chapter 6. The following describes the details of the concepts.

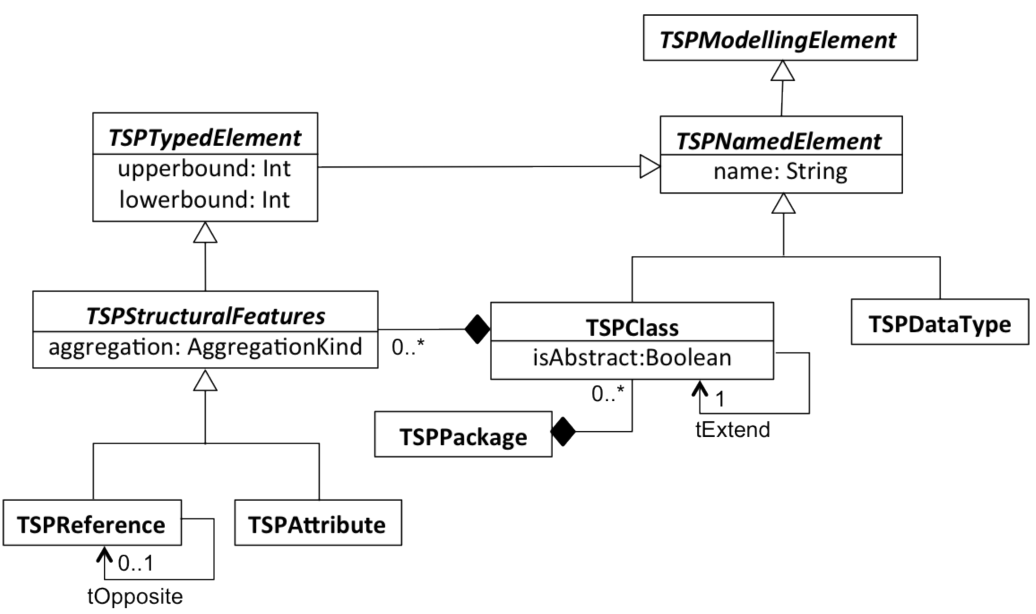


Figure 5.4: TSpecProber Metamodelling Language

TSPPackage: A package acts as the containment for the user metamodel. This construct provides the modularity that distinguishes parts of independent components. In this case, TSPPackage identifies a set of metamodel elements that define an area of concern.

TSPClass: Provides the notions for metamodel object definition. They are enclosed in a package (*TSPPackage*). The TSPClass element provides the object type definition. A TSPClass can be abstract or concrete. A TSPClass can also extend to another class, creating subclass(es). There should be no cyclic inheritance (where a subclass is a super class to itself).

TSPAttribute: A class can have attributes defining related features of the class.

TSPDataType: Supports primitive data types, namely, *string*, *character*, *integer*, *float* and *Boolean*. These data types are composite and therefore supported by almost any implementation when the user metamodel is to be translated into other formats for execution.

TSPReference: TSPClasses can have associations that link between objects of each class. Association ends defines how these classes participate in the associations. These are provided by the **TSPReference** element in TSP metamodel. Bidirectional associations are provided by *tOpposite* reference. In this framework, there are two ways of defining bi-directional association, using role name with biojectivity function or two uni-directional associations with association end name and symmetrical constraints. The latter is useful when there are uni-directional associations in models.

TSPTypedElement: Provides multiplicity for association elements. It can also be the point of extension to other types, such as *operation types.*

TSPStructuralFeatures: Defines traits of an association. Aggregation is a type of relation that defines containment properties of an object. Types of aggregations can be broken down into *strong* and *weak* aggregations. Strong aggregation annotates that the head class object holds a definite link with its end class objects (or a composition), while a weak aggregation may state that a head class object has a special link to end class objects, but end class objects can exist independently. This is significant to provide dynamic features of objects.

The TSP metamodelling language can be extended with other features, but to ensure analysis covers all properties, new templates have to be added into the catalogue. Before we get into the details of the process of creating a contextualized user metamodel, we define the our models and their relations in the next section.

TSP metamodelling language has a set of visual notation for defining user metamodel. The description of the notations are given in Appendix G.1.

5.2.3 TSP framework and their level of abstraction

The organization of TSP models used within this framework adopt the concepts of the *four level of abstraction* in its architecture [MDA03]. Figure 5.5 shows the models in the TSP framework and their location in the level of abstraction.

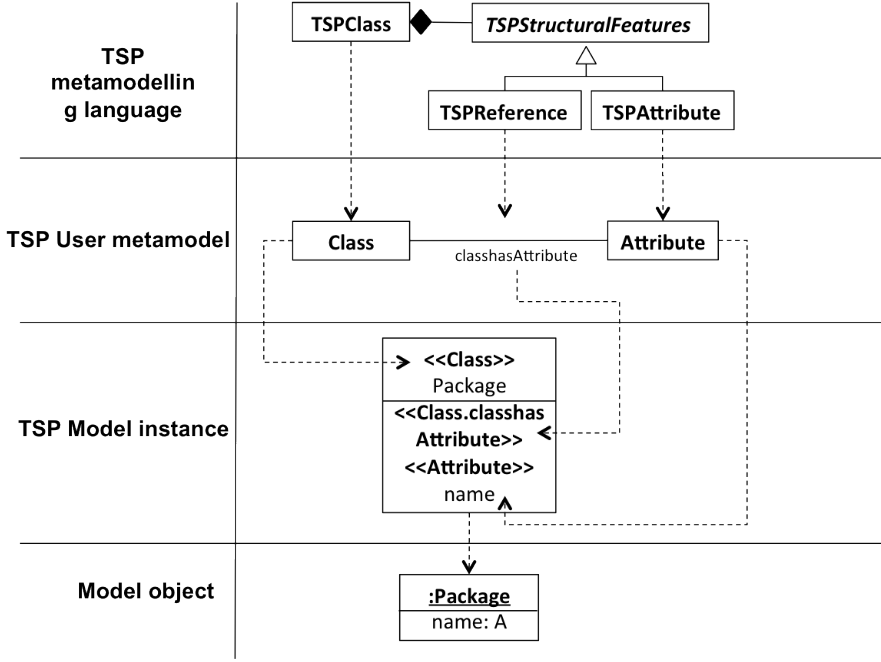


Figure 5.5: TSpecProber model level of abstraction

As stated in the previous section, we have provided *TSP metamodelling language* to provide the syntax and semantics for a *user metamodel*, the metamodel for the transformation under development. An instance of a user metamodel (*model instance*) is the model that is used as an input, or is a resulting model of a transformation. These model instances are representations of a domain object (*model object).* To note, TSP framework supports object-oriented metamodels and model transformation.

5.2.4 TSP metamodeling approach

This section demonstrates how a TSP metamodelling approach is used to develop a user metamodel. This is particularly for a model that does not have any metamodel, to create a metamodel for a transformation. This can also be used to guide the extraction of existing parts of a huge metamodel to: (1) identify the mimimal set of elements for a transformation; (2) analyse the metamodel for syntactic and semantic correctness and well-formedness; and/or (3) prepare the

metamodel for analysing model transformation in TSP framework. The approach has two parts: (1) defining classes and features; and (2) defining relations.

5.2.4.1 Defining classes and features

From the metamodel requirements view table (in section 5.1.4), we have identified a set of elements that are required in transformation rules, as defined in the rule mapping requirements view. In our Book to Publication example, we assume we do not have a metamodel to define Book and Publication. In the metamodel requirements view table, we have identified two classes for defining a book. Figure 5.6 visualizes the Book (source model) and Publication (target model) classes.

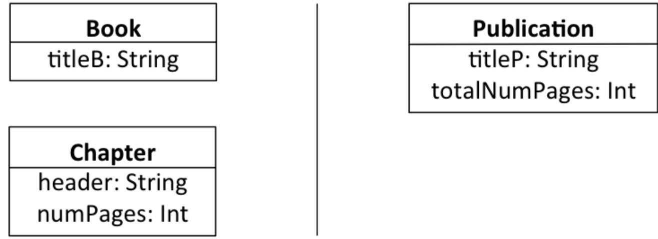


Figure 5.6: Meta classes for Book and Publication

Again, our Book to Publication model transformation example is trivial, but in real cases, we may need to identify other classes that relate to the classes discovered during elicitation. For example, if we are extracting elements from a huge metamodel like the UML, a class attribute, *name*, is inherited from class, *NamedElement*. We can include the *NamedElement* class in the user metamodel, or we can have a simplified metamodel that extracts the attributes into the classes.

5.2.4.2 Defining relations

To complete defining the user metamodel, we define the relations of classes. Mellor [MB02] introduces the concept of the *importance in defining relations* in models. He proposed that a relation in a model is critical in providing the precise semantics to a class model. The approach has then been adopted in [SW05] for data modelling.

The motivation for this concept is that, relations hold all the important details that provides the conceptualisation of a domain: an object is like the 'actor' of the domain, and it is the relations that describe the 'script' determining the whole story. Relations contain communication details between objects, not just in terms of structural features, but strongly dictating the behavioural state of a class in a system.

In object-oriented models, it is essential that the relations between identified classes are explored and defined with appropriate annotations. Specifically in this approach, the way relations are specified plays an important part in providing the details for generating templates with associated constraints that condition the user metamodel for automated analysis and verification. We have a collection of relations pre-defined for the user metamodel. A different template is instantiated according to the kinds of relations, annotated using {*relationKind*} notation.

The relations between classes in a user metamodel can be in a form of *generalization* and *association*. The structural features allowed in a relation for this framework have been briefly explained in Section 5.2.2. The syntax and semantic definition for the *relationship categories* are as follows:

Generalization.

The TSP supports variations of generalization that can be use to define instance behaviours of a model. These variations, have been used in *entity relationship diagrams* (participation and disjoint constraint) [TLNJ11]. In UML, a subclass type partitioning is called *discriminator*.

In this approach, the user metamodels are annotated with additional generalization properties using {*relationKind*} to represent *the generalization relationship types*, to enhance the semantics of model instance. Particularly in the TSP framework, the details are used for template instantiation for analysis.

There are four kinds of generalization properties: (1) complete subclass type partition; (2) incomplete subclass type partition; (3) Disjoint subclass type partition; and (4) overlapping subclass type. Each of these generalization definitions are provided in Appendix A.

A generalization relationship type can be a combination of *complete* | *incomplete* and *disjoint* | *overlapping*. *Complete and disjoint* can mean either an abstraction of features, where the realization is fully imposed by the subclasses, or a *refined type*, where the class is defined by their subclasses. *Incomplete and disjoint* is where features of the superclass are shared with the subclasses. *Complete and overlap* means that the refined type can be combined features of several subclasses. We could not think of a suitable case for *Incomplete and overlap*, therefore it is omitted for now.

Association.

The concept of association in this framework is taken from UML [Fow04]. An association is a basic relationship that a class can have to define any consisting communication between each individual of a class instance. It can be *bi-directional* or *uni-directional*. An association has two ends, each end is attached to a class. A reflexive association links between two instances of the same class. Bi-directional association comes with multiplicity at each end, defining the number of instances of each class and an association name that identifies the relation. Figure 5.7 shows the variety of multiplicity.

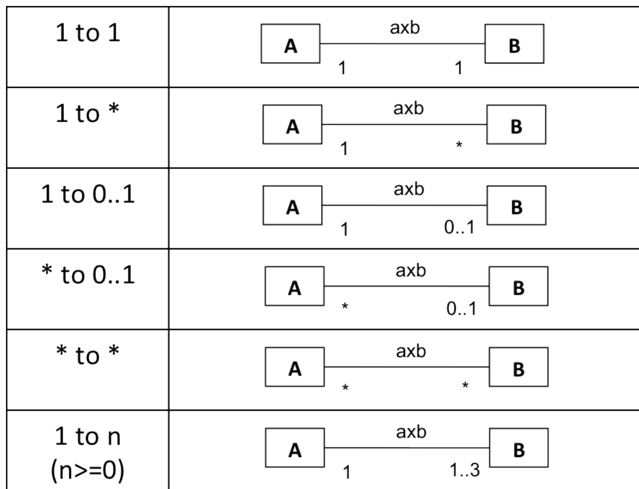


Figure 5.7: Association multiplicity

We provide the mechanism to restrict how the association names are written to standardise the naming convention and make it easier to comprehend during analysis. This is particularly helpful when the templates are instantiated, we can easily identify which association it is applied for. This is particularly helpful when the templates are instantiated, we can easily identify which association it is applied for. To standardize them, the template/mechanism has the following format:

$$\ll\text{Class1}\gg\ll\text{verbstatement}\gg\ll\text{Class2}\gg$$

Where, *Class1* and *Class2* is the class name, and *verbstatement* is a verb that represent the role of the relation between the two classes.

For uni-directional association, the navigational end class (target) have a role name instead:

$$\ll\text{verbstatement}\gg\ll\text{TrgClass}\gg$$

Where, *TrgClass* is the name of the end class of a directed association, and *verbstatement* is a verb that represent the role of the relation between the classes.

It is also possible to define a bi-directional association with two symmetrical uni-directional associations. The role name is used at each end instead of an association name. Role name has the following format:

$$\ll\text{verbstatement}\gg\ll\text{Class}\gg$$

Where, *Class* is the name of the end class of an association, and *verbstatement* is a verb that represent the role of the relation between the classes.

For reflexive association, there are five generic types that are supported by the framework: (1) irreflexive; (2) symmetric; (3) anti-symmetric; (4) asymmetric; and (5) acyclic; based on [CCGT06]. The definition for each of these types is provided in Appendix B. These types will be included in the user metamodel using {*relationKind*} notation for the relation.

Each of the reflexive association types may be associated with more than one characteristics. Figure 5.8 shows the relationships between these types.

Anti-symmetric and symmetric are always disjoint, in fact they are contrasting. Irreflexive types can be anti-symmetrical or symmetrical. Asymmetric is anti-symmetric and irreflexive while acyclic is always asymmetric.

The reason for distinguishing the types of reflexive associations is to allow behavioural properties of the object in this relation to be constrained and analysed. Appendix B, contains how our templates provide *integrity constraint* for each instantiation of reflexive association. The multiplicity and association naming convention will adhere to normal bi-directional association using association names.

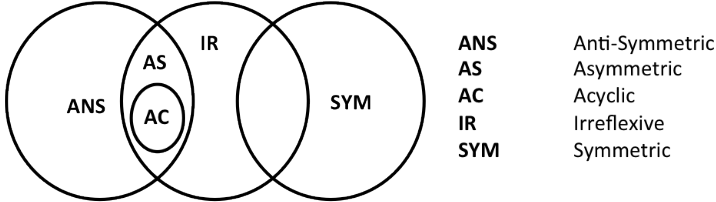


Figure 5.8: Relationship between reflexive association types [CCGT06].

Aggregation.

Aggregation is a type of association but with an additional dependency constraint that binds the two classes. Likewise, the usage of aggregation in this framework is from UML [Fow04]. It is a type of relation that captures the containment features between individuals of related class instances. An aggregation constrains the existence and dependencies between instances of elements. This relates to the dynamic behaviour analysis. Section 5.2.2 briefly describes the two categories of aggregations. Figure 5.9 depicts how an aggregation is used.

Figure 5.9: Strong (composition) and weak aggregation example

The semantics of aggregation is also adopted from the UML [Fow04]. Aggregation consists of a *whole* class and its *part* class. The aggregation links between University and Department show a strong aggregation (composition), whereas part class (Department) instances cannot exist independently without the relating whole class (University) instances. Unlike the weak aggregation between Department and Lecturer, instances of Lecturer (part class) may exist without the relating Department instances (whole class).

Now, we will continue to define our user metamodel. We have specified the classes and features of the user metamodel element. Based on the metamodel requirements view, a book has a relation with chapter, and a publication has no relation.

Figure 5.10 shows the user metamodel, Book and Publication, that can be used for the analysis of model syntax and semantic correctness.

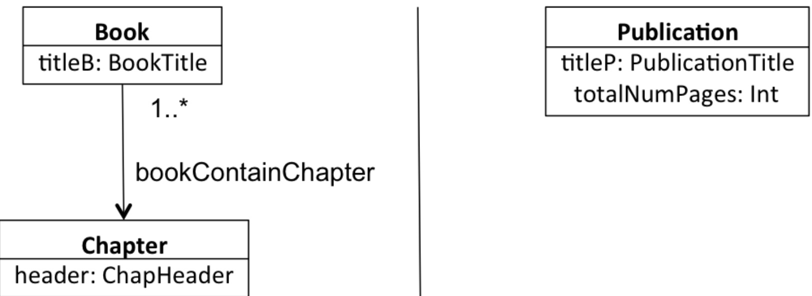


Figure 5.10: User metamodel for Book and Publication

5.2.5 Metamodeling semantics

There is a limitation on how we can describe the user metamodel to include the abstract syntax for the domain model required in a transformation. We presented how some of the class and association semantics for the user metamodel is included via additional stereotypes added to the user metamodel. To provide a more precise meaning of the concept, we require a supporting construct that further describes the semantic requirements. Based on the definition of semantic definition techniques for programming languages, there are three ways to do

this; (1) axiomatic, (2) operational, and (3) denotational approaches [CRC+06]. Commonly, modelling communities adopts the axiomatic approach, using language such as OCL to further define model features. Formalization of OCL for a class model has been looked at in [ABGR10]. We will extend the template for formalizing OCL in future work.

5.3 Summary

In this chapter, we have defined how we approach elicit model transformation requirements and contextualize a metamodel for model transformation. In the next chapter, we present how our approach analyses the contextualized metamodel for being correct and well-formed.

Chapter 6

Analysing metamodel

In the previous chapter, we have presented how a model transformation requirement is specified and how it can be used to produce a requirements model and contextualized user metamodel. This chapter proceeds to analysing the user metamodel to check that it is correct and well-formed. As stated in Section 4.9, the example models in this chapter have been manually translated into XML (Appendix C) and its formal Alloy model have been created using the tool described earlier.

6.1 Analysis of user metamodel

TSP generates a formal counterpart of the user metamodel as part of providing a clear definition of the needed features of a model instance in a transformation. This allows models to be type checked for consistency and analysed for correctness. The templates used to generate the formal Alloy models are equipped with *integrity constraints* that express how well-formed the elements are in the user metamodel, making it tractable to automated analysis. Consistency between the user metamodel and the formal metamodel specification is provided by the templates which are *correct-by-construction* [Am7].

Once a formal specification of a user metamodel is generated, we can perform formal analysis. The definition of validation of the user metamodel, in our approach, is to check for the existence of anomalies in our model instances. Alloy provides this by performing the process of *finding models* of a type checked

and consistent specification. We can determined how well-formed the user metamodel is from this. To determine the correctness, we do a verification of the user metamodel. A snapshot instance of a model based on the requirements is created and transformed into Alloy, via templates; this is used to check against the specification. This allows for verification that the user metamodel supports the features.

6.1.1 Generating formal model for user metamodel

The formal model of the user metamodel is generated by applying a collection of templates. The templates are separated into views, representing patterns for each user metamodel component.

Figure 6.1 shows the views of formal specification for the TSP User Metamodel. An Alloy representation of each of these views is generated by templates, which define properties according to the user metamodel. In Amálio's framework [APS05], templates are organized into views according to the structure of a UML Class diagram. For the user metamodel, the views of Alloy templates consider the structures of both the metamodel and Alloy building blocks. The *Class* and *Relational* views define structural properties, with additional facts and predicates that describe conditions applied to instances of user metamodel. *Module*, *Assertion*, *Check*, *Command* and *Run* are views related to Alloy structure. Module provides a header used by Alloy Analyzer to include other specifications. A command will provide the order for Run, for finding model instances, or running predicates and verifying assertions respectively. We can have a user defined assertion to perform a check on the specification. The instantiation is provided by the user metamodel.

The properties of a user metamodel in the TSP are provided by the TSP Metamodel. Therefore, each element is represented by certain parts of Alloy fragments, as shown in Figure 6.1. It shows how the structural elements of a TSP User Metamodel are addressed by the Alloy components. Additional Alloy sections, that are responsible for providing the analysis, will be attached accordingly during the elements' template instantiation. This is where the details provided

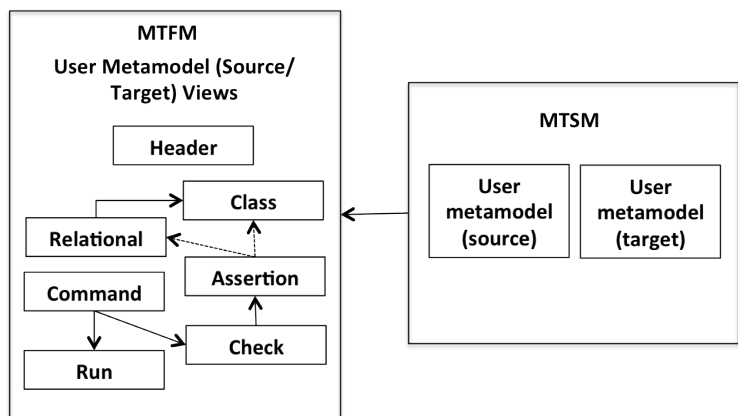


Figure 6.1: View of user metamodel formal specification

in the user metamodel are used to validate and verify the well-formedness and the correctness of the user metamodel.

Table 6.1: TSP metamodel elements corresponding to Alloy components

TSPMetamodel Element	**Alloy Component**
TSPPackage	Module header
TSPClass	Signature
TSPTypedElement	Expression
TSPStructuralFeatures	Expression
TSPAttribute	Declaration
TSPReference	Signature
TSPDataType	Signature

The templates in this approach are devised to be able to *fully generate* Alloy fragments for each of the elements represented. The instantiation will get the needed information from the user metamodel specification model. The predefined facts and predicates that represent the constraints for each feature are also *fully generated* by the templates. The complete instantiation is a formal model for the user metamodel that is amenable to automated analysis. An example of template instantiation is presented in Section 6.1.3.

6.1.2 Analysis methods using Alloy Analyzer

Analysis of TSP models mainly relies on executing their model formal specifications, which mechanically produced from instantiations of templates. For user metamodel formal specification, transformation engineers will manually examine the instances given by Alloy Analyzer. If there is no irregularities in the small universe of instances generated and they are conforming to the requirements specified, transformation engineers can be sure that the model is valid.

For checking user metamodel correctness, patterns (user metamodel instance model) are produced based on the requirements and its formal specification (user metamodel instance model formal specification) is executed. The classification of scenario in relation to applying and executing this is presented in Figure 6.19. The classification also applies for analysing transformation model formal specification and transformation instance model formal specification (see Section 7.3.2). Similarly, transformation engineers will manually go through instances generated by Alloy Analyzer.

6.1.3 User Model template instantiation

In the generation of the user metamodel formal specification, all the classes and relations of the user metamodel are translated to Alloy. The formal specifications are fully generated by instantiating templates; **User Metamodel: Class** templates and **User Metamodel: Relation templates**. The existing templates provided by the TSP templates catalogue are given in Appendix I.

6.1.3.1 Class instantiation

There are two types of classes predefined in the TSP framework; *abstract* and *concrete*. Conceptually, abstract classes provide generic features of a set of classes; in their implementation, abstract classes always require a concrete class for them to be instantiated. Class instantiation is provided by **User Metamodel: Class** templates.

In Alloy, each TSPClass (from now on, we refer to TSPClass as class) is represented as a *signature* and class instances are that signatures *atom*. The concept

of specifying a class as a singleton can be assumed by Alloy by including a set multiplicity in the signature. For a singleton, the signature set multiplicity keyword is ***one***. If there can be more than one instance of the class, the multiplicity keyword is ***some***

The attributes for classes are modelled as an Alloy relation from a signature to another signature, via a *field declaration.* The attribute can be a single (with cardinality of ***one***) or multi-value (with cardinality of ***some***) attribute. This framework has provided a mechanism to specify these via the predicate, AttrSingleValue and AttrMultiValue with a field name for the attribute and its type signature as parameters.

```
(( one || some ))? sig ≪ElmtName≫ {
   /*If class is with attribute.  For multiple, iterate for each attribute*/
   ≪AttrName≫:  (( one || some )) ≫≪Type≫
}
/*For single value attribute*/
fact SingleValue≪AttrName≫ {
   AttrSingleValue[≪AttrName≫, ≪Type≫]
}
/*For multi-value attribute*/
fact MultiValue≪AttrName≫ {
   AttrMultiValue[≪AttrName≫, ≪Type≫]
}
```

Figure 6.2: Template C2: Class (Appendix I.3.2)

Listing 6.1 shows two instantiations of template **C2: Class** (Appendix I.3.2), one with single value, and the other with multi-value attributes that produces a fragment of Alloy specification.

```
1 sig A{
2   attrA: one AttrA
3   }
4
5 fact SingleValueattrA{
6   AttrSingleValue[attrA,  AttrA]
7   }
8
```

```
9   sig B{
10    attrB: some AttrB
11    }
12
13  fact MultiValueattrB{
14    AttrMultiValue[attrB, AttrB]
15    }
```

Listing 6.1: Single and multi-value attributes in Alloy

Line 1 - 7 in Listing 6.1 is a result of class **A** with a single value attribute *attrA* of type *AttrA* instantiating template **C2** (Appendix I.3.2) from the templates catalogue. Line 9 - 15 in Listing 6.1 is a result of class **B** with a multiple value attribute *attrB* of type *AttrB* instantiating template **C2** (Appendix I.3.2) from the templates catalogue.

To constrain the instance of class attribute, an additional *fact* is included. The fact contains a predicate *AttrSingleValue* (line 4) and *AttrMultiValue* (line 12) provided by *TSP Alloy Generics* (Appendix H) that constrains the attribute as a single value attribute.

Executing Alloy specification in Listing H.1 produce instances of the specification. Figure 6.3 is one of the instances.

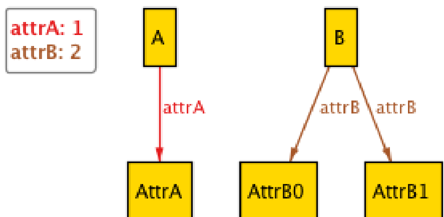


Figure 6.3: Result of executing Listing 6.1 in Alloy Analyzer

Classes in the user metamodel can participate in two types of relation; *generalization* and *association* (the definitions are previously discussed in Section 5.2.4.2). The templates provide the definitions of structure as well as the behavioural features that are attached to the relations, as specified in the user metamodel.

6.1.3.2 Generalization instantiation

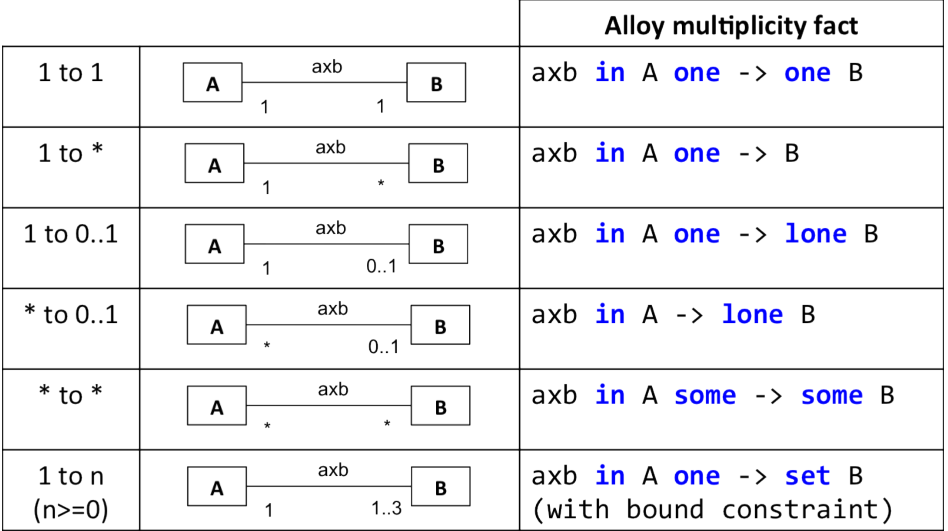
The templates for generalization relations address each of the generalization variants, ensuring that the classes participating in a generalization, have a valid inheritance. For classes that are part of a generalization relation, templates for instantiation are provided by the **User Metamodel: Relation - Generalization** (Appendix I.4.1) templates. The templates instantiation and the Alloy execution to demonstrate the different characteristic of generalization is provided in Appendix A.

6.1.3.3 Association instantiation

The default navigational type provided by the Alloy for a relation between two classes is bi-directional, as presented in [Jac06]. In the TSP, we provide a way to model a uni-directional association as well. Adopting the concept inspired from [RBR03], we provide the templates that distinguish uni-directional from bi-directional. Association can also be reflexive, where a relation exists between two instances of the same class. Reflexive associations have several categories that define the behaviour between the instances. The templates for association instantiation is provided by the **User Metamodel: Relation - Association** (Appendix I.4) templates.

Association multiplicity facts

In Alloy, during model finding, every signatures atom represents an instance of the elements it represented. Alloy has the mechanism to specify multiplicity in relation via functions. For example, a one-to-one multiplicity is of type bijective function that maps one-to-one object correspondingly, while an association with one-to-many relations is of type injective. For association multiplicity, Figure 6.4 shows how Alloy accords with multiplicity used in the user metamodel.



		Alloy multiplicity fact
1 to 1	A axb B (1, 1)	axb in A one -> one B
1 to *	A axb B (1, *)	axb in A one -> B
1 to 0..1	A axb B (1, 0..1)	axb in A one -> lone B
* to 0..1	A axb B (*, 0..1)	axb in A -> lone B
* to *	A axb B (*, *)	axb in A some -> some B
1 to n (n>=0)	A axb B (1, 1..3)	axb in A one -> set B (with bound constraint)

Figure 6.4: Association multiplicity facts

Bi-directional Association

Figure 6.5 shows a bi-directional association between *Customer* and *Order*, with *CustomermakesOrder* as association name and multiplicities of *Customer makes many (*) Order* and *each Order is made by one (1) Customer*. The model represents a requirement where a customer can make more than one order to the system, but every committed order has to belong to a customer.

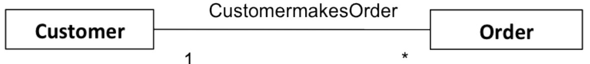


Figure 6.5: Model with bi-directional associations and role name

Listing 6.2 is the result of instantiating **R5: Association (Bi-Directional Only Model)** (Appendix I.4.2) templates. The templates consist of class instantiation line 1 and 5 with a declaration for relations between Customer and Order in Customer (line 2). Line 6 further defines the multiplicities between the two element classes, *Customer* ***one*** $\rightarrow$ ***some*** *Order*.

```
1 sig Customer{
2   customermakesOrder: set Order
3 }
4
5 sig Order{}
6
7 fact MultiplicityCustomer{
8   customermakesOrder in Customer one -> Order
9 }
```

Listing 6.2: R5: Association (Bi-Directional Only Model) (Appendix I.4.2) instantiation

Executing Listing 6.2, creates an instance, as depicted in Figure 6.6, that shows that a customer can make multiple orders for each order belong to a customer. Therefore, the model is valid.

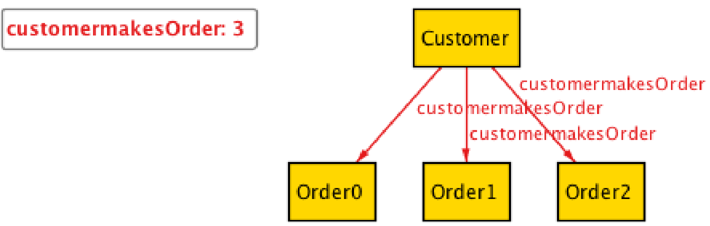


Figure 6.6: Result of executing Listing 6.2

Template **R5: Association (Bi-Directional Only Model)** (Appendix I.4.2) also supports a relation with an absolute number of instances, as shown in Figure 6.7, where a Car has exactly four Tyres. Listing 6.3 shows the generated Alloy model. Figure 6.8 shows an instance of execution.

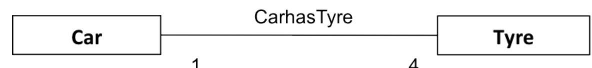


Figure 6.7: Model with bi-directional and numbered multiplicity

```
1  sig Car{
2    carhasTyre: set Tyre
3  }
4
5  sig Tyre{}
6
7  fact MultiplicityCar{
8    carhasTyre in Car one -> Tyre
9  }
10 fact NumberedMultiplicityCarcarhasTyre{
11   all car: Car | #car.carhasTyre = 4
12 }
```

Listing 6.3: R5: Association (Bi-Directional Only Model) (Appendix I.4.2) instantiation for numbered multiplicity

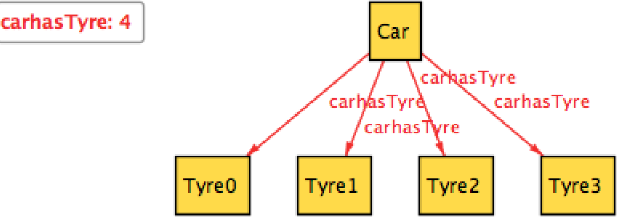


Figure 6.8: Results of executing Listing 6.3

Bi-directional Association with two Uni-directional Association

The difference with modelling bi-directional relations with association names rather than role names in Alloy is, the latter treat the bi-directional relations as two, symmetrical uni-directional relations. This is useful to distinguish between bi-directional and uni-directional relations, it adds explicit details to the

instance model. Figure 6.9 shows how a bi-directional relation is modelled with association end names. Listing 6.4 is the result of instantiating template **R6: Bi-Directional (In hybrid)** (Appendix I.4.3).

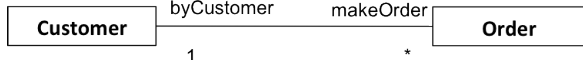


Figure 6.9: Model with bi-directional relations with association end names

```
1  sig Customer{
2    makeOrder: set Order
3  }
4
5  sig Order{
6    byCustomer: one Customer
7  }
8  fact BidirectionalMultCustomer{
9    Customer <: makeOrder in (Customer) one -> some (Order) and
10   Order <: byCustomer in (Order) some -> one (Customer)
11   makeOrder in ~byCustomer
12 }
```

Listing 6.4: R6: Bi-Directional (In hybrid) (Appendix I.4.3) instantiation

As depicted in Figure 6.10, in reference to Figure 6.6, we still get the same instance that concludes it is a valid model. The only difference is, there are three additional relations that indicate bi-directional association explicitly.

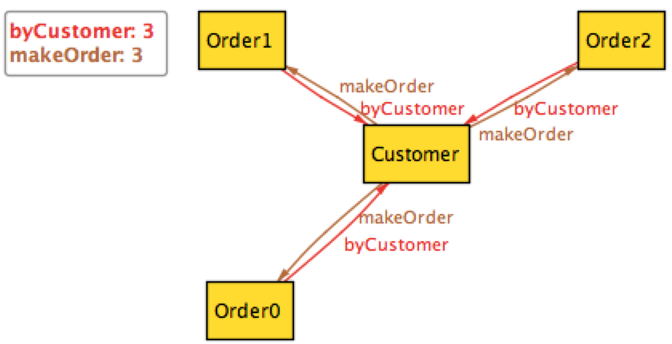


Figure 6.10: Result of executing Listing 6.4

Bi-directional Association and Uni-directional Association

When a model has both bi-directional and uni-directional relations, it is clear which relation is defined as which by using role names rather than association names. Figure 6.11 shows a model that has both bi-directional and uni-directional relations.

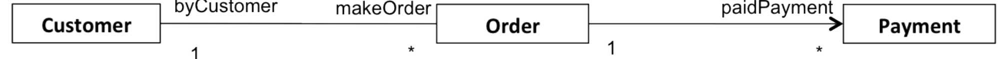


Figure 6.11: Model with bi-directional and uni-directional associations

Listing 6.5 is the result of instantiating template **R6: Bi-Directional (In hybrid)** (Appendix I.4.3) for bi-directional relations and template **R7: Uni-Directional (In hybrid)** (Appendix I.4.4.1) for uni-directional relations.

```
1 sig Customer{
2   makeOrder: set Order
3 }
4
5 sig Order{
6   byCustomer: one Customer,
7   paidPayment: set Payment
8 }
```

```
9
10 fact BidirectionalMultCustomer{
11   Customer <: makeOrder in (Customer) one -> some (Order) and
12   Order <: byCustomer in (Order) some -> one (Customer)
13   makeOrder in ~byCustomer
14 }
15
16 sig Payment{}
17
18 fact DirectionalMultOrder{
19   Order <: paidPayment in (Order) one -> some (Payment)
20 }
21 *Bidirectional fact is included manually.
```

Listing 6.5: Bi-directional and uni-directional (In hybrid) association instantiation

Using this approach, we can see that during the model finding process we can identify which relations are bi-directional and which are uni-directional as depicted in Figure 6.12.

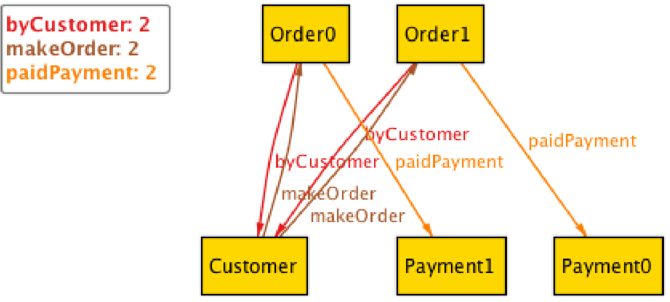


Figure 6.12: Result of executing Listing 6.5

Reflexive Association

Another association type that is used to model relation of elements is the reflexive association. Reflexive association defines a link between two instances of the same class. For example, Figure 6.13 shows a reflexive association for a class **A**, that has a reflexive association ***r***.

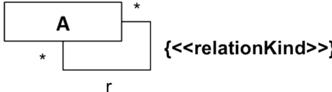


Figure 6.13: Model with reflexive association

Types of reflexive association are instantiated through *relationKind* included in models, which is similar to generalization association (depicted in Figure 6.13). Section 5.2.4.2 presented the five categories of reflexive association: *irreflexive*, *symmetric*, *anti-symmetric*, *asymmetric* and *acyclic*. Appendix B provides the instantiation of templates for each of the reflexive associations.

Based on the Venn diagram of relationship between reflexive types in Figure 5.8, the types have some relation with each other, whether they are *disjoint*, *overlap* or *sub-set*. This therefore creates another set of relations; those which are *allowed* to be combined to further describe the association, those which are *not allowed* be combine, as they contradict each other and those which are *redundant* to be defined together, as violation in one may invalidate all. Figure 6.14 shows the dependency between reflexivity type. Templates for each of the types in this framework have incorporated the restrictions.

6.1.3.4 Aggregation instantiation

Another special kind of association is the aggregation. It defines the dependence of an instance of a class to the existence of another instance from another class. The instantiation of an aggregation is similar to association but it will have an additional constraint, enforcing existential properties between the class instances in the relation. The aggregation relation is defined by template **User Metamodel: Relation - Aggregation** (Appendix I.4.5).

	Irreflexive	Symmetric	Anti-symmetric	Asymmetric	Acyclic
Irreflexive	-	✔	✔	O	O
Symmetric	✔	-	X	X	X
Anti-symmetric	✔	X	-	O	O
Asymmetric	O	X	O	-	O
Acyclic	O	X	O	O	-

Figure 6.14: Allowed, conflicted and redundant combination of reflexive association type

The constraint for aggregation relation provided by the TSP template originates from [GR98], which provides a definition of constraint in OCL for aggregation association. [GR98] defines the constraint in two parts, existential dependency and forbidding sharing. We adopt his definition of constraint and create templates to represent them.

To demonstrate the application of templates, we are going to use Figure 5.9 from Section 5.2.4.2 to show how the template defines the semantics of the two types of aggregation. Listing 6.6 is the result of instantiating the template for Department that has a composition relation (**R12: Strong Aggregation**) (Appendix I.4.5.1) to University, and Lecturer that has an aggregation relation (**R13: Weak Aggregation**) (Appendix I.4.5.1) to Department.

```
1  sig University{
2    universityhasDepartment: some Department
3  }
4
5  fact{
6    universityhasDepartment in University one -> some Department
7  }
8
9  fact{
10   all university: University | some department: Department |
11     university.universityhasDepartment in department
```

```
12 }
13
14 fact{
15   all department: Department, university1, university2: University |
16     university1.universityhasDepartment in department and
17       university2.universityhasDepartment in department implies
18     university1 = university2
19 }
20
21 sig Department{
22   departmentrunsbyLecturer: some Lecturer
23 }
24
25 fact{
26   departmentrunsbyLecturer in Department one -> some Lecturer
27 }
28 fact{
29   all lecturer: Lecturer | some department: Department |
30     department.departmentrunsbyLecturer in lecturer
31 }
32
33 fact{
34   all lecturer: Lecturer, department1, department2: Department |
35     department1.departmentrunsbyLecturer in lecturer and
36       department2.departmentrunsbyLecturer in lecturer implies
37     department1 = department2
38 }
39
40 sig Lecturer{}
```

Listing 6.6: Aggregation instantiation

Looking at the result of the execution of Listing 6.6, Figure 6.15 illustrates an instance that shows the dependencies between the related classes.

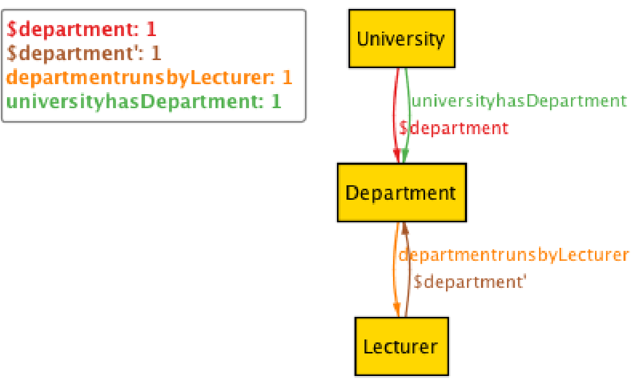


Figure 6.15: Result of executing Listing 6.6

6.1.4 Formalizing user metamodel

We have presented how each of the structures of user metamodel can be formalized using the templates to produce Alloy specifications. Now, we are going to formalize our Book user metamodel from Figure 5.10.

The Alloy specification produced by instantiating the template generated by the tool on the Book user metamodel is presented in Listing 6.7. We will use this again later for our snapshot analysis and analysis of model transformation specification.

```
1  sig Book{
2    titleB : one BookTitle,
3    bookContainChapter : set Chapter
4  }
5
6  fact MultiplicityBookChapter{
7    bookContainChapter in Book one -> Chapter
8  }
9
10 fact SingleValuetitle{
11   AttrSingleValue[titleB, BookTitle]
12 }
13
14 sig Chapter{
15   header : one ChapHeader,
```

```
16     numPages : Int
17   }
18
19   fact SingleValueheader{
20     AttrSingleValue[header, ChapHeader]
21   }
22
23   sig BookTitle{}
24
25   sig ChapHeader{}
```

Listing 6.7: Book user metamodel formal model from Figure 5.10 generated by the tool

Listing 6.7 is type correct in Alloy. We can now perform metamodel analysis on Listing 6.7. We define the execution for one Book and three Chapters. One of the instance results of executing Listing 6.7 is shown in Figure 6.16.

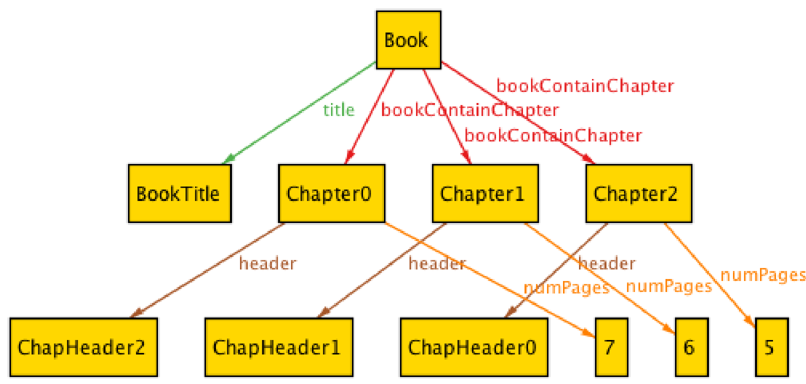


Figure 6.16: Result of executing Listing 6.7 in Alloy Analyzer

Figure 6.16 shows a correct instance generated by Alloy Analyzer. We can vary the execution scope for Listing 6.7. If no invalid instance is produced, we can deduce that our Book user metamodel is *consistent* and *well formed*. Now we need to proceed to snapshot analysis to further verify that the model is sufficient to address every occurance based on the requirements.

6.1.5 User metamodel correctness

In the previous section, we have looked at how a user metamodel can be specified and annotated with certain relation behaviours. We then can generate instances and observe any anomaly in instance behaviour, where we may have detect a structurally under/over constraint model. To further check its correctness, ensuring that the user metamodel sufficiently fulfils the requirements of supporting valid model instances, an instance level analysis is performed.

The Alloy model is generated via Alloy Analyzed by which, a set of satisfiable solutions are mapped, representing *type-checked* instances within a specified scope. The instances are well-formed according to the specification but may also include invalid models due to faults in conceptual design, such as missing elements or constraints. The specified scope of a specification will only find instances within the box, shown in Figure 6.17, based on Alloy *small scope hypothesis*.

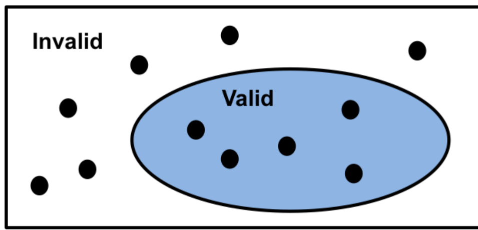


Figure 6.17: Possible instances generated through the user metamodel formal model

To ensure that a valid and invalid model instance exists within the valid and invalid instance set, respectively, we include a process of identifying *positive* and *negative patterns*, a snapshots depicting possible scenarios of a *valid* and *invalid model* respectively, based on the model transformation requirements. A similar approach has been used by [Am7] to perform a snapshot analysis, which verified valid or invalid instances within the scope of its UML+Z model, via defining positive and negative scenarios. In [GdLW^{+}12], an almost identical concept is used, where positive and negative patterns are identified as contracts of a model transformation, imposed on a source model (as pre-condition), target model (as

post-condition) and mapping (as invariants that defines any enabling conditions) of a model transformation.

Based on these, the framework provides a way for transformation engineers to manually construct positive and negative patterns of model instances in accordance to the user metamodel defined in the previous steps. The model instances are to be substantiated against the user metamodel. Through this process, transformation engineers can detect if a user metamodel has appropriately been defined and constrained to represent structural and behavioural features of a domain. Additionally, if there is any insufficiencies where the user metamodel has missing elements.

6.1.6 Model instance notation scheme

To perform the snapshot analysis, we provide a notation for representing the patterns. A defined pattern is an instance model. The instance model is produced manually by the transformation engineers based on the requirements and they are instantiated from the user metamodel. The language is defined in Figure 6.18.

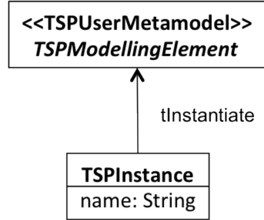


Figure 6.18: Modelling language for instance model

Instance model instantiation is represented using instance model notation (description in Appendix G.2). It uses *stereotypes* to signify the originating elements. The stereotypes will assist in instantiating templates for producing the instance model formal specification. In the snapshot analysis, the instance model formal specification is executed on top of the model (in this case, the user metamodel) formal specification. TSPInstance element is mapped to Alloy model via *signature declaration.*

6.1.7 Positive and negative patterns analysis

In this section we are going to demonstrate the snapshot analysis using model instances. Before we look at how analysis is conducted, Figure 6.19 shows the relations between patterns, the results of generating TSP Model Instance via a template and its verification against user metamodel formal specification will decide the review actions.

Patterns	*Instance model*	*Instance*	*Valid visualzation*	*Correct/ Sufficient*	*Review action*
P	✔	✔	✔	✔	No action
P	✔	✔	x	x	Originating elements
P	✔	x	--	x	Originating elements
P	x	--	--	x	Add missing elements
N	x	--	--	Undecidable	No action
N	✔	x	--	✔	No action
N	✔	✔	x	x	Originating elements
N	✔	✔	✔	x	Originating elements

Figure 6.19: Relation between patterns, the results of applying a template to generate instances and their review actions

When a pattern is able to be fully represented using a model instance, this shows that the defining model (user metamodel) has provided all the required elements. An instance is produced when the instance model formal specification is executed against the defining model (user metamodel) formal specification. For positive patterns, valid instance visualization means that the defining model is correct and sufficient, if otherwise, the defining model needs to be revised. For negative patterns, if a valid instance is produced, the defining model needs revising.

The concept of the snapshot analysis is to see if the pattern constructed manually by the transformation engineer to represent the model instance, is consistent

with its metamodel. Here, we can analyse models to see, not only if they can generate syntactically and semantically correct models, but can also ensure that an invalid model is detected by applying the negative patterns.

The pattern is derived based on the requirements view defined in Step 1. The advantage of this is that we can select which properties we want to be verified. This ensures only relevant patterns are tested. We demonstrate our snapshot analysis by applying it to our Book to Publication model transformation example. We have identified two patterns: (1) positive patterns that shows a book has chapters; and (2) negative patterns that shows chapters can belong to multiple books.

6.1.7.1 (1) Positive pattern - Book has chapters

In the metamodel requirements view, we have defined that a book can have *one or many* chapters. Based on this, we can check if the user metamodel can support this feature. Figure 6.20 shows the instance model for this scenario.

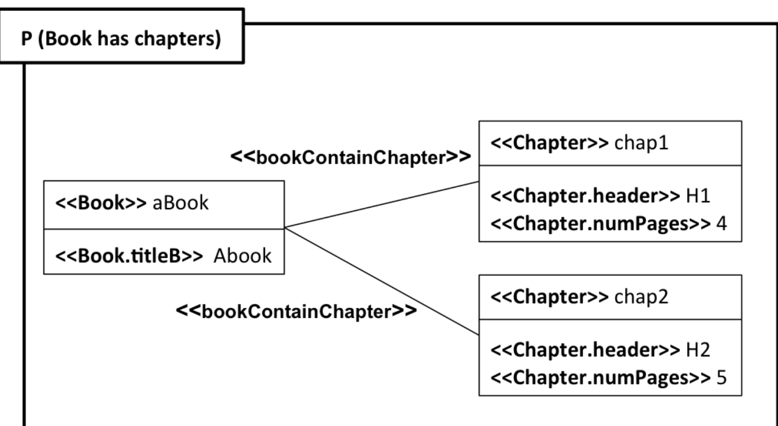


Figure 6.20: Positive pattern Book has chapters instantiated from the user metamodel in Figure 5.10

The instance model *fully* instantiates the template **Instance Model: Defining Model Instance** in Appendix I. The resulting instantiation produces a

model instance formal model in Listing 6.8.

The model instance formal specification will use the user metamodel formal model to provide its definition. The formal model for the user metamodel generated by the tool is given in Listing 6.7. Both models will be included during the execution in Alloy Analyzer for snapshot analysis.

```
fact abookAttrValue{
  abook.titleB = ABook
}

one sig chap1 extends Chapter{}

fact chap1AttrValue{
  chap1.header = H1
  chap1.numPages = 4
}

one sig chap2 extends Chapter{}

fact chap2AttrValue{
  chap2.header = H2
  chap2.numPages = 5
}

fact ElementInstance{
  Book = abook
  Chapter = chap1 + chap2
}

fact ModelStructure{
  abook.bookContainChapter = chap1 + chap2
}

one sig ABook extends BookTitle{}
one sig H1 extends ChapHeader{}
one sig H2 extends ChapHeader{}
```

Listing 6.8: Positive pattern - Book has chapters instance model formal specification from Figure 6.20 generated by the tool

In Listing 6.8, Line 1 - 17 is the declaration of model instances object features for the two chapters from the Positive Pattern in Figure 6.20. Each instance is defined as a type element from the metamodel (Line 19 - 22). The structure of the model is declared in Line 24 - 26.

Executing Listing 6.8 produces a successful verification by producing a valid instance, as depicted in Figure 6.21. This shows that the features are correctly defined by the user metamodel.

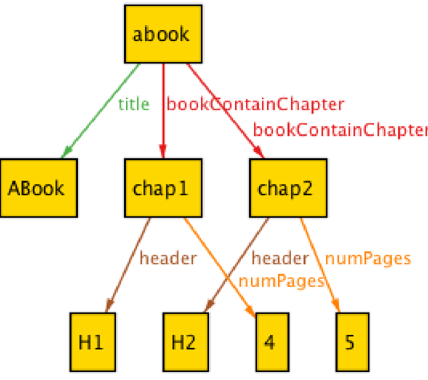


Figure 6.21: A successful verification of positive pattern by Alloy Analyzer - Book has chapters

6.1.7.2 (2) Negative pattern - Chapter belongs to multiple books

The scenario in Figure 6.22 is a negative pattern for our Book to Publication model transformation example. In the metamodel requirements view, we have stated that chapters can only belong to *one and only one* book.

When instantiating the model instance template, the model instance formal specification (Listing 6.9) is produced. Executing the specification does not produce any instance in which chapter is linked to more than one book. A negative pattern should not produce an example in the Alloy Analyzer, therefore, we can conclude that the model conforms to its defined metamodel.

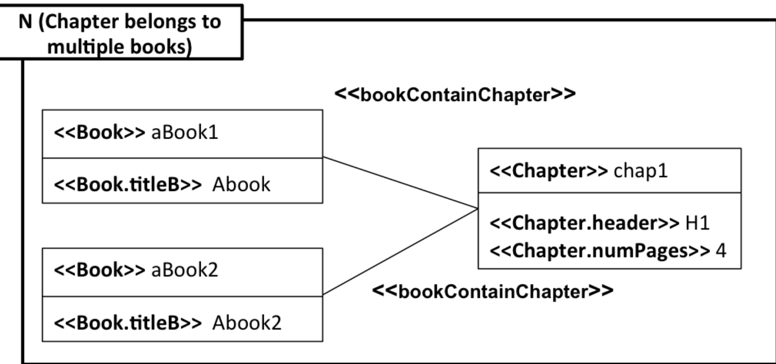


Figure 6.22: Negative pattern - Chapter belongs to multiple books

```
1  one sig abook1 extends Book{}
2
3  fact abook1AttrValue{
4    abook1.titleB = ABook1
5  }
6
7  one sig abook2 extends Book{}
8
9  fact abook2AttrValue{
10   abook2.titleB = ABook2
11 }
12
13 one sig chap1 extends Chapter{}
14
15 fact chap1AttrValue{
16   chap1.header = H1
17   chap1.numPages = 4
18 }
19
20 fact ElementInstance{
21   Book = abook1 + abook2
22   Chapter = chap1
23 }
```

```
24
25 fact ModelStructure{
26   abook1.bookContainChapter = chap1
27   abook2.bookContainChapter = chap1
28 }
29
30 one sig ABook1 extends BookTitle{}
31 one sig ABook2 extends BookTitle{}
32 one sig H1 extends ChapHeader{}
```

Listing 6.9: Negative pattern - Chapter belongs to multiple books instance model formal specification from Figure 6.22 generated by the tool

The Book to Publication model transformation example uses very small metamodels, therefore, we can easily conclude that the user metamodels are sufficient to produce and define syntactically and semantically correct input and output models for a transformation. For more complex metamodels, more patterns could be identified and verified to ensure the metamodels are correct and sufficient.

6.2 Summary

In this chapter, we have defined how our approach formally analyses a contextualized metamodel to ensure the metamodel is correct and well-formed. By doing this, we have established that the source and target metamodel for the transformation are *syntactically* and *semantically correct*.

In the next chapter, we begin specifying model transformations. Once a model transformation specification is produced, we can formally analyse it to check *metamodel coverage* and *semantically correct transformation*.

Chapter 7

Specifying and analysing model transformation

In the previous chapters we identified the requirements for model transformation, production of a contextualized user metamodel and checks for well-formedness, correctness and sufficiency. In this chapter, we proceed with the next step towards specifying and formally analysing model transformation. We have defined the process into three further steps, (Step 4) Generating rule mapping, (Step 5) Decomposing model transformation, and (Step 6) Analysis of model transformation. TSP models in this chapter have been manually translated into XML (Appendix C) and its formal Alloy model have been created using the tool described in Section 4.9.

7.1 Generating rule mapping

Conceptually, a transformation describes how each element in the source model of the required transformation maps to concepts in its target model. A model transformation contains mappings that define the relations between the source and target metamodel, and these are normally implemented as rules. These relations specify associated model elements of the transformation domains and any conditions that ensure the relations to be valid.

In our approach, we are able to generate the model transformation mapping model from the requirements model, where we can identify which elements partic-

ipate in each transformation rule. When we decompose our model transformation specification, the mapping will be used to specify what is being transformed in each of the phases.

7.1.1 Formalizing requirements

Giving formal semantics to the requirements model for model transformation allows it to be used to generate the mapping model.

The concept of giving formal semantics to requirements of model transformation has been inspired by [GdLK+12], using the SysML. The language definition for a requirements model is defined in Figure 7.1

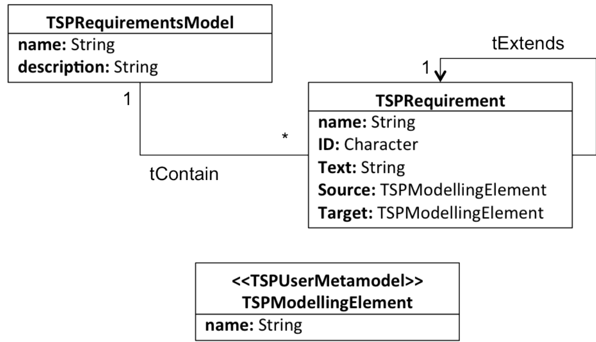


Figure 7.1: Requirements model modelling language

The requirements model allows the functional requirements for model transformation to be organized in a hierarchical manner. Each requirement contains name and text as brief description. An ID is included which corresponds to the requirements ID, in the rule mapping requirements view table. This is to allow the requirement to be traced back to the tables, which contain more descriptive conditions. The requirements will include the corresponding source and target elements associated with the requirements. These elements are part of the user metamodel. The description of the notation for representing a requirements model is given in Appendix G.3.

Figure 7.2 depicts the requirements model for our Book to Publication example, produced from requirements table (Table 5.1).

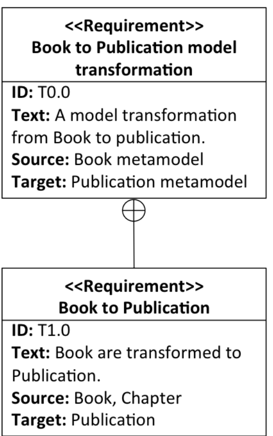


Figure 7.2: Requirements Model for Book to Publication model transformation

7.1.2 Producing mapping model

In this step, we produce the first specification model of model transformation: the *mapping model*. The mapping model is produced based on the requirements model defined Figure 7.2. This model forms the basis for decomposing rules into modules. This is so that it can be further refined to include the details of structural and behavioural features of the required transformation.

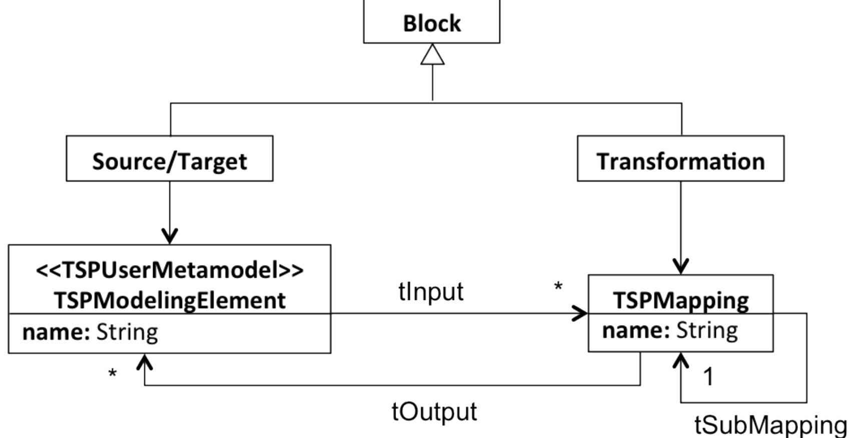


Figure 7.3: Mappings modelling language

Figure 7.3 shows the modelling elements for the mapping model. It extends the *requirements model* and includes elements defined in the source and target *user metamodels*.

The rule mapping model consists of three blocks: (1) source, which elements are defined in the source user metamodel; (2) transformation contains mapping, which details are extracted from the requirements models; and (3) target block, which elements are defined in the target user metamodel. The notation for the rule mapping model is given in Appendix G.4.

Using our Book to Publication model transformation example, from the requirements model, source and target user metamodel, we construct our mapping model, presented in Figure 7.4.

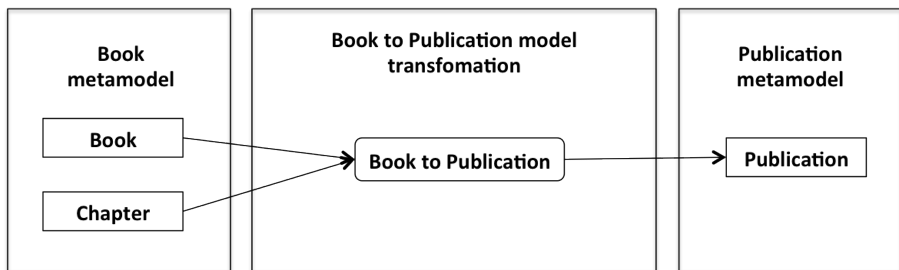


Figure 7.4: Mapping model for Book to Publication model transformation

The next section presents the step where the rules are used in the transformation phase definition. This helps to define the model transformation specification further to include model transformation *operational* features.

7.2 Decomposing model transformation

Decomposition, in the context of this thesis, refers to the process of breaking down a model transformation specification into several module compositions within a single transformation. In our approach, we support the use of decomposition to create a model transformation specification that is made of several smaller transformations, using simple rules. This creates a specification that is made up of independent fragments that can be verified independently.

7.2.1 Reason for decomposition

Most of the time, model transformation specifications are built as a singular module consisting of a set of rules. Rules are the basic modular constructs in model transformation languages [KG06]. Rules can be too fine grained to be the sole unit of composition as they introduce strong dependencies between components.

Compositions are generally considered at an architectural level, where modules of several different transformations are chained via orchestration. The orchestration of model transformation can be between homogeneous languages [RRgLr^{+}09] (*external transformation composition*) or multiple languages [Kle06] (*external transformation composition*).

Goals for composition in general, regarding specifying transformation, are used to create reusability and adaptability [KG06], comprehensibility and maintainability [DKST05]. Incorporating these goals generically in designing transformation specification is often constrained by the features of implementation language, such as rule inheritance, which is not supported by the tool ModelMorf[1].

Particularly for the TSP, we define a decomposing mechanism to address the scalability issues in analysing model transformations in Alloy. [ABK07] claimed that one of the problems with analysing model transformations with Alloy, is the requirement for memory resources and execution time, which increased exponentially with the size of the specification.

Architectural components and rules are the two extremes in promoting some kind of composition in model transformation. In our approach, we address a composition that is coarser-grained than a rule to specify model transformation, not only for enabling scalability in analysis, but also incorporating qualities such as reuse, maintainability and portability in model transformation specification. We have adopted the phasing method for decomposing model transformation [CM09].

To use the template-based analysis, we provide a visual notation for specifying transformation. Inspired by [GdLK^{+}10], we produce a set of notations that specify features of model transformation, which also incorporate the support for

[1] http://www.tcs-trddc.com/trddc_website/ModelMorf/ModelMorf.htm

decomposition of model transformation specification. Having these, we are able to generate a model transformation formal specification via template instantiations that are amenable to formal analysis. The concept of template instantiation for model transformation has similar applications to template instantiation for user metamodels presented in Section 6.1.3.

7.2.2 TSP model transformation specifications modelling language

To create effective fragments that are not just functional, but also incorporate a focused *logical concern* that creates independent verifiable parts, we adopt the phasing mechanism presented in [CM09].

Our model transformation specification is decomposed from the mapping model using phases. Fundamentally, phasing is used to define individual transformations and implies which rules are invoked when, for each phase. [CH06]. But due to the nature of explicitly determining the organization of rules using phases, it is also used for composing model transformation.

Figure 7.5 depicts the features of TSP modelling language for model transformation that supports phasing, and in parallel, constrained the notation for our template instantiations.

There are two type of phase: (1) primitive phase; and (2) composite phase. A *primitive phase* contains a set of rules, and it is executed by evaluating its rules. Each phase contains rules that implement the mappings and well-formedness constraints that define the condition and assignment operation for the rule to be applied. *Composite phases* contain nested primitive phases and execution of composite phase is by executing the nested phases.

Each phase contains *rules* that implement the *mappings* identified in the *mapping model.* The phases use domain elements from the metamodels as *parameters.*

Model transformation specification is usually a composite phase that executes in a *single stage* [CM09]. With the phasing mechanism, model transformation specification can have an *internal composition* that allows *multi-stage* execution [CM09].

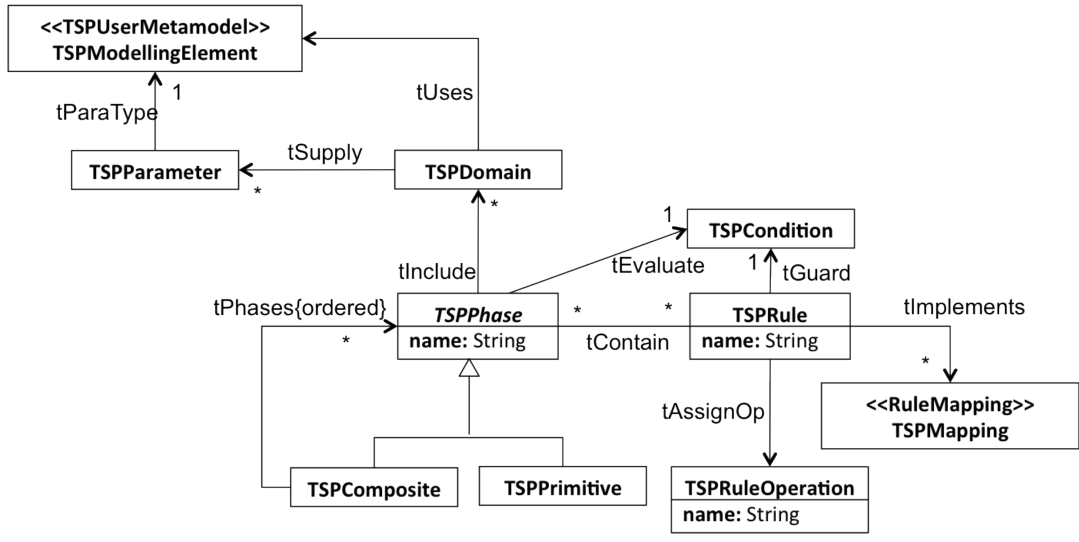


Figure 7.5: Model transformation specifications modelling language with phasing support

A multi-stage generated approach allows transformation to create parts of the target model and merge the parts to produce the whole target model. In TSP, the phases are used in a similar way; to decompose model transformation specification to have an internal composition. The dependency between phases are explicit, where we state which phases needs to be applied first (we do this using the *refinement arrow* in our modelling notation; *top phase* is applied first before the *refinement phase*).

[CM09] presents a comprehensive overview of phasing for model transformation, in terms of both structural and behavioural mechanisms used. Before we explain how phasing is applied to specify model transformation in our approach, the following sections introduce the components of phasing.

7.2.3 Specifying model transformation with phases

Our modelling language for model transformation implements phasing. In the next section, we present the concepts of phasing.

7.2.3.1 Scope

The phase in model transformation is determined by a *scope*. The scope was defined originally in [WV03] for defining steps of program transformation. Applied in the context of a model, a scope describes the steps that define the coverage of a subset of the source and target model, associated in a single rule application. A *pivot* element of the scope denotes the root element, invoked by a rule application. There are four types of transformation scope that define the possibilities of transformation steps that include: (1) local source to local target; (2) local source to global target; (3) global source to local target; and (4) global source to global target. We now describe in detail each of the steps (based on [CM09]).

Local source to local target (local-to-local)

This is the most basic transformation where the pivot element in the source model can be directly transformed to a complete target element. It is a one-to-one source to target mapping in a transformation.

Local source to global target (local-to-global)

A one-to-many source to target mapping is defined as a local source to global target transformation, where the pivot elements in the source model are to be transformed into multiple target elements by the transformation rules. Figure 7.6 depicts a condition where element a, b and c is transformed into w, x and y, and an additional *non-local* element z, generated from a. The reference from generated element y to z is outside the scope of the rule that transforms a to x.

Global source to local target (global-to-local)

When the pivot element in the source model needs to be computed before it is used by a rule, is called the global source to local target transformation (many-to-one source to target mapping). Figure 7.7 shows a transformation of element b to x, where b needs an additional information by querying about *a1* and *a2* in order to generate x.

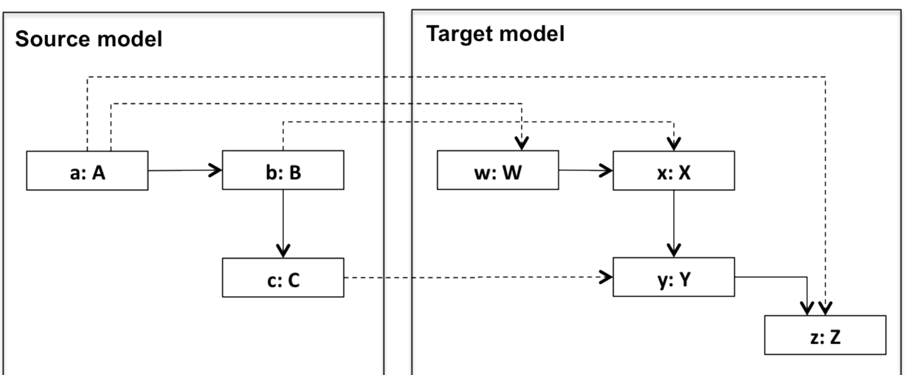


Figure 7.6: A local to global transformation [CM09]

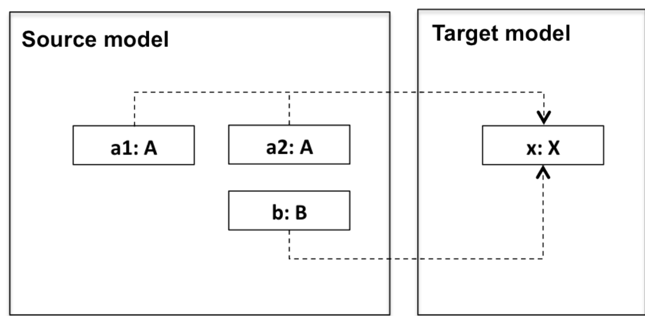


Figure 7.7: A global to local transformation [CM09]

Global source to global target (global-to-global)

A global source to global target transformation (many-to-many source to target mapping) is a combination of a local-to-global and global-to-local transformation. Depicted in Figure 7.8 is an example where a rule is used to transform element b to element x and generating a non-local result y. The rules are required to do queries about $a1$ and $a2$ before generating x from b. The references between x and y are outside the scope of b to x.

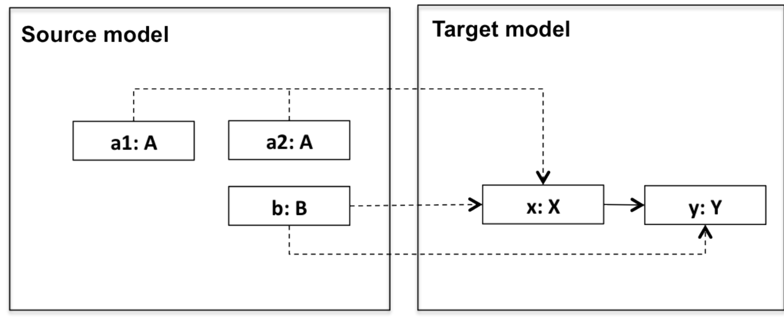


Figure 7.8: A global to global transformation [CM09]

7.2.3.2 Phase application example

To demonstrate how the transformations are realized with phases, we use an example of a class hierarchy in class to relational database transformation that uses the foreign key concept. The phase that defines the transformation that generates a relational database table for each class in the hierarchy connected by foreign keys, is shown in Figure 7.9.

This is an example of a local to global transformation. To recap, a local to global transformation is a transformation between one source element to one target element and other non-local elements that are part of the target model that may or may not have been generated. This kind of transformation, can be generically specified using three phases; (1) apply any local to local transformation, (2) compute and generate the non-local target element, and finally (3) merge the non-local target element to the previously generated element. For our example, *Phase 1* transforms the classes to tables, *Phase 2* generates the primary and foreign key for the tables (primary and foreign key are non-local elements). *Phase 3* and *Phase 4* merge the generated primary and foreign key with a foreign key reference.

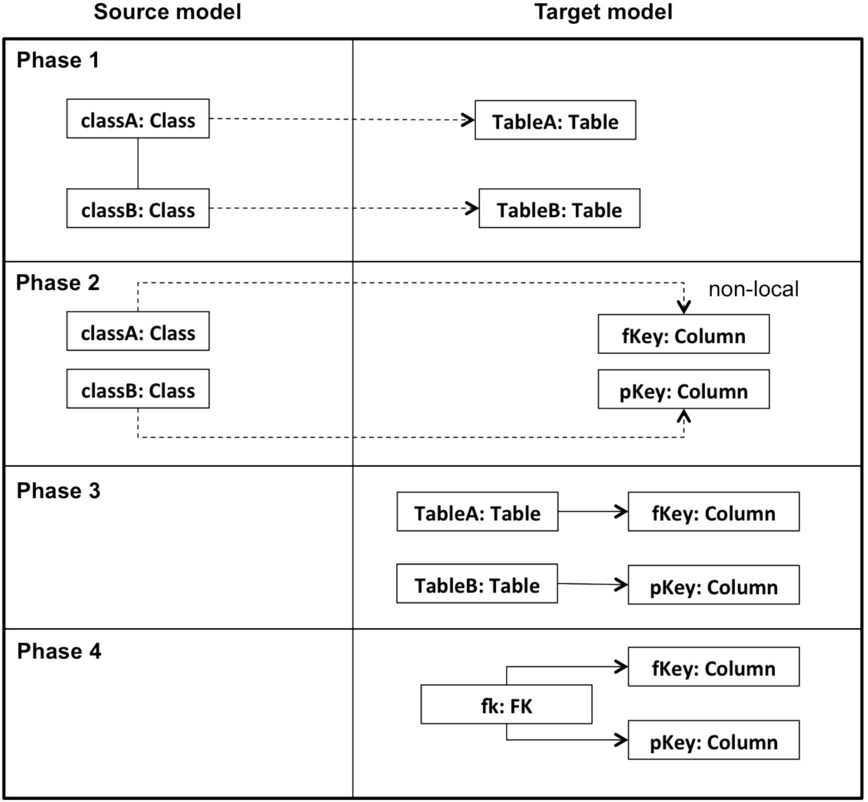


Figure 7.9: A phasing mechanism defining two related classes to individual tables with foreign key reference transformation, specified as local to global transformation

7.2.4 Model transformation specifications modelling language notations

The TSP model transformation specification modelling language provides a set of notations for specifying model transformation with phases. The notations contain elements required to specify a transformation in phases. The detailed descriptions of the notations are included in Appendix G.5.

The TSP model transformation specification notations have the capability to represent, not only the structural features of the transformation according to the modelling language specified in Section 7.2.2, but also the behavioural features of a transformation. The notation has the capability to include the

assignment operations using *assignment operation* notation for the phases. This clearly describes how an element is being assigned values.

In the next section, we demonstrate how we specify model transformation specification using the notations and the approach we have presented so far. We applied them to our Book to Publication model transformation example.

7.2.5 Model transformation specification

In Chapter 5, we defined the requirements for Book to Publication model transformation. We have also defined a contextualized user metamodel for the Book and Publication Model. We showed how to produce the Alloy formal specification for the user metamodel, using templates.

Now, we are going to create a transformation specification between the user metamodels. We produced one rule mapping in Step 4 and from it, we decomposed our specification into phases. This enables model transformation to be specified in smaller logical fragments. In Section 7.3, we present how the phases can be used to perform formal analysis of model transformation specification.

7.2.5.1 Phase identification

Phases can be identified by distinguishing parts of the specification that cover a specific *model transformation logic*. This is a logical concern that allows fragments of model transformation to be applied and analysed independently. Our Book to Publication does not have a complex transformation logic. We will discuss it further when we apply TSP to a bigger model transformation in Chapter 8.

For now, we are going to show how TSP model transformation specification is produced using our simple Book to Publication model transformation example. Figure 7.10 shows a phase for Book to Publication model transformation, using the *phase notation*.

Phase publication_definition

Figure 7.10: Phase for Book to Publication model transformation

A phase can be, (1) root, or (2) refine. A root phase contains transformation that can be applied independently, while refine is a phase that is used to support the root phase and cannot be applied independently. *Phase publication_definition* in Figure 7.10 is a root phase.

7.2.5.2 Example: Phase defining publication from book

A phase contains rules for model transformation. The TSP model transformation specification language defines model transformation structural and behavioural aspects using; (1) rule mapping, input, output, non-local input and non-local output element notations, and (2) assignment operation notation, respectively. A phase can have a condition (defined using condition notation) to provide a constraint for a valid execution of a phase. A phase can use functions (defined using function notation) to specify any *query operations* required by them.

Figure 7.11 shows the phase definition for Book to Publication model transformation. The phase uses the *BookToPublication* rule (from the mapping model) to transform book to publication. This phase is a global-to-local transformation, therefore we have to include a function that queries additional non-local input elements for the *BookToPublication* rule.

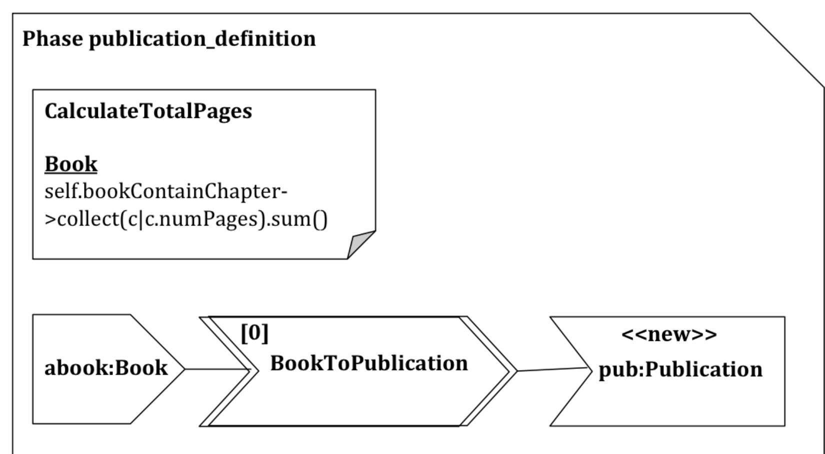


Figure 7.11: Specification of defining the publication phase using rule mapping, input and output element, and function notations

Functions in TSP can be expressed using OCL. To note, we have yet to include formal templates for formalizing OCL into Alloy specification. Identifying OCL patterns for model transformation is a whole new challenge, which we plan to include in the future. However, work on formalizing OCL to Alloy has been looked at in the context of UML models [ABGR10].

The rule *BookToPublication* in phase *publication_definition* contains two operations: (1) assigning publication title; and (2) calculating total book pages from chapters. Assignment operation for phase *publication_definition* is shown in Figure 7.12.

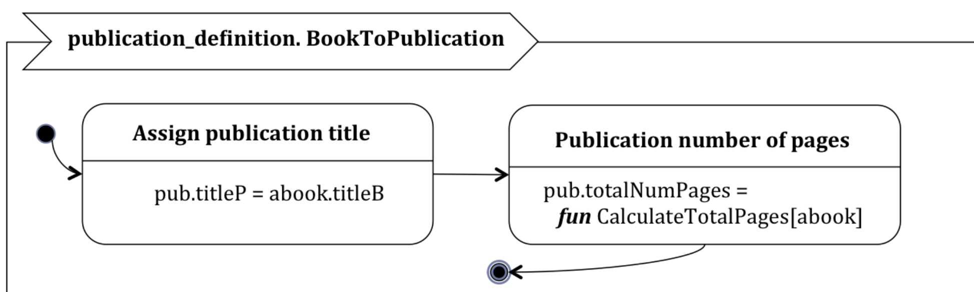


Figure 7.12: Assignment operation of defining publication phase

At this point, we have specified the Book to Publication model transformation. This specification can be used to instantiate the formal templates to produce Alloy specification for analysis.

7.3 Analysis of model transformation

We have introduced how TSP analyses the user metamodel in Chapter 6. The concept for analysis of model transformation specification takes a similar approach. Except for model transformation, executing the specification alone cannot fully determine the correctness and the well-formedness of model transformation. Analysis of model transformation using Alloy is an input-dependent formal methods [SCD12]. Therefore, we need to specify our input model to analyse our specification. Pattern snapshot analysis is fitting for this approach.

We have stated, a phasing mechanism incorporated in TSP model transformation specification, is to address the limitation of scalability in using Alloy. In the next section, we explain how TSP does the pattern snapshot analysis with phasing.

7.3.1 Pattern snapshot analysis and phasing

We introduce pattern snapshot analysis for the user metamodel in Chapter 6. The analysis is used to check for the well-formedness of the models that have been specified and formalized in Alloy. To address scalability problems of SAT-based analysis, we propose a model transformation specification using phases.

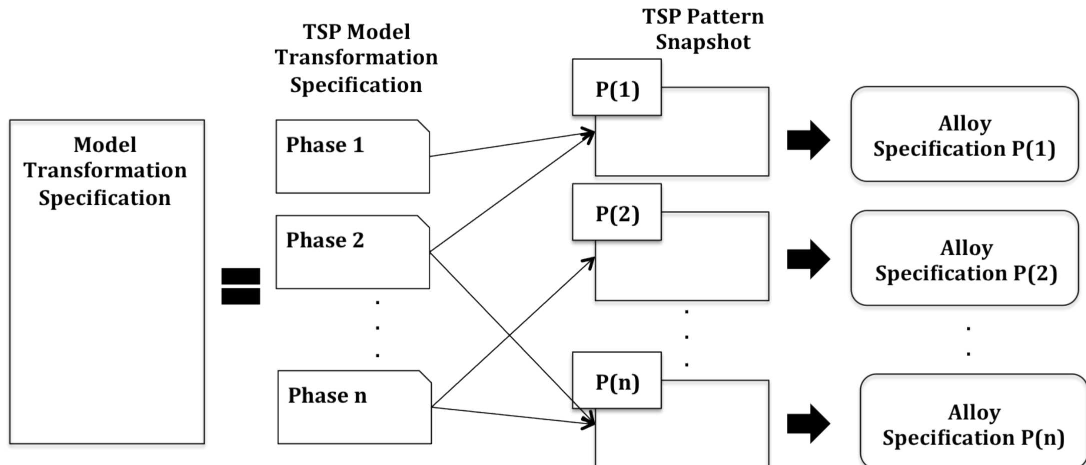


Figure 7.13: The association between phasing and pattern analysis using Alloy

Figure 7.13 shows how phasing can help to do analysis based on the *small scope hypothesis*. The TSP framework represents the model transformation specification in a form of phases, where these phases can be selected according to the pattern snapshots of an instance of a transformation to be analysed. Selected phases define the scope of the metamodels and transformation. Therefore, there is no need to include the remaining unrelated elements for the pattern snapshot analysis.

Using this approach, we can check for *metamodel coverage* by defining patterns to represent the desired features of a transformation, based on the requirements

specified in the requirements view tables. With this, we can also verify if we have specified a *semantically correct model transformation* because we devised our patterns to represent the correct transformation. A semantically incorrect transformation will give out an error.

7.3.2 Transformation instance notation scheme

Similar to what we did for analysing our user metamodel presented in Chapter 5, we apply the same analysis technique to model transformation specification. We do this using the pattern snapshot analysis by producing model transformation instances (a description of notations is given in Appendix G.6). The additional step that we need to include here is that first we have to select which phases are required to support the analysis. Once we have decided on the phases, the analysis begins by formalizing the phases. The formalized specification can then be checked against the pattern snapshots.

To enable templates to produce an Alloy specification, the TSP model specification has corresponding Alloy components, as shown in Table 7.1.

Table 7.1: TSP model transformation specification elements corresponding to Alloy components

TSP Model Transformation Specification Element	**Alloy Component**
TSPDomain	Module header
TSPParameter	Signature
TSPPhase	Predicate
TSPRule	Declaration
TSPCondition	Expression

Transformation instance model is used to represent the pattern for model transformation specification snapshot analysis. The transformation instance model is defined by the TSP modelling language in Figure 7.14. Transformation instance model instantiation is represented using instance model notation. It uses

stereotypes to signify the originating elements. The stereotypes will assist in instantiating templates for producing the instance model formal specification.

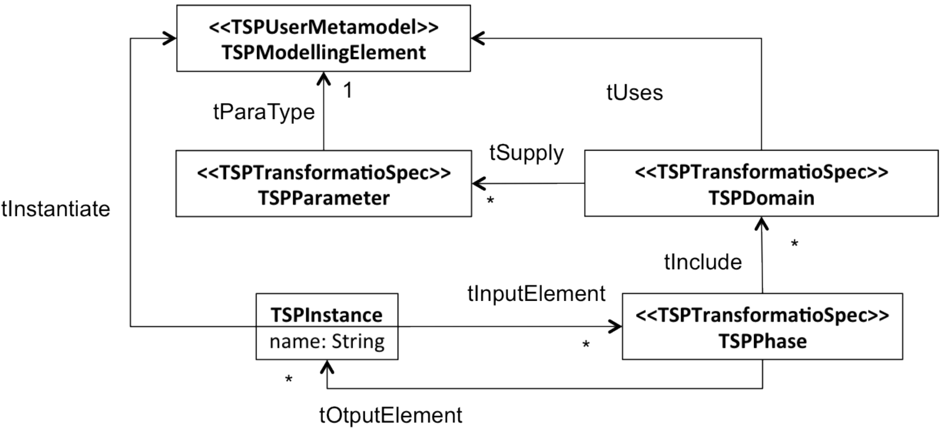


Figure 7.14: Modelling language for transformation instance model

Now, we demonstrate how to formally analyse the model transformation specification. We have specified for the Book to Publication model transformation example, the use of pattern snapshot analysis. Again, due to the fact that our Book to Publication example is trivial, we may not be able to demonstrate the full capability of TSP. However, we will demonstrate and evaluate this when we apply TSP to a bigger model transformation in Chapter 8.

The TSP approach requires analysis patterns to be identified for snapshot analysis to be performed. Once the pattern has been identified, we can select the required phases that address the area of concern for analysing the pattern.

Figure 7.15 shows an instance model for model transformation that represents a positive pattern for a correct generation of *Publication* from *Book*.

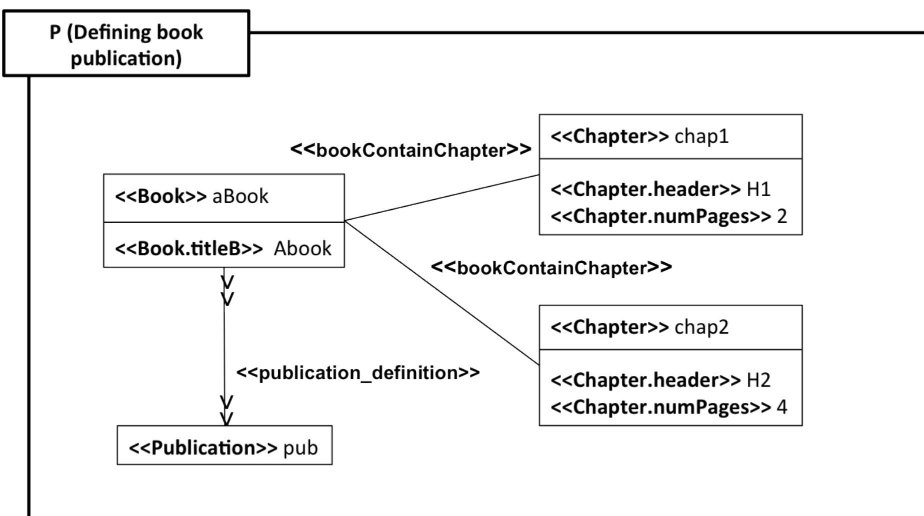


Figure 7.15: Transformation instance model of transformation from book to publication

To analyse this pattern, we need to formalize our model transformation specification. In Book to Publication model transformation, we will formalize the *publication_definition* phase (Figure 7.11 and 7.12). It is a global-to-local transformation, therefore, use templates **TM3: Global-to-local transformation phase** (Appendix I.6.3). The Alloy code generated by instantiating this template is in Listing 7.1.

```
1  pred publication_definition
2    (abook:Book, pub:Publication){
3      pub = BookToPublication[abook] and OP_publication_definition[
          abook, pub]
4  }
5
6  pred OP_publication_definition
7    (abook:Book, pub:Publication){
8      pub.titleP = abook.titleB
9      pub.totalNumPages = CalculateTotalPages[abook]
10 }
```

Listing 7.1: Model transformation formal specification - Defining publication from Figure 7.11 and 7.12 generated by the tool

When analysing Listing 7.1, the Book (Listing 6.7) and Publication (Listing in Appendix D) user metamodel formal specification is included, providing the definition for Book and Publication instances.

We have stated previously, that the current version of the template catalogue does not support (but potentially automable) the formalization of functions specified using OCL. For calculating the total number of pages from the book chapters for the publication's number of pages, the function definition in Listing 7.2 is manually added into Listing 7.1.

```
1 fun CalculateTotalPages(abook:Book): Int{
2   sum c: abook.bookContainChapter|c.numPages
3 }
```

Listing 7.2: Function fragments manually added to Listing 7.1

For transformation specification that only includes certain phases, the source and target metamodel formal specification will only contain the elements required by that particular part of the specification. For now, the tool require the elements to be extracted manually from the source and target user metamodel formal specification and included when necessary. In our Book to Publication model transformation example, the whole Book and Publication user metamodel formal specifications are used. According to the template **TM3: Global-to-local transformation phase** (Appendix I.6.3) instantiation, an additional field declaration is made in the Book formal specification, to specify elements that are being used in a rule. Listing 7.3 shows the inclusion of mapping relations to the Book elements, to specify the association of the elements to the rule *BookToPublication* that produces one Publication in Line 6.

```
...
sig Book{
  title: one BookTitle,
  bookContainChapter: set Chapter
  /*Mapping relation*/
  BookToPublication: one Publication
}
...
```

Listing 7.3: Snippet of Book user metamodel formal specification that includes mapping relations

Once we have the required segment of model transformation formal specification, we can instantiate templates for the transformation instance model that represent the pattern. The resulting Alloy specification is in Listing 7.4.

```
one sig abook extends Book{}
fact abookAttrValue{
  abook.titleB = ABook
}

one sig chap1 extends Chapter{}
fact chap1AttrValue{
  chap1.header = H1
  chap1.numPages = 2
}

one sig chap2 extends Chapter{}
fact chap2AttrValue{
  chap2.header = H2
  chap2.numPages = 4
}

one sig pub extends Publication{}
fact ElementInstance{
  Book = abook
  Chapter = chap1 + chap2
  Publication = pub
}
fact ModelStructure{
  abook.bookContainChapter = chap1 + chap2
```

```
26 }
27 fact Transform{
28   publication_definition[abook, pub]
29 }
30
31 one sig ABook extends BookTitle{}
32 one sig H1 extends ChapHeader{}
33 one sig H2 extends ChapHeader{}
```

Listing 7.4: Transformation instance model formal specification - Defining publication from Figure 7.15 generated by the tool

The transformation instance formal specification in Listing 7.4 is a result of formalizing the transformation instance model in Figure 7.15. The instantiation uses templates **Instance Model: Defining Model Instance** (Appendix I.5) and **Instance Model: Defining Transformation Instance** (Appendix I.7).

Executing Listing 7.4 produces an instance in Figure 7.16. It shows that transformation features for transforming a book to publication are correctly defined.

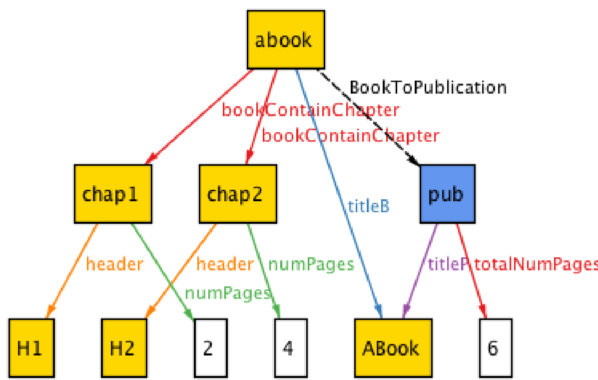


Figure 7.16: Successful verification of defining publication transformation from executing Listing 7.4 in Alloy Analyzer

We have included a standard theme for our visualization of Alloy instances: (1) *yellow* for source elements; (2) *blue* for target elements; (3) *black-dashed line* for mapping relations; and (4) *white* for generic elements. We also include a means to notify whether a transformation is successful or fails, based on the condition given. We will demonstrate this feature in Chapter 8.

7.4 Summary

We have presented the final parts of our framework, which are the decomposing and refining of the model transformation specifications. We produced a set of transformation phases that create modularizations in the model transformation specifications. These phases can be analysed independently, thus a smaller, more focused analysis can be performed.

In the next chapter, we are going to evaluate our approach on a bigger transformation.

Chapter 8

Applying and evaluating the TSP framework

We have outlined in Figure 4.4 the steps in TSP framework: (1) elicit model transformation requirements; (2) contextualize a metamodel; (3) analyse a metamodel; (4) generate rule mapping; (5) decompose and refine a model transformation specification; and (6) formally analyse a model transformation. We have presented the TSP framework for specifying and formally analysing model transformation specification in Chapter 5 - 7 by applying templates to produce formal model. The consistency of the generated formal model presented in this thesis is maintain by the TSP tool (Section 4.9). In this chapter, we will show how TSP can be applied to another example with more transformation features to further evaluate the capability of the framework.

TSP can be used to formalise transformations from any type of user metamodel. In this chapter, we apply the TSP framework, to an example, transforming from a UML class model notation to a Relational Database notation. The transformation follows the six TSP steps presented in the previous chapters; the only different in this chapter is that the example uses a bigger, more familiar model transformation to demonstrate the capability of the framework to cater for real world applications. The example models in this chapter have been manually translated into XML (Appendix F) and its formal Alloy model have been created using the tool described in Section 4.9.

The user metamodel used in Book to Publication and UML class model to a Relational Database model transformation has one dissimilarity; they belong to a different level of abstractions. The Book user metamodel in Book to Publication example have one level of instantiation (that is from Book user metamodel to a Book model), while in UML class model to a Relational Database example, Class user metamodel may have several instantiation (producing Bank account model which can be instantiated further to, for example, John's bank account). In this case, the differences does not present any significant impact as TSP is capable to address any type of user metamodel, provided it is used in a transformation.

8.1 Data modelling and class to relational database transformation

Data modelling [SW04] is a process that defines the features of data using three kinds of model structures: (1) a conceptual model, that identifies and documents the required entities and their relationships to the system; (2) a logical model, that defines the entities and their relationships, excluding implementation details; and (3) a physical model, that defines the database structure based on the logical model in a specific database implementation format [Spa11].

Object-oriented data modelling (OODM) is an approach that allows database design using object concepts. OODM contains two components: (1) conceptual schema that uses objects and relations between them to represent the domain; and (2) data operations that define the data model operations [ZR88].

OODM extends data modelling languages capabiity such as the Entity-Relationship Diagrams. OODM incorporates data modelling support using a class diagram [GL03; AT05; SS03]. There are also software development suites that support the specification and data models generation, such as relational database models for implementing SQL from a class diagram, such as the UML Class Diagram. Examples of these tools are, IBM InfoSphere Data Architect[1], Enterprise Archi-

[1]IBM InfoSphere Data Architect: http://www-01.ibm.com/software/data/optim/data-architect/

tect[1], and Visual Paradigm[2].

Challenges in analysing a class diagram to a relational model transformation includes, ensuring the generated relational model is *complete* and *semantically correct* over a set of rule mapping from a class diagram. The *object-relational impedance mismatch* expresses the semantic gap between an object and relational model [IBN+09] when specifying a *semantic equivalent* transformation. In TSP, an analysis of model transformation is performed by formalizing the model transformation specification.

Class to Relational Database model transformation is a model-to-model transformation. It is used to translate a class diagram to a relational model that defines a database structure. We present our approach to analysing this transformation, following the TSP steps defined in Chapter 4.

8.2 Step 1: Eliciting class to relational database model transformation requirements

Specifying model transformation requirements between a class and relational model is a complex task, due to the *object-relational impedance mismatch* problem. [IBN+09] highlights a list of mismatches and proposes a framework that defines four levels of impedance mismatch organization: (1) paradigm; (2) language; (3) schema; and (4) instance, to address this problem.

For transformation engineers that need to specify model transformation between a class and relational database model, identifying *compatibility concerns* requires extra effort. We are not focusing on an approach for analysing object and relational models in particular, therefore we focus on the fundamental features of class to relational database transformation. The aim is to assess whether our approach can specify and analyse model transformation from the identified requirements.

The first step is to elicit requirements for class to relational database model transformation to produce the MTSM (Figure 4.4). In our transformation, we

[1]Enterprise Architect: http://www.sparxsystems.com/products/ea/index.html
[2]Visual Paradigm: http://www.visual-paradigm.com/

have identified the following features explaining in terms of semantic concepts of the two types of model:

1. For each instance of persistent Class, an instance of Table and a primary key column is created. We assume all classes are persistent.

2. For every child class, an instance of Table and a foreign key Column is created, pointing to the primary key of the parent class.

3. For each instance of attribute that belongs to a persistent Class, an instance of Column is generated.

4. For every attribute with multiple values, a Table with Columns to store values and their IDs is created. A foreign key Column is added into the owner's Table for reference to the value table.

5. For each class with an association, a table for each class is created. The first class has a primary key column and the second class has a foreign key pointing to the first class.

Table 8.1 and 8.2 presents a full set of transformation rules . They contain the rule mapping requirements view for class to relational database transformation.

ReqID	Description	Condition	Source	Target
T1.0	For each instance of Package, an instance of Schema is created.	Schema name = Package name.	Package	Schema
T2.0	For each instance of persistent Class, an instance of Table and a primary key column is created.	(1) Table name = Class name. 2) Primary key column with name = Class name + *ID* and type = integer.	Class	Table Column
T2.1	For every child class, an instance of Table and a foreign key Column is created, pointing to the primary key of the parent class.	1) Table name = Class name. 2) Foreign key column with name = Class name + *ID* and type = integer. 3) Foreign key referencing parent table primary key.	Class FKey	Table Column

Table 8.1: Class to relational database rule mapping requirements view - Part 1

ReqID	Description	Condition	Source	Target
T3.0	For each instance of Attribute that belongs to a persistent Class, an instance of Column is generated.	1) Column name = Attribute name. 2) Column type = Attribute type. 3) Added to the Table created from the owner class.	Attribute	Column
T4.0	For every attribute with multiple value, a Table with a foreign key and value Column are created.	1) Table name = Attribute owner Class name + Attribute name + *Values*. 2) Values column = *Value* and type = Attribute type. 3) Foreign key column = Class name + *ID* and type = integer. 4) Foreign key links to owner class table primary key.	Class Attribute FKey	Table Column

Table 8.2: Class to relational database rule mapping requirements view - Part 2

To show if our approach capable of detecting errors and insufficiencies, we purposely left out the rule mapping requirement for dealing with associations.

Next, we produce the metamodel requirements view. From the source and target column of rule mapping requirements (Table 8.1 and 8.2), we identify the required features of the source and target metamodel elements. Table 8.3

describes the feature requirements for Class model elements and Table 8.4 outlines the feature requirements for relational database model elements.

Element	**Description**	**Attribute**	**Relation**	**Comment/ Condition**
Package	Provide the containment for classes.	name: String	(1) has [1..*] Class	-
Class	Class define object.	(1) name : String (2) isPersistent : Boolean	(1) has [0..*] Attribute (1) isParent to [0..*] Class	(1) Class has a unique name
Attribute	Attribute holds class features. Can have multi value attributes.	(1) name: String (2) type: Datatype (3) multivalue: Boolean	belongs to [1] Class	-

Table 8.3: Class metamodel requirements view

Element	Description	Attribute	Relation	Comment/ Condition
Schema	Containing table structure.	(1) name : String	has [1..*] Table	-
Table	Containing a collection of values.	name : String	(1) has PKey[1..*] Column (2) has value [1..*] Column (3) has ForeignKey [0..*] Column	-
Column	Containing specific values.	(1) name : String (2) type : DataType	belongs to [1] Table	-
FKey	Links between tables.	-	(1) referParent [1] Column (2) referChild [1] Column	- -

Table 8.4: Relational database metamodel requirements view

TSP is used to analyse the transformation specification. To evaluate the usability of the resultant transformation, we are going to apply this to transform *customer banking account details* into a database. Figure 8.1 is the class diagram that defines our customer banking account structure.

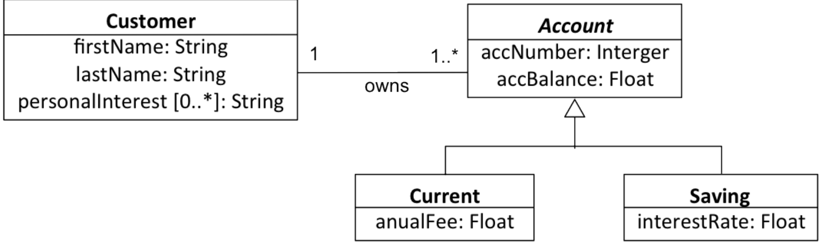


Figure 8.1: Customer banking account

This example model defines a business level structure that enables us to define business rule requirements. The customer banking account has the features as listed in Table 8.5. The example model can also be used to create snapshot patterns for model analysis.

Requirement	**Description**	**Condition**
IM1.0	Account type can be Saving or Current.	(1) Each account has a unique account number and holds the customers account balance. (2) Current account will have an annual fee. (3) Saving account will have an interest rate.
IM2.0	A customer can have both current and saving or either one of them. A customer cannot have duplicate accounts of the same type	Valid customer account: (1) Saving and current (2) Saving or current Invalid customer account: (1) Multiple saving accounts (2) Multiple current accounts

Table 8.5: Banking model derived from class model requirements view

8.3 Step 2: Contextualizing class and relational database metamodel

From the metamodel requirements view (Table 8.1 and 8.2), we identify source and target metamodels. As previously noted, the metamodel required for a transformation might be part of a larger metamodel, readily available or non-existent.

In practice, models produced using MDE tools typically conform to a metamodel such as Ecore's EMOF (a large metamodel). Here, we retrofit a metamodel, a situation that is typical of manually produced models. We use existing metamodels for class and relational database models from the Eclipse Epsilon SVN

Repository[1]. The metamodels are thus *readily available*. However, we have no means of checking that the metamodels are sufficient to express the semantics required for our example transformation.

There are two ways to analyse readily available metamodels: (1) translate the metamodels into TSP Alloy specification to enable model and model transformation analysis; or (2) define and analyse user metamodels and transformation in TSP, and compare the user metamodel with the readily available metamodel, to ensure they have the required elements and relations for model transformation implementation.

Method (1) is ideal, but there could be some elements in the metamodel that are incompatible with the templates, which may produce an incomplete or imprecise Alloy specification. For example, a lack of generalization and reflexive association details. Furthermore, if we look at the Class[2] metamodel provided in the SVN, the metamodel includes other elements that are not required by our transformation (for example, *Operation*). Because we do not need to formalize all elements in the metamodels, we chose to do method (2).

From the metamodel requirements view (Table 8.3), we have identified three elements for a class model: (1) Package, (2) Class, and (3) Attribute. Each of these elements has a name, so, following the approach taken by OMG metamodels, we introduce an abstract element, ModelElement that generalizes these features. The generalization relationship of ModelElement with Package, Class and Attribute is of the kind *complete, disjoint*, this is because ModelElement attributes are used by its subclasses.

Next, we specify the associations that exist between the classes. There are three associations in the Class metamodel: (1) Package-Class, where each package contains many classes and classes belongs to one package; (2) Class-Attribute, where a class can have many attributes and each attribute belongs to one class; and (3) Class-subClass, where a class can extend from another (one) class. Association (3) is of type reflexive-acyclic, where subClass should never be a parent to its own parent Class instances. Each association have role names attached. The resulting user metamodel, based on these statements, is as shown in Figure 8.2.

[1]Eclipse Epsilon SVN Repository: http://dev.eclipse.org/svnroot/modeling/org.eclipse.epsilon/
[2]Provided in Eclipse Epsilon SVN as OO.ecore

A similar approach is applied to produce the relational database user metamodel, as depicted in Figure 8.3.

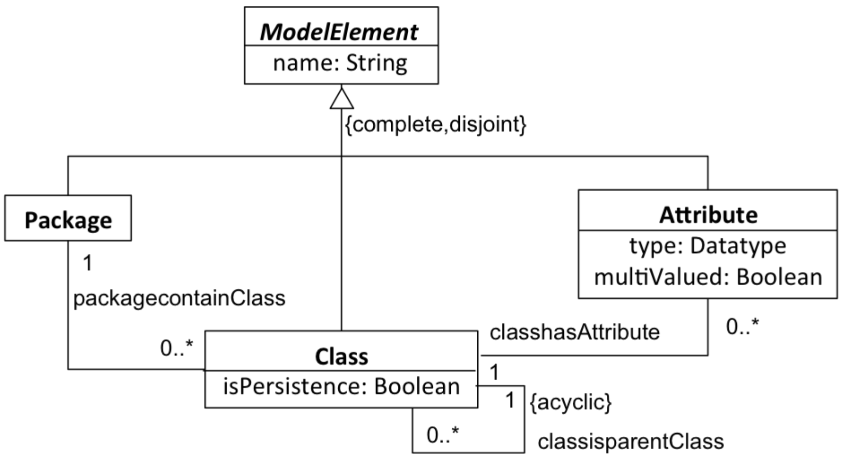


Figure 8.2: TSP user metamodel for Class model

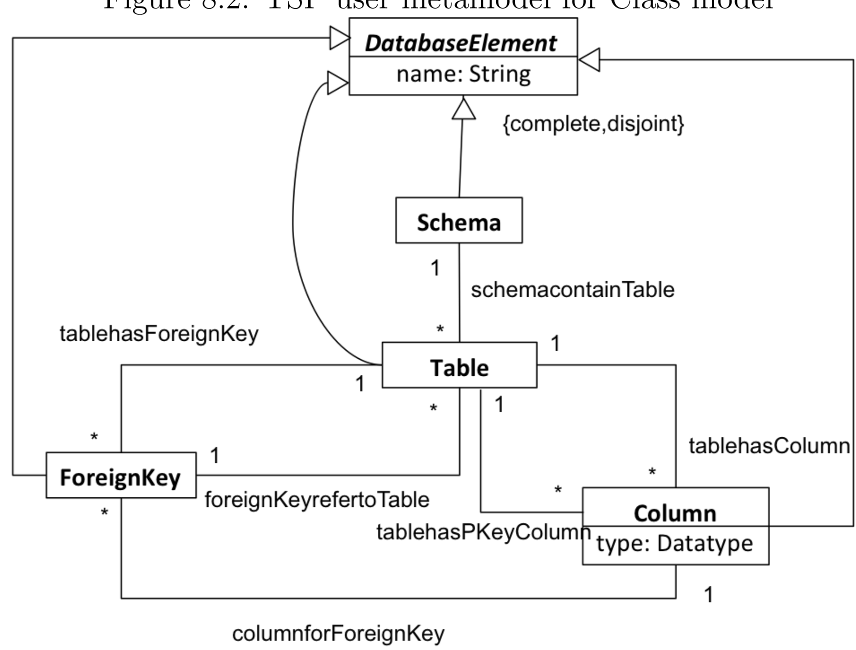


Figure 8.3: TSP user metamodel for Relational Database model

The source and target user metamodels created from this step are now contextualized, annotated with meaningful and defined relations to represent the source and target metamodel for the model transformation. Formal specifications that

enables an effective analysis in TSP is produce from these models.

To use the readily available metamodel (for example, the one provided in the SVN) for implementing transformation, we need to identify that the specified user metamodel is a subset of the existing metamodel. Alternatively, we can translate the user metamodel into a tool supported format such as Ecore for implementation.

Between the two alternatives, detecting that the user metamodel is a subset of the existing metamodel is the best way to ensure properties preservation. Translating the user metamodel into another model may cause alterations to some properties.

8.4 Step 3: Analysis of class user metamodel

For the purpose of brevity, we are going to discuss the analysis of the Class model only. We have a separate analysis for the Relational Database user metamodel, which is ready to be used for model transformation specification. Relational Database user metamodel formal specification is given in Appendix E.

Listing 8.1 are the results of instantiating the templates by the user metamodel defined in Figure 8.2.

```
1  abstract sig ModelElement{
2    name : one String
3  }
4
5  fact SingleValuename{
6    AttrSingleValue[name, String]
7  }
8
9  sig Package extends ModelElement{
10   packagecontainClass1 : set Class
11 }
12
13 sig Class extends ModelElement{
14   isPersistence : Boolean,
15   classhasAttribute1 : set Attribute,
16   classisparentClass : set Class,
17   packagecontainClass2 : one Package
```

```
18 }
19
20 fact BidirectionalMultPackage {
21   Package <: packagecontainClass1 in (Class) set -> one (Class) and
22   Class <: packagecontainClass2 in (Class) one ->
23   set (Package) packagecontainClass1 in ~packagecontainClass2
24 }
25
26 sig Attribute extends ModelElement{
27   type : Datatype,
28   multivalued : Boolean,
29   classhasAttribute2 : one Class
30 }
31
32 fact BidirectionalMultClass {
33   Class <: classhasAttribute1 in (Class) set -> one (Attribute) and
34   Attribute <: classhasAttribute2 in (Attribute) set ->
35   one (Class) classhasAttribute1 in ~classhasAttribute2
36 }
37
38 fact SingleValuetype{
39   AttrSingleValue[type, Datatype]
40 }
41
42 fact MultiplicityClassAttribute{
43   classhasAttribute in Class one -> Attribute
44 }
45
46 fact AcyclicclassisparentClassClass{
47   acyclic[classisparentClass, Class]
48 }
49
50 sig String{}
51 sig Datatype{}
52 *Bidirectional fact is included manually.
```

Listing 8.1: Class user metamodel formal specification from Figure 8.2 generated by the tool

Templates instantiated include (all templates are provided in Appendix I): (1) C1: Abstract Class for ModelElement (Appendix I.3.1); (2) C2: Class for Pack-

age (Appendix I.3.2), Class and Attribute; (3) R1: Complete, disjoint (Abstraction) (Appendix I.4.1.1) for generalization of ModelElement and its subclasses, Package, Class and Attribute; (4) R5: Association (Bi-Directional Only Model) (Appendix I.4.2) for *PackasgeContainClass* and *ClassHasAttribute* relation; (5) R11: Reflexive - Acyclic (Appendix I.4.4.5) for *ClassIsParentClass* relation; and (6) Module header from M1:TSpecProber Generics (Appendix I.2.1) and M2: User Metamodel Header (Appendix I.2.2). The instantiation of classes preceeds the instantiations of relations.

8.4.1 Automated metamodel analysis of class

Based on Listing 8.1, we now perform an automated analysis of the Class user metamodel. We conduct the analysis to validate the user model through several runs, each defined by a specific scope to allow focus on the instances. The number of runs depend on how Alloy Analyzer produces the instances where in each run, we will have different configuration to observe a certain features based on the requirements defined earlier in the process. If the features are not given within the first few instances, the specification is re-run with different run configurations. Models are valid if they can produce valid instances for all run configurations while an invalid instances occurence indicate inconsistencies in the model.

Here, we execute Listing 8.1 and look through a series of instances generated by Alloy Analyzer. Any anomaly is detected by examining the instances. We do not include instances here, but we state the result of our observation of the instances generated by Alloy Analyzer. The scope setting is based on the concept of *small scope analysis*, which enables each run to be manually decided. This gives some level of confidence that the focus part is adequately covered. The decision that a model is finally correct will be based on an educated judgement of transformation engineers. This has a similar act to *unit testing* in programming.

Alloy Run 1

For the first run, we chose to consider one Package, two Classes and two Attributes, on Alloy for the scope of six (the scope has to consider the minimal

number of elements that creates a valid instance) which are required to represent the complete instantiation of metamodel elements; one Package contains three Classes, class1 is a parent to class2; and classes can have none or many Attributes, an Attribute belongs to one Class.

Alloy Analysis of Run 1

From Run 1, we have observed from the instances generated by Alloy Analyzer, that there is no anomaly present in the series of instances, for Package and its Class(es), where every class belongs to a package. We can also validate that there are no inconsistencies between a Class and its Attribute(s), where each attribute belongs to a class. Attributes, too, do not show any anomaly. We can increase the number of each element to see if Alloy Analyzer still generate valid instances for any possible number of elements. For this case, no inconsistencies are detected.

However, based on the requirement, it is not clear how the relations feature, *classisparentClass* behaves within this model. Therefore, we are going to create a scope of Run 2 to have these relations.

Alloy Run 2

For Run 2 we can specify the scope configuration as follows: one Package, three Classes, three *classisparentClass*, for the scope of four in Alloy Analyzer. *classisparentClass* is acyclic, so the minimal number of instance to see if this is simulated, is with three classes with three *classisparentClass* relations.

Alloy Analysis of Run 2

From Run 2, we can observed from the instances generated by Alloy Analyzer, that there are no anomalies for *classisparentClass* relation.

Analysis result

The two runs are able to generate several sets of instances in the Alloy Analyzer. Based on our observation on those sets, we did not detect any anomaly in the model. Therefore, we can conclude have a structurally consistent and well-formed user metamodel.

Even though the we did not detect any inconsistency, we still need to do further analysis to check if we have a model that is sufficiently address all scenario required by the requirements. We will proceed with the snapshot analysis.

8.4.2 Class user metamodel pattern snapshot analysis

The TSP analysis of the user metamodel can be performed using the pattern for snapshot analysis (Chapter 6). This is to check that the models are *syntactically* and *semantically correct* to be used as the source and target metamodel for the transformation.

We have discovered several patterns and selected three to demonstrate using the scenarios. We use the customer bank account detail example, to check if the metamodel is sufficient. The scenarios are: (1) Positive patterns that instantiate and generate a valid instance; (2) Positive patterns that do not completely instantiate the template; (3) Negative patterns that instantiate and generate a valid instance. We also include an example that shows (4) Positive patterns that instantiate but do not generate any instances.

(1) Positive patterns that instantiate and generate a valid instance

In Step 1, we have defined some model instance requirements for a customer banking account. ***ReqIM1.0*** defines the types of account existing. From this, we can write a positive pattern snapshot that describes a valid account type, using a class user metamodel we have defined. Figure 8.4 shows a positive instance model for ***ReqIM1.0*** where an account has type **Current** and **Saving**.

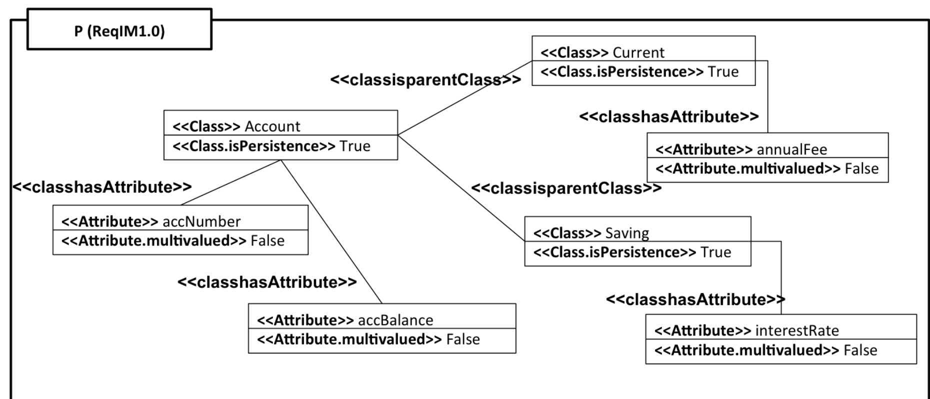


Figure 8.4: A positive snapshot for ReqIM1.0

Listing 8.2 is the result of instantiating template *Instance Model: Defining Model Instance* (Appendix I, Section I.5).

```
one sig Account extends Class{}
one sig Current extends Class{}
one sig Saving extends Class{}

one sig accNumber extends Attribute{}
fact accNumberAttrValue{
  accNumber.multivalued = False
}

one sig  accBalance extends Attribute{}
fact accBalanceAttrValue{
  accBalance.multivalued = False
}

one sig  annualFee extends Attribute{}
fact annualFeeAttrValue{
  annualFee.multivalued = False
}

one sig interestRate extends Attribute{}
fact interestRateAttrValue{
  interestRate.multivalued = False
}

```

```
25 fact ElementInstance{
26   Class = Account + Current + Saving
27   Attribute = accNumber + accBalance + annualFee + interestRate
28 }
29
30 fact ModelStructure{
31   Account.classisparentClass = Current + Saving
32   Account.classhasAttribute = accNumber + accBalance
33   Current.classhasAttribute = annualFee
34   Saving.classhasAttribute = interestRate
35 }
```

Listing 8.2: Instance model formal specification for P(ReqIM1.0) from Figure 8.4 generated by the tool

Execution on Listing 8.2, ***successfully*** produces an instance as shown in Figure 8.5 that proves for the case of positive pattern **P (*ReqIM1.0*)**, class user metamodel is *correct* and *sufficient* to support this requirement.

From this, we can conclude that the class user metamodel has included the concepts to support these features.

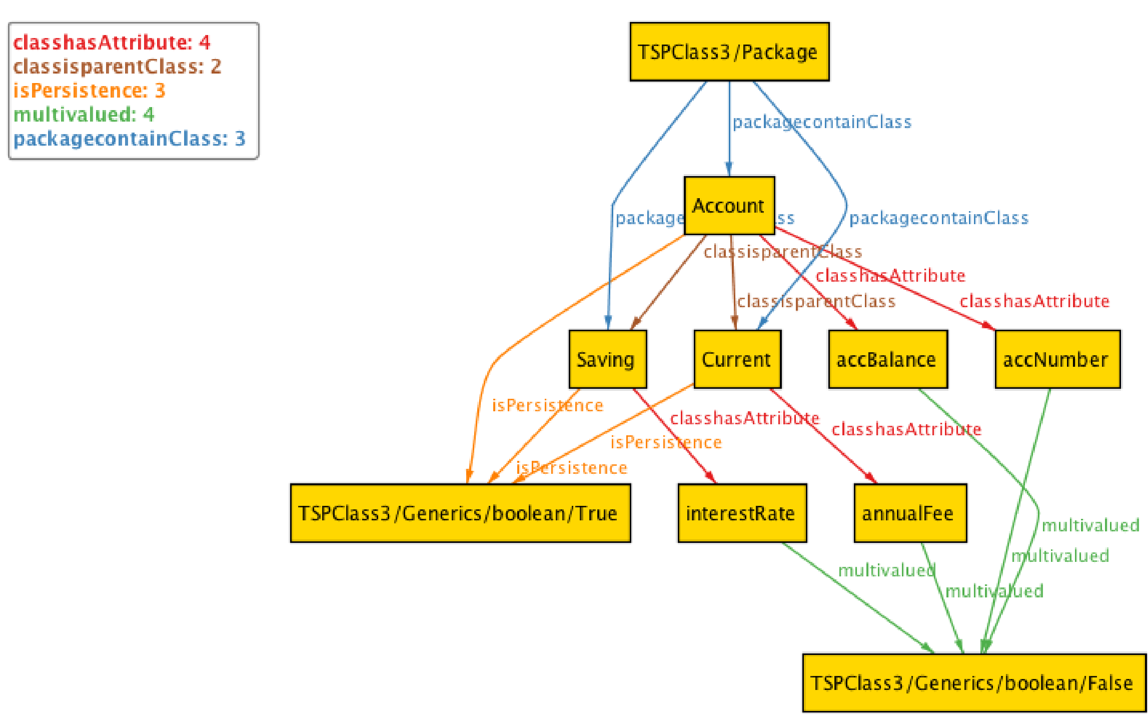


Figure 8.5: A successful verification of ReqIM1.0 generated by Alloy Analyzer

(2) Positive patterns that do not completely instantiate

We now look at patterns for ***ReqIM2.0*** of customer banking account requirements, which state that a customer owns the account, of type current and saving; or any one these types. From this we can derive three positive patterns: (1) customer owns a current account; (2) customer owns a saving account; and (3) customer owns current and saving. Figure 8.6 depicts a positive pattern snapshot for (1). Through the process of identifying patterns, we can discover any insufficiency in our user metamodel. Here, the insufficiency is identified from the customer account requirements (Table 8.5), our input model for transformation. Remember, in Step 1, we purposely left out the requirements for transforming associations. The result of that is the missing association between class features in a class metamodel. In a transformation tool, this error would be captured

only when the input model (customer bank account detail model, Figure 8.1) is loaded, because the model would not conform to the tool's metamodel for that language. In TSP, when we analyse metamodels, changes would include; adding metamodel features and revising the model transformation specification, to ensure this feature is transformed. This allows for insufficiency to be detected at a conceptual level, early in the model transformation specification development.

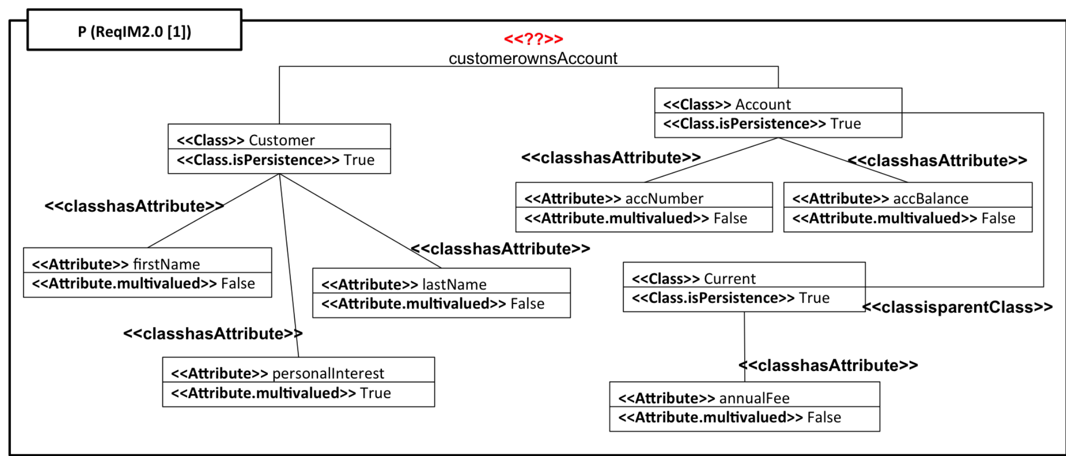


Figure 8.6: A positive snapshot pattern for ReqIM2.0(1) with the discovery of insufficiency - a missing association that defines between two class elements marked by the question mark

Here, we have identified we that the user metamodel does not include these features. Therefore, it requires a transformation engineer to add new elements. From the instance model, we need to add elements for defining relations between classes. After reviewing the current specification, the following requirements (Table 8.6) are added.

ReqID	Description	Condition	Source	Target
T2.2	For every class that relates to another class, a table for each class is created. The first class has a primary key column and the second class will have a foreign key pointing to the first class.	1) Table 1 name = Class 1 name. 2) Primary key column with name = Class 1 name + ID and type = integer. 3) Table 2 name = Class 2 name. 4) Foreign key column with name = Class 2 name + ID and type = integer pointing to primary key column of Class 1.	Class	Table

Table 8.6: New rule mapping requirements for model transformation for handling links between two classes

The class user metamodel is amended to include a relation that states an irreflexive and symmetrical relation between two instances of a class called *classhasrelClass*, as shown in Figure 8.7. The additional structure is used to instantiate template **R7** (Appendix I.4.4.1).

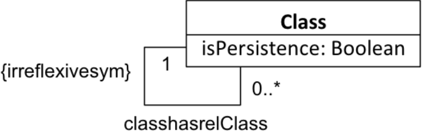


Figure 8.7: Amended class user metamodel to include a relation between two instances of a class

Now, the instance model for P(ReqIM2.0(1)) can fully instantiate templates, generating Listing 8.3 and find a valid instance, as shown in Figure 8.8.

```
one sig Customer extends Class{}
fact CustomerAttrValue{
  Customer.isPersistence = True
}

one sig Account extends Class{}
one sig Current extends Class{}

one sig firstName extends Attribute{}
fact firstNameAttrValue{
  firstName.multivalued = False
}

one sig lastName extends Attribute{}
fact lastNameAttrValue{
  lastName.multivalued = False
}

one sig personalInterest extends Attribute{}
fact personalInterest{
  personalInterest.multivalued = True
}

one sig accNumber extends Attribute{}
fact accNumberAttrValue{
  accNumber.multivalued = False
}

one sig  accBalance extends Attribute{}
fact accBalanceAttrValue{
  accBalance.multivalued = False
}

one sig  annualFee extends Attribute{}
fact annualFeeAttrValue{
  annualFee.multivalued = False
}

```

```
39 fact ElementInstance{
40   Class = Customer + Account + Current
41   Attribute = firstName + lastName + personalInterest + accNumber +
        accBalance + annualFee
42 }
43
44 fact ModelStructure{
45   Customer.classhasAttribute = firstName + lastName +
        personalInterest
46   Customer.classhasrelClass = Account
47   Account.classisparentClass = Current
48   Account.classhasAttribute = accNumber + accBalance
49   Current.classhasAttribute = annualFee
50 }
```

Listing 8.3: Instance model formal specification for P(ReqIM2.0(1)) from Figure 8.6 with newly included relation generated by the tool

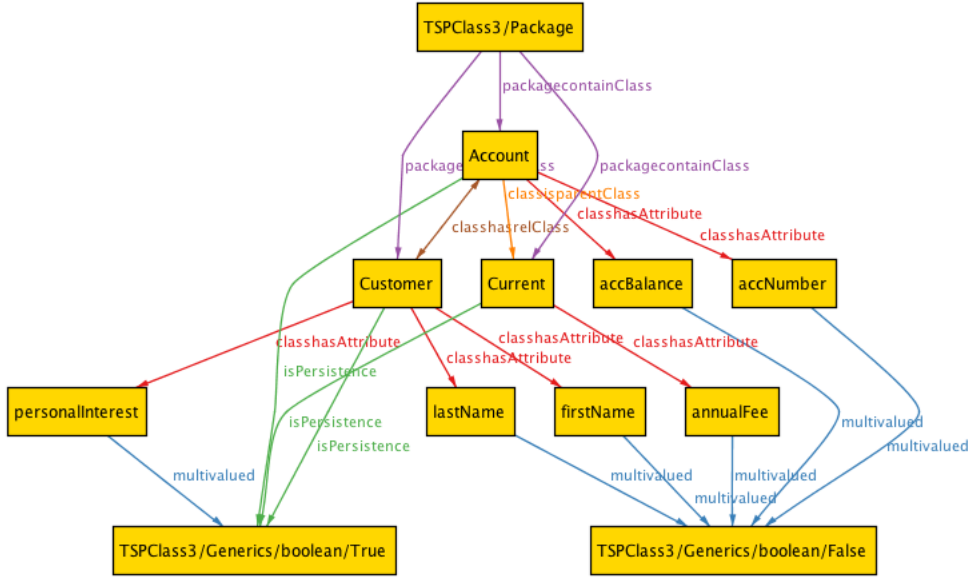


Figure 8.8: Successful verification of P (ReqIM2.0[1]) after amendment generated by Alloy Analyzer

Now, we can conclude that our user metamodel supports these features for defining association mapping in our model transformation.

(3) Negative patterns that instantiate and generate a valid instance

To validate requirements ***ReqIM2.0***, we can also use negative patterns. For example, (1) a customer cannot have multiple current accounts; and (2) a customer cannot have multiple saving accounts. We will demonstrate (1) to show negative patterns that can be used to instantiate templates but generates an invalid instance.

Figure 8.9 (attributes are left out for simplicity) shows the instance model for this pattern. Listing 8.4 shows the generated Alloy model from template IM1 (Appendix I.5.1), IM2 (Appendix I.5.2) and IM3 (Appendix I.5.3) instantiation.

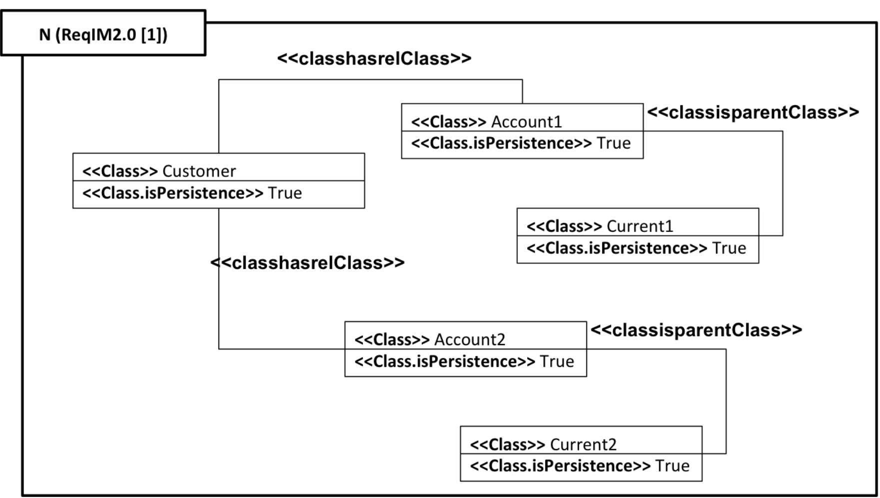


Figure 8.9: A negative snapshot for ReqIM2.0(1)

```
1  one sig Customer extends Class{}
2  fact CustomerAttrValue{
3    Customer.isPersistence = True
4  }
5
6  one sig Account1 extends Class{}
7  one sig Current1 extends Class{}
8  one sig Account2 extends Class{}
9  one sig Current2 extends Class{}
10
11 fact ElementInstance{
12   Class = Customer + Account1 + Current1 + Account2 + Current2
13 }
14
15 fact ModelStructure{
16   Customer.classhasrelClass = Account1 + Account2
17   Account1.classisparentClass = Current1
18   Account2.classisparentClass = Current2
19 }
```

Listing 8.4: Instance model formal specification for N(ReqIM2.0(1)) from Figure 8.9 generated by the tool

Executing Listing 8.4 generates an invalid instance, showing that there is a problem in the specification, as depicted in Figure 8.10.

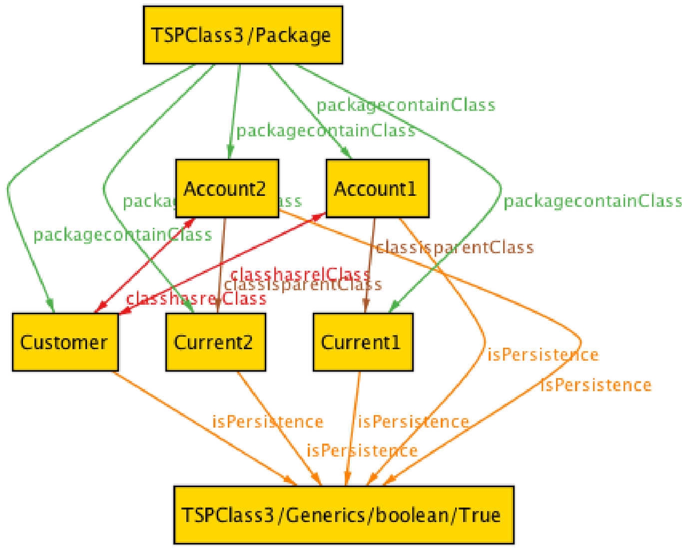


Figure 8.10: Successful verification of ReqIM2.0[1] generated by Alloy Analyzer

When negative patterns are able to generate an instance (or a positive pattern generates an invalid instance), it shows that there is a missing constraint that incorrectly or insufficiently defines the element. In Figure 8.10, we can see an instance that allows a customer to have two accounts of type current, which violates ***ReqIM2.0***.

One of the limitations of using templates is that they are not able to automate the instantiation of a condition at model level. Here, we define the user model to *classhasrelclass* elements to allow one to many relationship generically, but for the business level rule in the model, we need customer not to have more than one account of the same type.

To address this problem, further work on formalizing model level conditions (business rules) is required. [LP08] is an example work on specifying constraint in metamodels.

(4) Positive patterns that instantiate but do not generate any instances

To demonstrate a positive pattern of a failed verification, we will create a situation where a class *can* have a cyclic behaviour. Figure 8.11 shows a set of classes that allows cyclic inheritance. We can still instantiate a template to produce an instance model, but when executing it against a class user metamodel formal specification, we can see that it is unable to create any instance. To note, when using MDE modelling tools, the built-in metamodel compliance check would prevent us from creating this model.

Figure 8.11: A failed example of a positive pattern and its TSP Model Instance

If we wish to include models with cyclic inheritance, we need to amend our user metamodel to allow cyclic inheritance. We can trace the origin of the problem, which lies in conditioning the <<**classisparentClass**>> relation. In our class user metamodel specification, we can change the relation <<acyclic>> stereotype of the relation into <<asymmetric>> to allow cyclic inheritance. Instantiating the template again will produce a new specification that support cyclic inheritance between classes of the same type. Verification will successfully create an instance as depicted in Figure 8.12, therefore the user metamodel is sufficient to support this case.

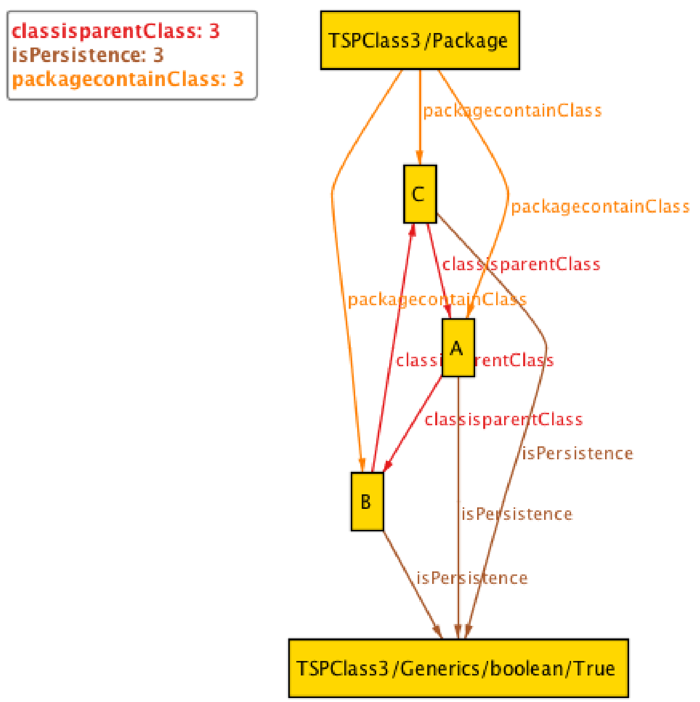


Figure 8.12: A successful verification after amending user model to support the notion of cyclic inheritance generated by Alloy Analyzer

8.5 Step 4: Generating class to relational database model transformation rule mapping model

To specify a model transformation, we need to produce the rule mapping model. The rule mapping model is generated from the requirements model. This step is presented in Chapter 7.

Figure 8.13 depicts the requirements model for our Class to Relational model transformation, extracting the details of from the transformation requirements view table (Table 8.1 and 8.2, and the new requirements in Table 8.6).

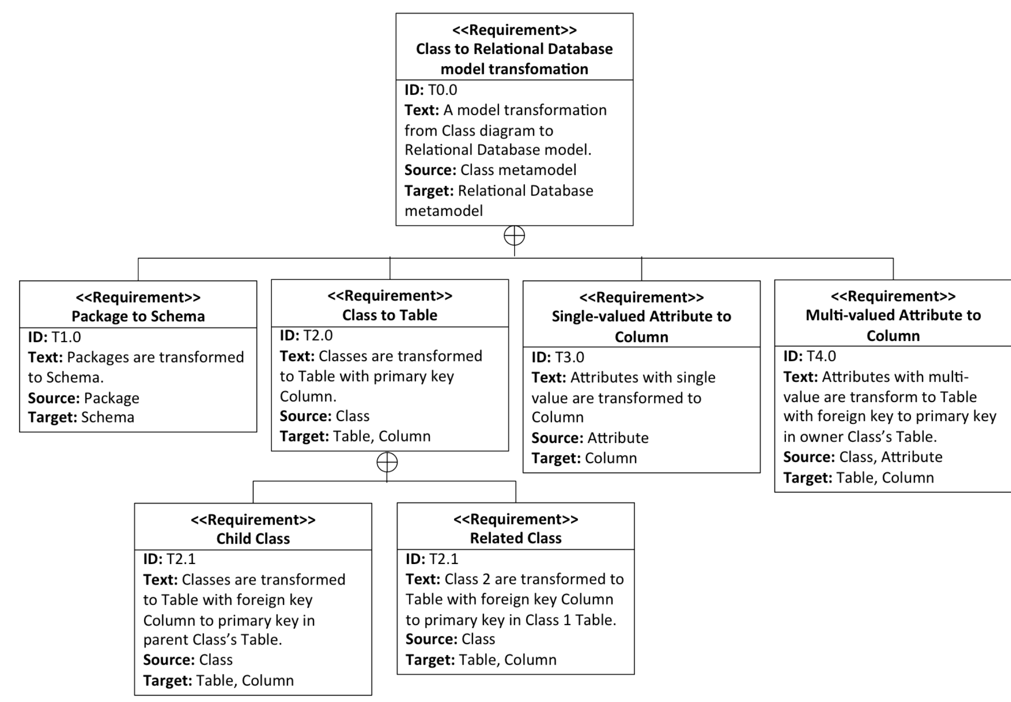


Figure 8.13: TSP Requirements Model

From the requirements model in Figure 8.13, we can generate the rule mapping model. Figure 8.14 shows the resulting rule mapping model for our class to relational database model transformation.

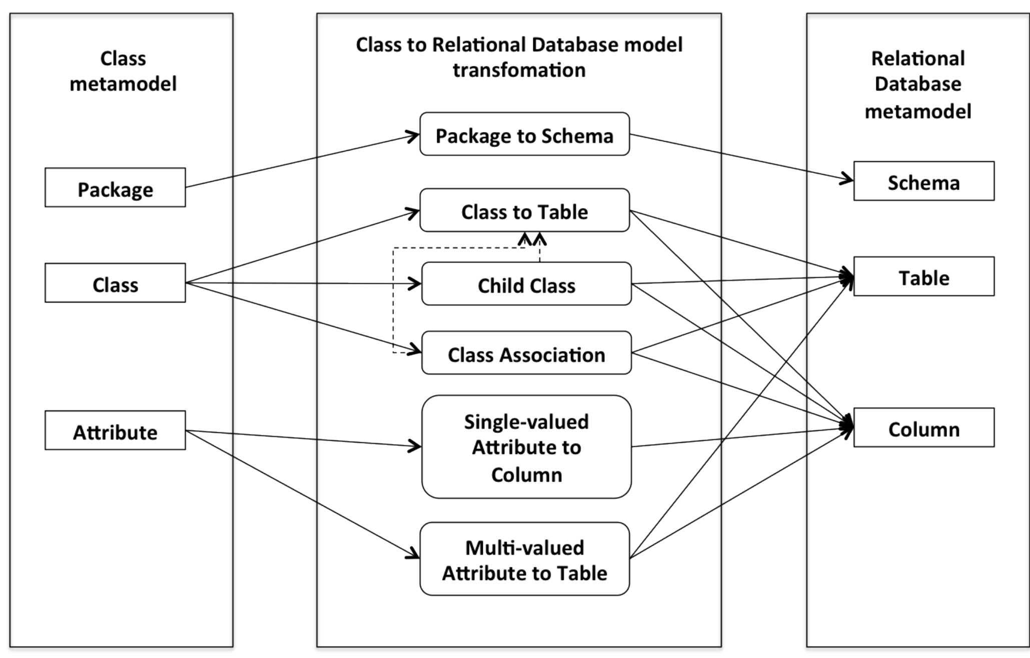


Figure 8.14: TSP Rule Mapping Model from Requirements Model in Figure 8.13

The rule mapping model specifies the main rules required to specify the relations between elements of our class to relational transformation. It shows the associated elements and rule dependencies. These rules will be used in decomposing our class to relational database transformation in the next chapter.

8.6 Step 5: Decomposing class to relational database model transformation

Decomposition of a model transformation is a process of specifying transformation into a smaller, independent module. In this step, we identify that phase and its operation to transform the source model into the target model, using the rules specified in the rule mapping model.

8.6.1 Phases

The task of identifying phases is significant to ensure that the specification can have individual components that cover a specific area of logical concern in a transformation. If the phases are done correctly, we can modularized the generation of complete target elements, within each root phase. This can also encourage component reuse.

For our class to relational database model transformation, we have identified nine phases: (1) Create schema; (2) Create table; (3) Add child table; (4) Create associating table of associating class; (5) Transform multi-valued attribute (refine); (6) Generate column for single-valued attribute (refine); (7) Generate primary key (refine); (8) Generate foreign key (refine); and (9) Generate foreign key column in associating table(refine). The phases are depicted in Figure 8.15.

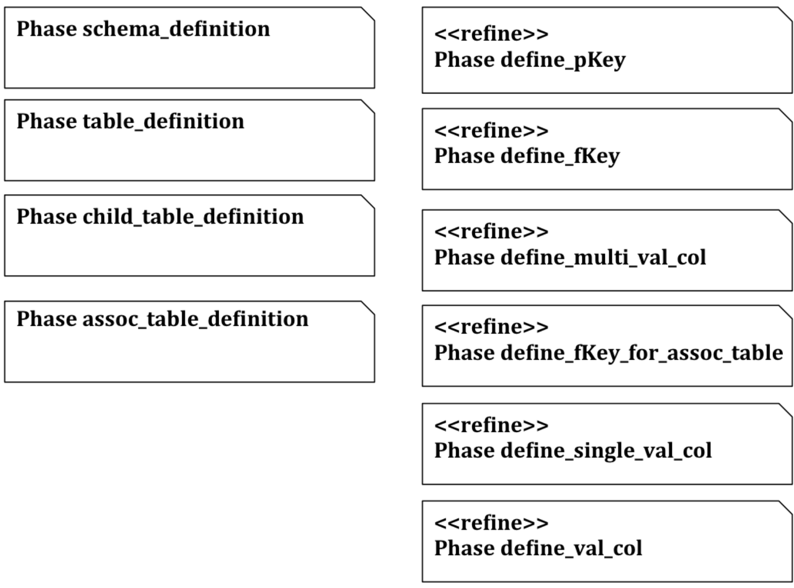


Figure 8.15: Phases for Class to Relational Model transformation

The rationale for these phasing decisions is as follows:

- A table can be generated from a class. A table can have a primary key column and single-valued column, therefore we have a separate phase for generating primary key and column for a single-valued attribute.

- A child table can have different implementations, therefore we separate the transformation of the child table from a parent table. If a table is created for the child table, it has a foreign key that refers to the parent table.
- A multi-valued attribute has a table and a foreign key pointing to the owner table.

Depending on the requirements of the model transformation, it is possible to decompose the phases in a different way. In the next sections, we present how the phases are used to define the model transformation specifications.

8.6.2 Phase: Defining schemas

We are going to specify the *schema_definition* phase. It is a local source to local target transformation. From the requirements, each Class package is transformed into a Relational schema. The schema name is equal to the package name.

Figure 8.16 is a visual representation of the *schema_definition* phase. It shows that an input, a package, will generate a new schema by using a PackageToSchema rule.

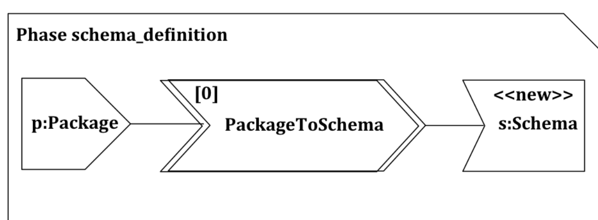


Figure 8.16: Specification of local-to-local Schema definition phase

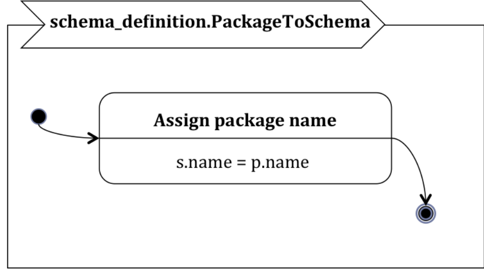


Figure 8.17: Assignment operation of specification Schema definition phase

We also need to assign the name of the schema. Figure 8.17 is a visual representation of the assignment operation.

8.6.3 Phase: Defining tables

The requirements for our Class to Relational Model transformation requires that each Class is transformed to a table with a primary key. To do this, we are going to include the *define_pKey* phase for our specification. This is a local source to global target transformation as depicted in Figure 8.18.

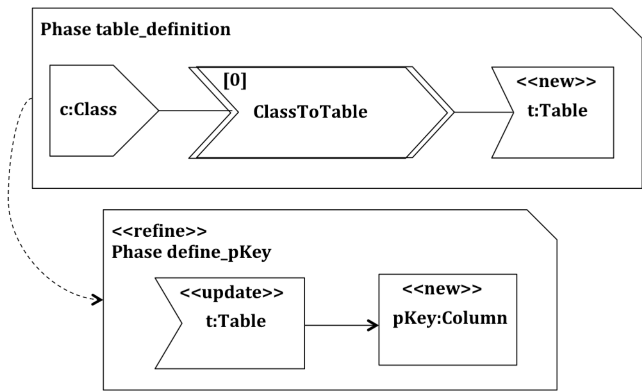


Figure 8.18: Specification of the table definition phase with a primary key

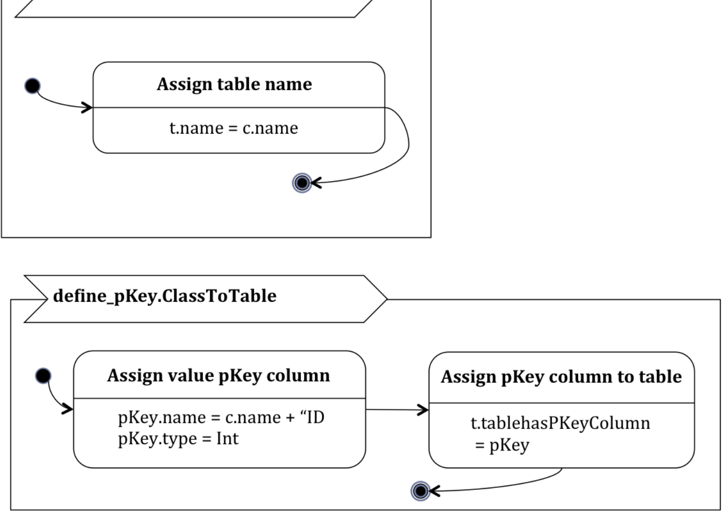


Figure 8.19: Assignment operation of the table and primary key definition phase

For *table_definition*, there is one assignment operation that assigns the table name. For defining the primary key, there are two assignment operations that take place; (1) assigning the value of the primary key column, and (2) assigning the primary key to the table. The assignment operation steps are depicted using the *operation assignment* notations shown in Figure 8.19.

A class has attributes; single or multiple valued. For a single value attribute, a column is generated and appends to the class's table. In this case, the *table_definition* phase can be extended to use the *define_single_val_col* phase, to specify the single-valued attribute to a column transformation.

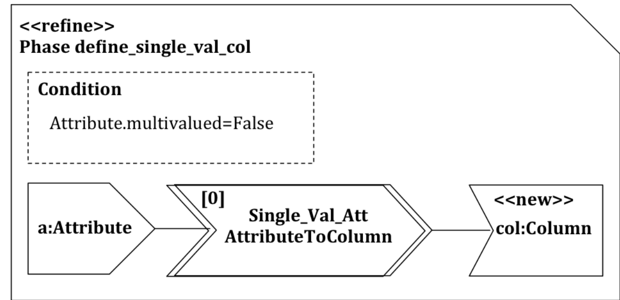


Figure 8.20: Specification of the single value column definition phase

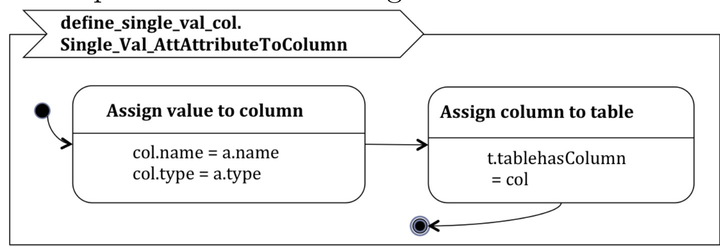


Figure 8.21: Assignment operation of single value column definition phase

Figure 8.20 shows a specification of a column generated from an attribute. For this phase to be applied, a condition on an attribute has to be valid; in this case, an attribute is *single valued*. There are two operations on the generated column; (1) assigning a value to column, and (2) assigning the column to the table. Figure 8.21 depicts these operations.

For a multi-valued attribute, the transformation requires a new table created with a primary key column, value column and a foreign key, which connects the

attribute table to the class's table. For these cases, phase *table_definition* will use a phase that defines a table, a value column, a primary key and a foreign key. The specification is depicted in Figure 8.22.

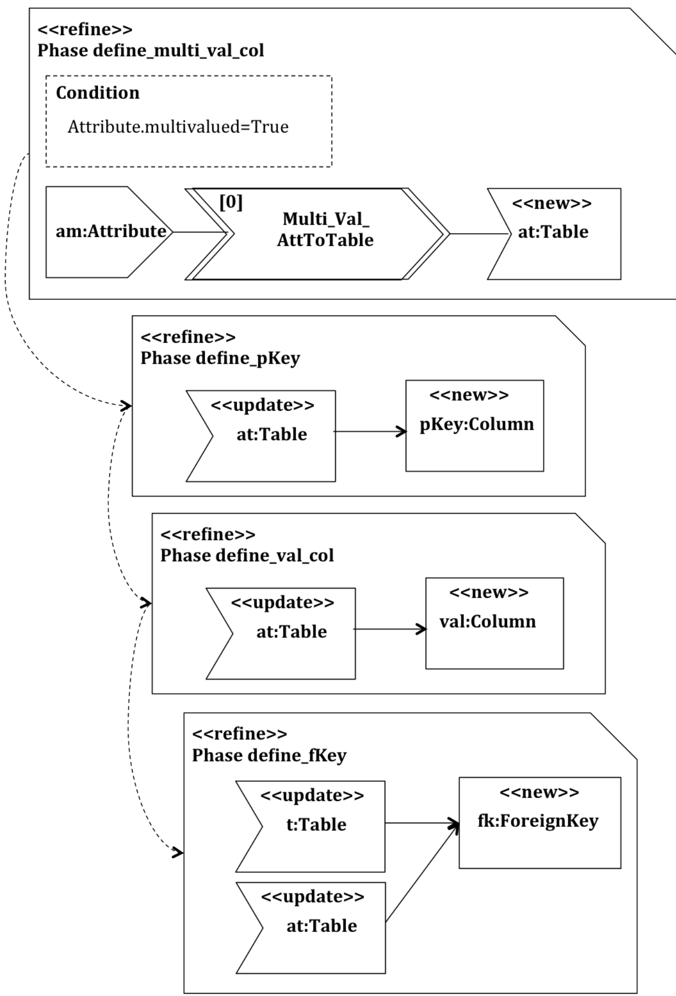


Figure 8.22: Specification of the multi-valued column definition phase

A table for a multi-valued attribute has several operations, and these operations are depicted in Figure 8.23. They are (1) assigning the table name, (2) assigning a primary key to the table, (3) assigning value column to the table and (4) assigning foreign key references.

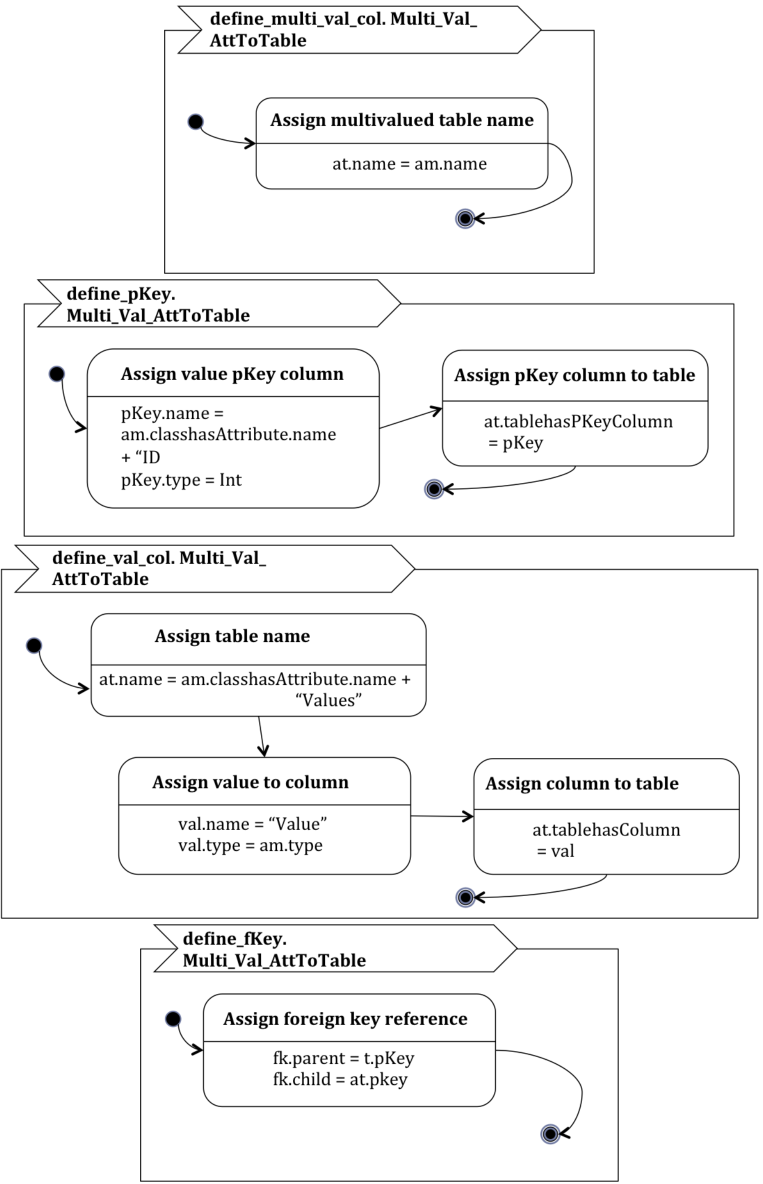


Figure 8.23: Assignment operation of the multi-valued column definition phase

A Class can have a relation to another class. For this, we need to create a new table for the associated class and connect the two tables with a foreign key, one pointing to the primary key of the associated class, and one to the newly added foreign key column of the originating class. The specification is represented in Figure 8.24, extending the *table_definition* phase.

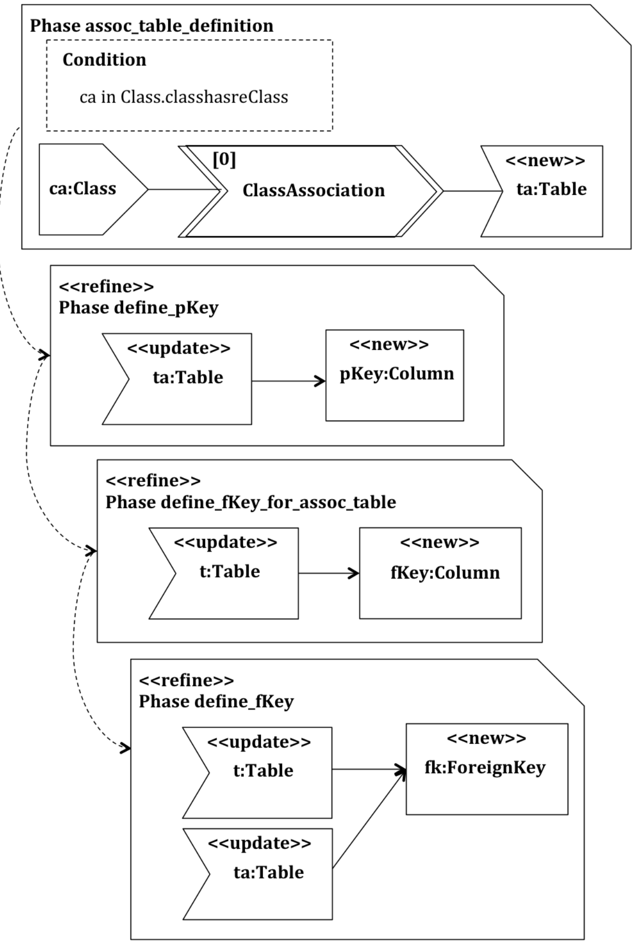


Figure 8.24: Specification of the table association definition phase

Figure 8.25 defines the assignment operations for table association definition for specification defined in Figure 8.24.

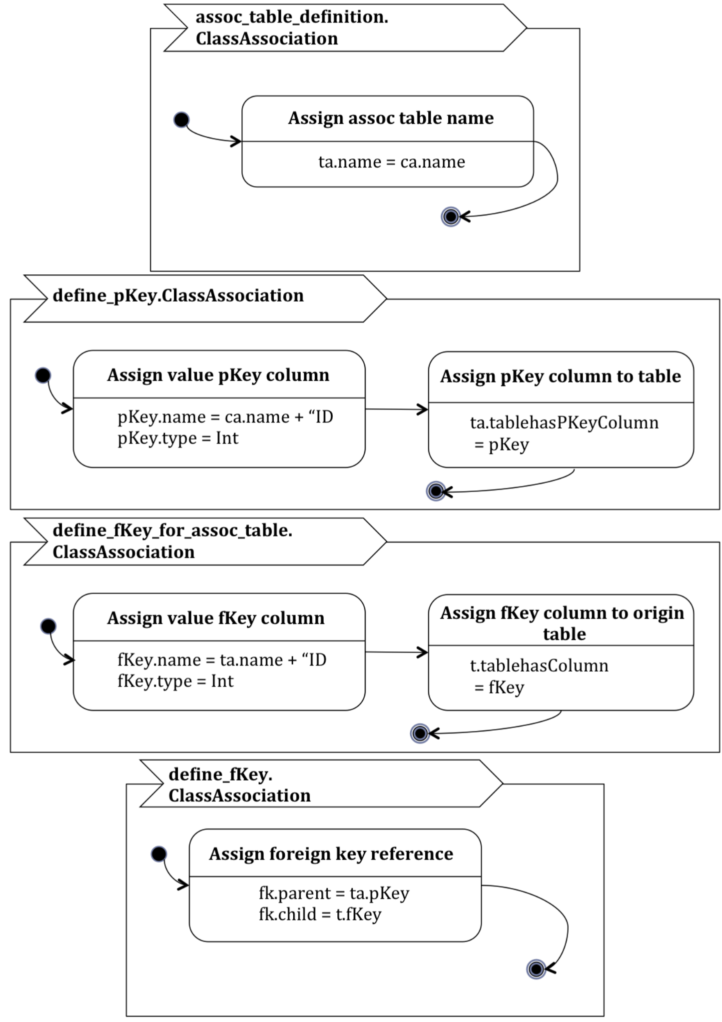


Figure 8.25: Assignment operation of the table association definition phase

8.6.4 Phase: Defining child tables

In the transformation requirements table, we have stated that a child class generates its own table and is connected to the parent class with a foreign key. A child table definition extends to use the primary key and foreign key definition phases. The specification of the attributes of the child class to tables and columns are similar to the previous attribute specification. Figure 8.26 depicts the child table definition phase, for the transformation of a child class to a new table with a foreign key connection to the parent class.

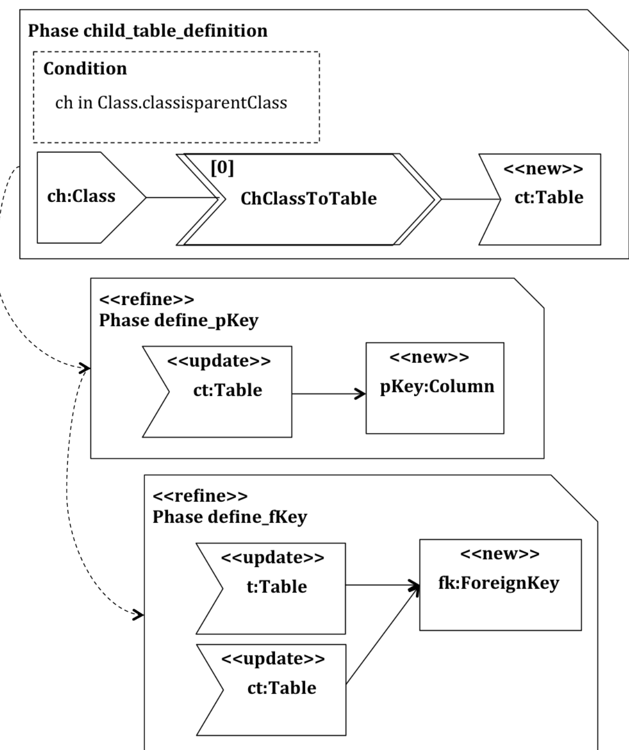


Figure 8.26: Specification of the child table definition phase

The operations for defining the child table are: (1) assigning a table name; (2) assigning primary key values; (3) assigning a primary key to the table; and (4) assigning foreign key references. Figure 8.27 specifies these operations.

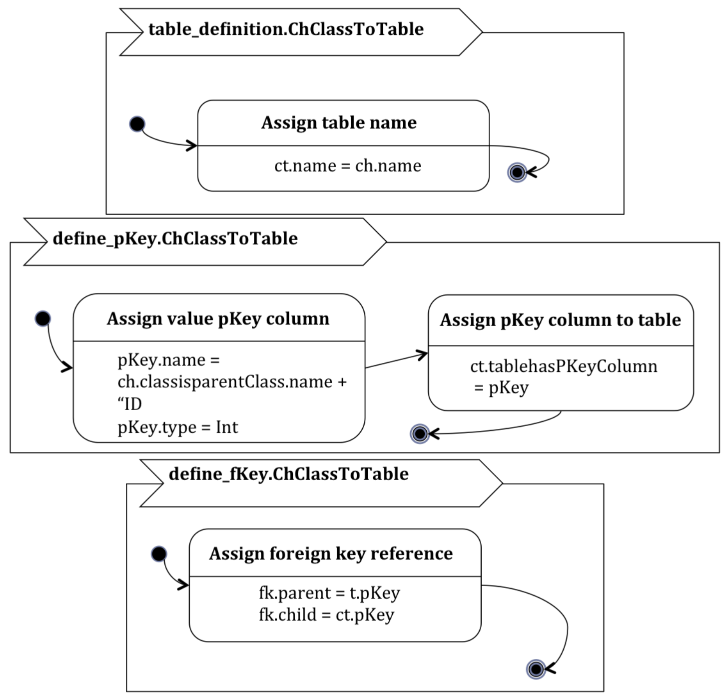


Figure 8.27: Assignment operation of the child table definition phase

8.6.5 Remarks

The rule mapping model contains the rules required for transformation based on the requirements model. Phases decompose the model transformation specification by implementing the required rules specified in the rule mapping model. The model transformation specification should be complete according to the requirements, provided all rules in the rule mapping model are used by the phases.

8.7 Step 6: Analysis of class to relational database model transformation

Now, we can use the transformation specification to do our pattern snapshot analysis. Similar to the step of analysing the user metamodel in Step 3 (Section 8.4), we produce a set of analysis patterns to check for *metamodel coverage* and *semantically correct transformation*.

8.7.1 Analysis patterns for class to relational model transformation

In the requirements elicitation step (Step 1, Section 8.2), we have defined the business rule requirements for the instance model; the customer bank account detail model. This model has to be transformed into the relational database model using the specification defined in the previous sections.

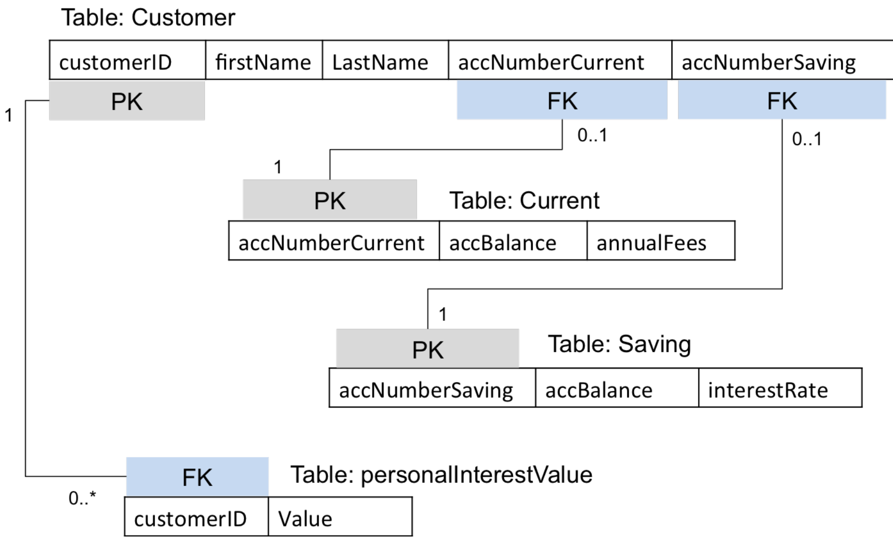


Figure 8.28: Expected relational model

Figure 8.28 shows the expected result of transformation. Due to the fact that this framework applies small scoped analysis, we have to decide which fragments of features need to be analysed. For our case of transforming the customer bank account model, there are several features that needs to be included in a transformation specification. These can be the patterns for our specification analysis:

1. Each table has a primary key.
2. Multi-valued attributes generate a table and a reference to the owner's table.
3. One-to-one relationships between classes are linked by a foreign key column in the originating classes.

We did not include an association that has other than one-to-one multiplicity. This is related to the concept in relational databases, when dealing with object classes in a relation that has other than one-to-one multiplicity. We do not elaborate on this, as this is not within the context of this thesis. This relates more to what transformation is required to transform a table with different multiplicity. Again, this can always be included in the specification by defining the transformation logic concerned using phases.

In the requirements, we do not include the requirements of transformation of a non-persistent class; we assume all classes are persistent. If we are expecting to have this feature, the analysis of the current specification should fail, and we would need to revise the requirements to include the features into the specification. This would be done by going through the steps defined in this framework again.

For the purpose of brevity, we omitted the name and the type assignment in our demonstration, as this follows a simple pattern presented in Section 7.3.2.

Now, we present the analysis of our class to relational database model transformation specification based on the patterns we have identified.

(1) Defining table with a primary key

Each table generated from a class has a primary key. This feature is defined via the *table_definition* and *define_pKey*. We can create a positive pattern to check if this feature is supported. Listing 8.6 is the result of instantiating phase templates that formalized the *table_definition* and *define_pKey*.

```
pred table_definition(c:Class, t:Table) {
  t = ClassToTable[c]
}

pred refine_define_pKey
  (t:Table, pKey:Column){
    OP_refine_define_pKey[t, pKey]
}

pred OP_refine_define_pKey(t:Table, pKey:Column){
  pKey = t.tablehasPKeyColumn
}
```

Listing 8.5: Model transformation formal specification for defining table transformation from Figure 8.18 and 8.19 generated by the tool

A positive pattern that shows a valid instance of a table and a primary key is depicted in Figure 8.29, which produced Listing 8.6 via templates (Appendix I.5 and I.7). Instance Model are checked against the specification.

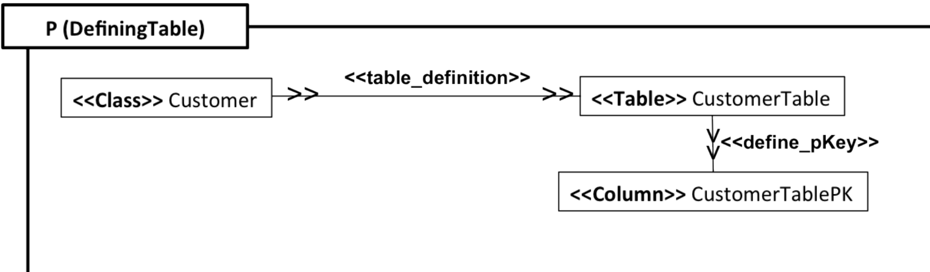


Figure 8.29: An instance of Class to Table with primary key transformation

```
one sig Customer extends Class{}
one sig CustomerTable extends Table{}
one sig CustomerTablePK extends Column{}

fact ElementInstance{
  Class = Customer
  Table = CustomerTable
  Column = CustomerTablePK
}

fact Transform{
  table_definition[Customer, CustomerTable]
  refine_define_pKey[CustomerTable, CustomerTablePK]
}
```

Listing 8.6: Transformation instance model formal specification for defining Customer table from Figure 8.29 generated by the tool

Executing the specification gives the results shown in Figure 8.30, which shows a success verification of this feature.

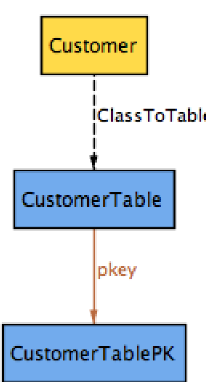


Figure 8.30: Result of executing Listing 8.6 in Alloy Analyzer

(2) Multi-valued attribute table

For one of the requirements of classes with multi-valued attributes, we need to generate a separate table with foreign key references. For these features, we use the *define_multi_val_col* that generates a table from multi-valued attributes. An attribute always belongs to a class, thus, the phase is a *refine* phase and it needs a root phase, in this case, it can either extend a *table_definition* or *child_table_definition* phase. We use the *table_definition* for now.

Listing 8.7 is the resulting formal model generated by the tool from Figure 8.22 and 8.19.

```
1  pred table_definition(c:Class, t:Table) {
2    t = ClassToTable[c]
3  }
4
5  pred refine_define_multi_val_col(am:Attribute, at:Table) {
6    am.multivalued in True implies
7      (at = Multi_Val_AttToTable[am] and
8          Result = Success) else
9      (Result = Fail)
10 }
11
12 pred refine_define_pKey(at:Table, pKey:Column){
13   OP_refine_define_pKey[at, pKey]
14 }
15
16 pred OP_refine_define_pKey(at:Table, pKey:Column){
17   pKey = at.pkey
18 }
19
20 pred refine_define_val_col(at:Table, val:Column){
21   OP_refine_define_val_col[at, val]
22 }
23
24 pred OP_refine_define_val_col(at:Table, val:Column){
25   val = at.tablehasColumn
26 }
27
28 pred refine_define_FK(fk:ForeignKey, t:Table, at:Table){
```

```
29    OP_refine_define_FK[fk, t, at]
30  }
31
32  pred OP_refine_define_FK(fk:ForeignKey, t:Table, at:Table){
33    t.pkey = fk.parent
34    at.pkey = fk.child
35  }
```

Listing 8.7: Model transformation specification model for defining multi-valued attribute from Figure 8.22 and 8.19 generated by the tool

Now we can apply the pattern snapshot analysis to see if there exists an instance of the specification that adheres to the pattern. Figure 8.31 shows a positive pattern for multi-valued attribute transformation into a table with foreign key references.

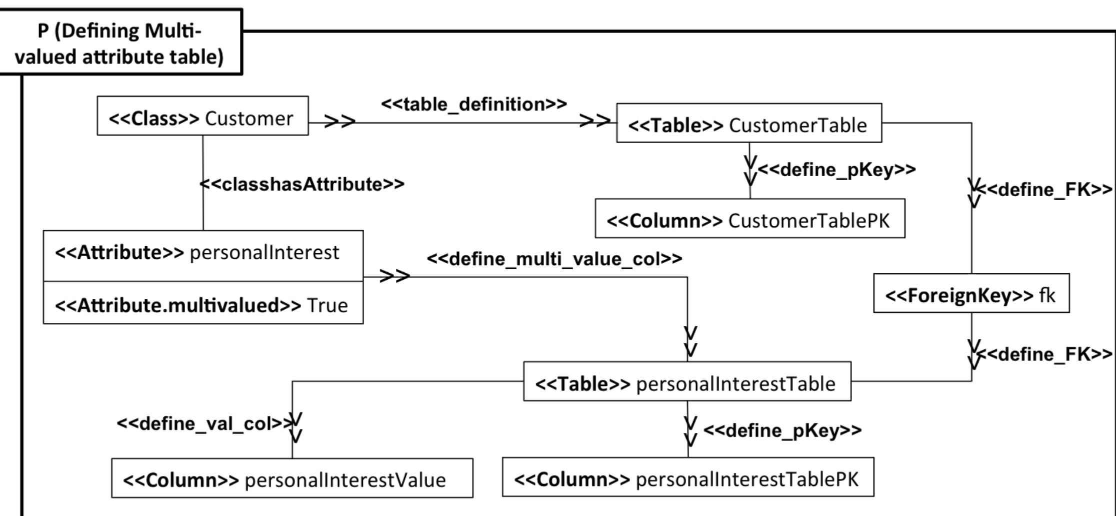


Figure 8.31: A positive pattern for a multi-valued attribute to table and foreign key reference transformation

The instance model instantiate the templates and produces the Alloy equivalent model to be used against the specification, as shown in Listing 8.8.

```
one sig Customer extends Class{}
one sig personalInterest extends Attribute{}
one sig CustomerTable extends Table{}
one sig CustomerTablePK extends Column{}
one sig personalInterestTable extends Table{}
one sig personalInterestTablePK extends Column{}
one sig personalInterestValue extends Column{}
one sig fk extends ForeignKey{}

fact ElementInstance{
  Class = Customer
  Table = CustomerTable + personalInterestTable
  Column = CustomerTablePK + personalInterestTablePK +
      personalInterestValue
  ForeignKey = fk
}

fact ModelStructure{
  personalInterest.multivalued = True
}

fact Transform{
  table_definition[Customer, CustomerTable]
  refine_define_pKey[CustomerTable, CustomerTablePK]
  refine_define_multi_val_col
    [personalInterest, personalInterestTable]
  refine_define_pKey[personalInterestTable, personalInterestTablePK]
  refine_define_val_col[personalInterestTable, personalInterestValue
      ]
  refine_define_FK[fk, CustomerTable, personalInterestTable]
}
```

Listing 8.8: Transformation instance model formal specification for defining multi-valued attribute from Figure 8.31 generated by the tool

The execution provides a successful analysis of the pattern, as shown in Figure 8.32. For this pattern feature, we need to check that for a correct transformation, we ensure that the attribute is multi-valued. This is checked when we achieve a successful application, noted by the success atom (green). If we create a negative pattern of this feature, for example, that multi-valued is *false*, analysis should

inform that the transformation has failed (red), as shown in Figure 8.33.

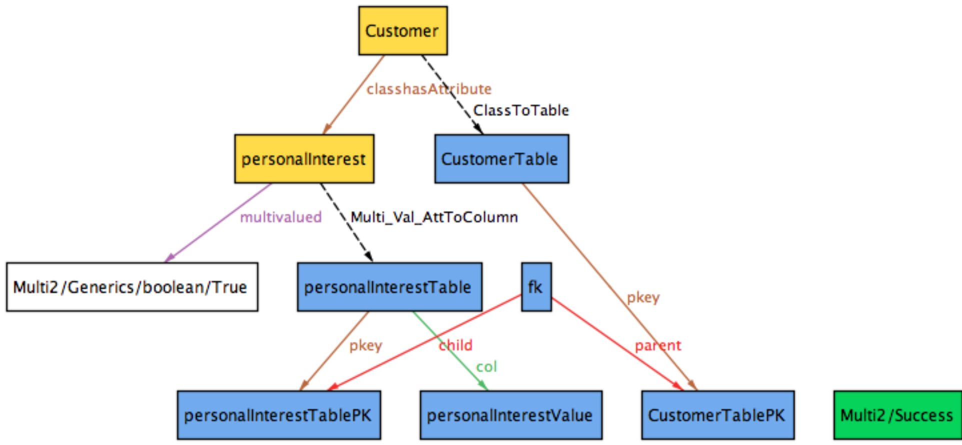


Figure 8.32: A successful validation of a multi-valued attribute to table and foreign key reference transformation by Alloy Analyzer

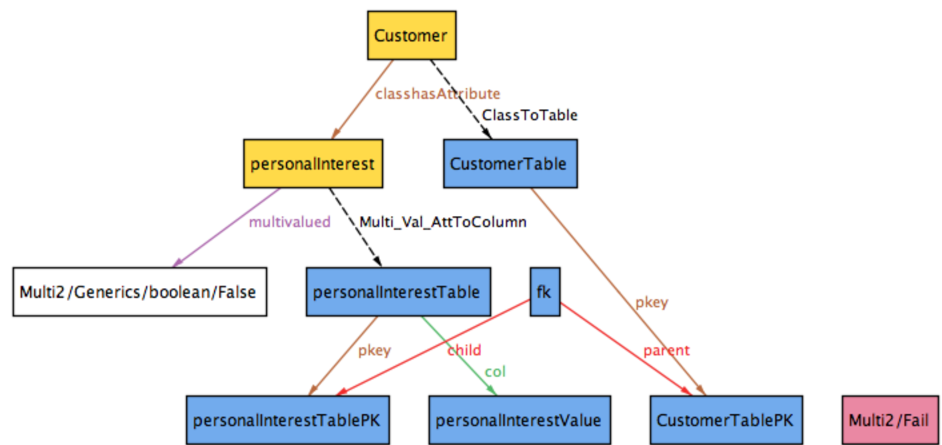


Figure 8.33: A failled validation of a multi-valued attribute to table and foreign key reference transformation by Alloy Analyzer

(3) One-to-one relationship between classes

For this case, we need to address the limitations of the templates and Alloy, to represent a scenario where the related instances come from the same class, particularly, of elements with reflexive association. In our Class user metamodel, we defined a reflexive association for a relation between two instances of the same class. This came down again to how Alloy represents model transformation systems. In a reflexive association, there are two instances originating from the same element within one relation. Therefore in Alloy, when two instances of the same element take part in a mapping relation, we need to define two distinct instances of the same element to enable us to check for the feature.

We define the two instances of an element, that take part in a reflexive association, using *membership* of two elements of the same type. In a reflexive association, the two objects of the class is of the same relation type. Therefore, capturing the reflexive association semantics for specifying two different objects of the same class transformation, can be done by assuming that there is two different types that are part of a class that relates to itself.

Let us say that, we have a reflexive association *rel* of element **A** that is acyclic. We can prepare the input parameter to include two sub-elements of **A** (**Ai** and **Aj**) to represent the pair ends of a reflexive association.

Listing 8.9 shows the definition of A for a transformation between elements in a reflexive association.

```
sig A{
  rel: set A
}

fact AcyclicrelA{
  acyclic[rel,A]
}

sig A_i in A{}
sig A_j in A{}

fact A{
 A = Ai + Aj
  disj[Ai,Aj]
}
```

Listing 8.9: Reflexive association definition for transformation specification

Applying this to our class model, we can now generate the formal specification for class association transformation. Figure 8.10 shows the results of applying templates to the phase for defining class association transformation.

```
pred table_definition(c:Class, t:Table) {
  t = ClassToTable[c]
}

pred assoc_table_definition(ca:Class, ta:Table) {
  ca in Class.classhasrelClass implies
    (ta = ClassAssociation[ca]
        and Result = Success) else
    (ca in Class.isParent implies Result = Fail)
}

pred refine_define_fkey_for_assoc_table(t:Table, fKey:Column){
    OP_refine_define_fkey_for_assoc[t, fKey]
}

pred OP_refine_define_fkey_for_assoc(t:Table, fKey:Column){
  classTable.fkey = fKey
}

```

```
20 pred refine_define_pKey(ta:Table, pKey:Column){
21   OP_refine_define_pKey[ta, pKey]
22 }
23
24 pred OP_refine_define_pKey(ta:Table, pKey:Column){
25      pKey = ta.pkey
26 }
27
28 pred refine_define_FK(fk:ForeignKey, ta:Table, t:Table){
29   OP_refine_define_FK[fk, ta, t]
30 }
31
32 pred OP_refine_define_FK(fk:ForeignKey, ta:Table, t:Table){
33   ta.pkey = fk.parent
34   t.fkey = fk.child
35 }
```

Listing 8.10: Model transformation formal specification for defining class association from Figure 8.24 and 8.25 generated by the tool

To check if the specification correctly specifies these features, we create a snapshots that represents a positive pattern. Figure 8.34 shows the pattern for a class association to table and foreign key reference to foreign key column transformation.

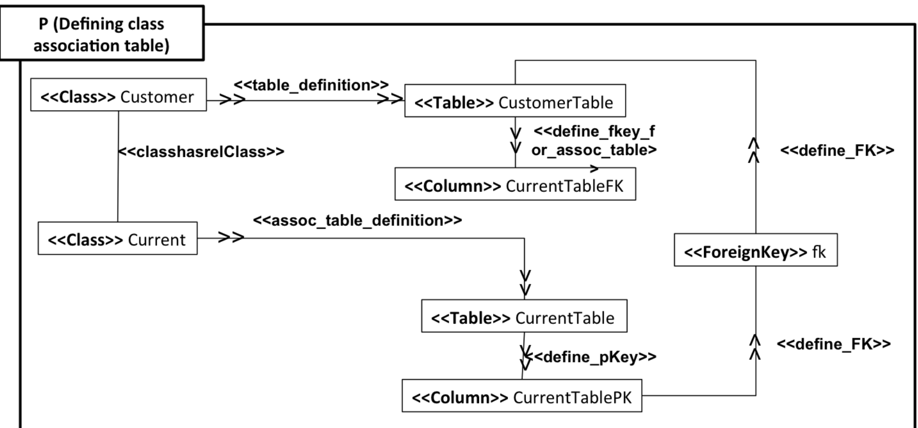


Figure 8.34: A positive pattern for a class association to table and foreign key reference to foreign key column transformation

Listing 8.11 is a formal representation of the pattern for a class association to table and foreign key reference to foreign key column transformation from Figure 8.34.

```
1  one sig Customer extends Class{}
2  one sig Current extends Class{}
3  one sig CustomerTable extends Table{}
4  one sig CurrentTable extends Table{}
5  one sig CurrentTableFK extends Column{}
6  one sig CurrentTablePK extends Column{}
7  one sig fk extends ForeignKey{}
8
9  fact ElementInstance{
10   Class = Customer + Current
11   Table = CustomerTable + CurrentTable
12   Column = CurrentTablePK + CurrentTableFK
13   ForeignKey = fk
14 }
15
16 fact ModelStructure{
17   Customer.classhasrelClass = Current
18 }
19
20 fact Transform{
21   table_definition[Customer, CustomerTable]
```

```
22     refine_define_fkey_for_assoc_table[CustomerTable, CurrentTableFK]
23     assoc_table_definition[Current, CurrentTable]
24     refine_define_pKey[CurrentTable, CurrentTablePK]
25     refine_define_FK[fk, CurrentTable, CustomerTable]
26 }
```

Listing 8.11: Transformation instance model formal specification for defining class association from Figure 8.34 generated by the tool

Executing Listing 8.11, we can prove that this feature is correctly supported, as indicated by the successful validation shown in Figure 8.35.

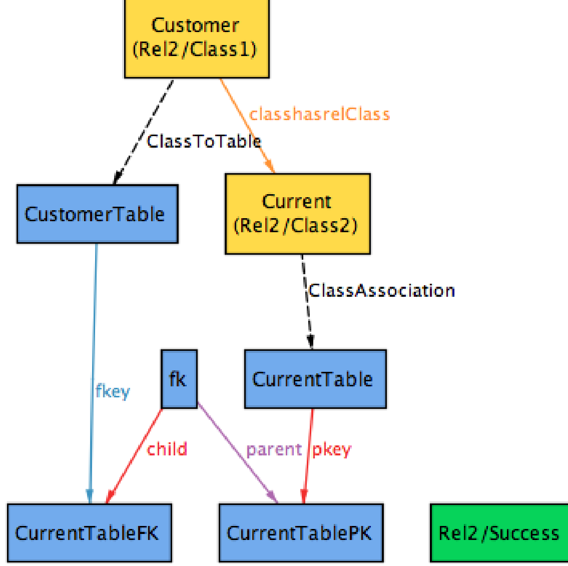


Figure 8.35: A successful validation for a class association to table and foreign key reference to foreign key column transformation by Alloy Analyzer

8.8 Discussion

We have applied TSP framework to specify and formally analyse class to relational database model transformation to produce a valid transformation specifications that fulfills the requirements. TSP has demonstrated the capability to clearly represent model transformation at a conceptual level, to allow analysis to be done

before the specification is implemented. It has raised some interesting questions and limitations, which we noted as future work to extend the capability of TSP framework

TSP framework allows transformation engineers to: (1) establish a set of model transformation requirements that define the required model transformation features by including the process of documenting model transformation requirements; (2) produce contextualized metamodels that ensure the sufficiency of elements from the process of identifying the necessary elements for the source and target model of the transformation; (3) perform formal analysis on a metamodel to check for a well-formed metamodel and correctness using snapshot analysis; (4) extract details from requirements and form the formal requirement model, for generating the rule mapping model that will be used to decomposing model transformation specification using phases and (5) formally analyse a model transformation specification using snapshot analysis.

TSP framework has demonstrate how a model transformation and their artefacts can be developed and analysed through a set of *processes*, *visual languages* and *template-generated formal specifications*. The approach systematically provides the means to unambiguously define model transformation and formally analyse the specification, without directly dealing with formal methods complexity.

Applying TSP to class to relational database model transformation raised several interesting questions; most are worth further work for extending TSP in the future and some are the limitations that we have to agree with. The following sections discuss the identified matters.

8.8.1 Extracting and detecting contextualized metamodel elements

The TSP has provided a way to produce a metamodel that is sufficient to satisfy the requirements of a transformation. This is useful for models without any existing metamodel. For existing ones, they could be, (1) large, or (2) include unrelated or missing related elements for the transformation. In an implementation, a large metamodel or a metamodel with unrelated elements are not much

of an issue. But it is difficult to ensure that the metamodel is sufficient for a transformation, especially for detecting missing elements.

Currently, the TSP is able to address the matter of ensuring metamodel sufficiency through contextualization and analysis. A contextualized metamodel is compatible with metamodel formats such as Ecore. To use the contextualized and analysed metamodel with existing metamodel, we could implement a tool that extracts or detects elements from existing metamodel, according to the contextualized metamodel.

8.8.2 Additional metamodel constraint

TSP has provided templates that address the structural features of the minimal set of elements for a metamodel in our metamodelling language. The templates have also provided *integrity constraints* that condition the behavioural aspect of the elements. We have found that we need to include some other behavioural patterns that define metamodelling elements, such as when multiple relations exist between two classes. We encounter this when we try to formalize the relations between a *Table* and *Column* that has three distinct types of relation: (1) a primary key; (2) a value; and (3) a foreign key. We do not include the analysis of the relational database metamodel in detail in this thesis.

With the current template instantiation, the specification still generates valid instances and allows positive patterns to be successfully verified. But the model is under-constraint, where it will allow an invalid instance to be generated and accepted. To extend the effectiveness of the framework, we need to developed an additional set of templates that represent model constraints by identifying more behavioural patterns of models.

8.8.3 Metamodel and model level constraint

We encounter this problem when we try to verify that the customer can only have one of each type of account (pattern snapshot (3) presented in Section 8.4). Normally, this is addressed by including an OCL constraint on the model. Our template has yet to include formalization of OCL expressions. This is a useful feature to have in TSP framework and we leave it as future work.

8.8.4 Contradicting feature changes

When TSP analyses a specification, particularly using the pattern snapshot analysis, it focuses on one specific fragment at a time. Therefore, it is possible that any changes in one of the specification fragments can cause contradicting issues in other parts of the specification.

We believe this problem can be avoided by implementing an analysis management tool for TSP, that checks if the changes have any effects on other parts of the specification.

8.8.5 Data type operation

One of the significant limitations of Alloy is relating to basic data types manipulations, such as strings and characters. At some level, we can still use Alloy to represent any data type as an atom, using *signature declaration* and they can be referred to by other elements in *field declaration*. We have used this in our specification, for example, an Alloy specification for Book that has an attribute title of type string in the model. This way, the title has a value, where operations such as a Publication title is equal to Book title can still be represented.

```
1 sig Book{
2   title: one BookTitle
3 }
4
5 sig BookTitle{}
```

Listing 8.12: How to represent data type such as string as atom

The problem occurs when we need to do operations on the data type such as, string manipulations (eg. concatenation or letter count). Still, we can represent the concept using atoms, but this could become expensive for the specification to be executed for simulation and analysis. We can use the *data type as atom* concept or we could develop a new set of template using other formal language that supports data type manipulation explicitly.

8.9 Summary

We have applied TSP framework to specify and formally analyse a class to relational database model transformation. TSP has demonstrated its capability to clearly represent model transformation at a conceptual level, to allow analysis to be done before the specification is implemented. It has raised some interesting questions and limitations that relates to the TSP framework as dicussed in the previous section which we noted as future work (Section 9.4) to extend TSP framework capability.

Chapter 9

Conclusion

This thesis aimed to address the broad question of how to obtain reliable model transformations, by presenting the TSpecProber (TSP) framework, which can be used for specifying and analysing model transformations. TSP was founded on previous work in the domain of formal methods and MDE (reviewed systematically in Chapters 2 and 3). An overview of TSP was presented in Chapter 4. We then presented the main parts of TSP in more detail. In particular, in Chapter 5, we described a set of techniques to elicit model transformation requirements, and also explained how metamodels could be contextualized for specific analysis problems. We showed how to analyse a contextualised metamodel, particularly to check for well-formedness, in Chapter 6. We then described in detail, how a model transformation can be specified and analysed (Chapter 7). The overall approach was evaluated by applying TSP to specify and formally analyse a specific instance of model transformation – class-to-relational-database – in Chapter 8.

9.1 Restatement of research aims

At the start of the thesis we identified the following key research questions:

1. How can we systematically and effectively *specify* a model transformation?

2. How can we formally analyse model transformation effectively using practical approaches? *Practical*, in this sense, refers to the ease of application

of formal methods, particularly not requiring significant expertise in understanding the theory behind the formal method.

With this in mind, we postulated the following thesis hypothesis:

> *In ensuring a **model transformation specification** is **precise**, we need to have a framework that provides (1) a set of **processes** for model transformation specification development, (2) **visual notations** for specifying model transformation specification, and (3) **templates** for producing model transformation formal specification that is tractable and amenable to **effective formal analysis** of model transformation.*

Based on the successful application of the framework presented in Chapter 8, we conclude that we have answered our initial research question and provided confidence that the hypothesis is correct. We summarise our contributions in the next section.

9.2 Research contributions

We have presented a novel approach to formally specifying and analysing model transformations, based on the use of templates and on a rigorous process in which transformations are specified and constructed. Overall, we have contributed an approach that can help increase engineers' level of confidence in their model transformations. We have also demonstrated the feasibility of the approach by showing how it can be used to analyse a typical model transformation (class-to-relational-database). More specifically, we have contributed:

- A *process* for model transformation specification development that focuses on discovering the essential features and components of a model transformation.
- A *visual modelling language* for representing a model transformation specification and its components.

- A catalogue of *formal templates* that can be used for producing formal specifications of model transformations that are amenable to effective formal analysis.

The following sections describe the contributions in detail.

9.2.1 Systematic development process for model transformation

Typically, model transformations are not developed systematically; there is no clearly understood or precisely defined process that is widely used. Development therefore, is normally ad-hoc and depends on the skills, insights, and intuition (or lack thereof) of the transformation engineers. Clearly this has drawbacks: (1) there is usually no clear documentation nor justification for the design decisions made; (2) there are limited ways of analysing transformations before they are implemented; and (3) repeatability of construction is difficult.

With TSP, we provided a way for model transformations to be systematically developed and analysed conceptually before they are implemented. We presented six steps to produce a precise model transformation.

Step 1 is the identification of model transformation requirements. We clarified the difference between software requirements and transformation requirements, why eliciting model transformation requirements is required, and, showed how this is done to support development. We described several *views* for model transformation requirements that capture their features and components. This is presented in detail in Chapter 5.

Step 2 is to create a contextualized metamodel (TSP user metamodel) that is sufficient according to the elicited requirements using visual notation provided by the framework. Contextualized metamodel contains a minimal set of elements for specifying the model transformation of interest. The contextualized metamodel can be used as (1) an implementation source and target metamodel (by encoding it in a suitable format readable by a tool, e.g., EMF/MDR), or (2) as a guide to extract or detect a sufficient metamodel embedded in an existing metamodel.

In Step 3, the contextualized metamodel is analysed for well-formedness; this is presented in Chapter 6. The contextualized user metamodel will instantiate a set of templates to generate an equivalent formal Alloy model which can be executed in Alloy Analyzer to ensures that the metamodel used for the transformation is *syntactically* and *semantically correct*. We introduced a snapshot analysis that includes user metamodel instance pattern that can be formalised into Alloy model via instantiating a set of templates to check if the user metamodel has been correctly and sufficiently defined based on the requirements. While we thoroughly presented the contextualization process and how such a metamodel can be analysed, we did not show how to implement such a metamodel in diverse technologies (this is standard practice and has been left for future work). This is presented in detail in Chapter 5.

Step 4 is where we begin specifying model transformations (TSP model transformation specifications) using visual notation provided by the framework. The requirements and specification is bridged via a formal requirements model which extracts the details of the model transformation's features. A requirements model is used to generate the rule mapping model that contains the rules required by the transformation. This is presented in Chapter 7.

An overall model transformation specification is decomposed from the rule mapping model using visual notation provided by the framework in Step 5. The decomposition uses the *phasing mechanism*, which provides modularization of a transformation into smaller, independent transformation parts, using the rules defined in the rule mapping model. The phases also help to address scalability issues associated with analysing transformations using SAT-based tools, but its application also encourages re-usability of model transformation specifications. Currently, TSP requires good judgement of a transformation engineers in deciding the phases of a model transformation. Automation of phasing is out of the scope of this thesis and will be included as further work.

Finally in Step 6, the model transformation specification instantiates a set of templates to produce an equivalent formal model that can be used for analysis to ensure *metamodel coverage* (i.e., that the transformation specification does not omit consideration of any elements in the transformation) and *semantic correctness*. The analysis includes snapshot analysis that uses model transformation

instance pattern, which can be formalised into Alloy model by instantiating a set of templates to check if model transformation specifications has been correctly and sufficiently defined based on the requirements.

In summary, TSP provides a systematic approach to develop a precise model transformation, from requirements to specification, that includes the necessary analysis to identify errors and faults at the component level.

9.2.2 Modelling language for specifying and analysing model transformation

The TSP framework addresses the absence of standard representations of model transformation, which makes it difficult for model transformation to be analysed at the conceptual level. For this purpose, we have defined a set of visual modelling languages for specifying transformations and their components. The language includes notations for the *requirements model*, *user metamodels*, *mapping model* and *model transformation specification.*

The TSP modelling language concrete syntaxes are conceptual models; it does not require any specific implementation. The modelling language is part of the framework, therefore it is designed to sufficiently represent the key concepts and logic of model transformations, while at the same time accommodating the templates used to support analysis. The modelling languages are presented in Chapter 5 (user metamodel) and Chapter 7 (requirements model, mapping model, model transformation specification). The TSP modelling language also supports the concept of phasing for decomposition of specification and analysis constructs.

The TSP framework incorporates a notion of pattern snapshot analysis for analysing model transformations. To do this, TSP provides another set of modelling elements for representing model instances. This is presented in detail in Chapter 6 and 7.

In summary, TSP has contributed to providing a set of representations that allow model transformation to be conceptually specified and analysed.

9.2.3 Formal templates catalogue

To address the complexity of applying formal methods, we have adopted a template-based approach for specifying and reasoning about transformations. Templates are a mechanism used to hide formalism from transformation engineers by generating formal specifications via instantiation. The templates are *correct-by-construction*, representing model transformation patterns and integrity constraints. The templates are populated in a catalogue to be instantiated by TSP models. The current version of the TSP formal templates catalogue is based upon Alloy, but templates can in principle, be specified in other languages (such as Z).

The current template catalogue is sufficient to completely represent model transformation specification provided by TSP models. The template catalogue can be extended accordingly whenever new elements are added in TSP models, provided they are also compatible with Alloy representation and analysis capabilities.

The use of templates for analysis is presented in detail in Chapter 6 and 7. The TSP Alloy template catalogue is provided in Appendix I.

In summary, we have produced a set of templates that can be used to create formal specifications from TSP models. The templates have demonstrated their ability to support formal methods 'under the hood', so that transformation experts can benefit from their use without having to work with them directly.

9.2.4 Effective formal analysis

We have identified Alloy as a *practical formal method*. The features of Alloy that provide effective formal analysis include: (1) the notation uses aspects of natural language for easy comprehension; (2) it provides analysis in a form of simulation and type checking; and (3) its tools support automated analysis of the specification.

We have shown how Alloy can be use to represent model transformation, and what kind of analysis Alloy supports to provide an effective analysis. The capability of Alloy to analyse model transformation is constrained by the capability of its modelling language and the templates to represent structural and behavioural

features. Currently, the analysis that is supported is *static*. To enable *dynamic* analysis, TSP models, particularly the instance model, have to provide a richer representation of state change to extend pattern snapshot analysis capabilities, to enable simulation.

In summary, we have provided an approach, together with TSP models and a template catalogue, enabling Alloy to be used to support effective analysis of model transformations.

9.3 Limitation of the approach

The TSP framework is not without limitations, which we now briefly outline.

9.3.1 Lack of support for endogenous model transformations

The approach has been successfully applied to exogenous, horizontal transformations (e.g., the class to relational database transformation) but has yet to be tried on endogenous transformations. The approach should be applicable to exogenous vertical transformations, as long as they have different source and target metamodels. This is due to the way Alloy specifications correspond to the TSP models and templates, and how they represent rule mapping and specification. In particular, the mapping to Alloy requires that each rule will have one source element and one target element, from different source and target metamodels and as such, endogenous transformations are excluded.

We cannot yet say whether TSP can support endogenous transformations (between models of the same metamodel) in the future. We would need to enhance our visual representations to support endogenous features (perhaps inspired by visual graph transformation approaches), and would also need to investigate the extent to which Alloy can reason about updates (state changes) to models from the same language.

9.3.2 Lack of support for dynamic analysis

TSP currently supports static analysis of model transformations. This is because the pattern snapshot analysis only captures one instance of the state of a transformation. Further work is needed to analyse dynamic properties, such as *confluence* and *termination*.

It is not impossible to implement dynamic analysis in TSP. We need to extend the instance model to represent dynamic behaviours of model transformations. One concern though, is that we may require more processing capacity (bigger memory and longer execution time) to handle dynamic analysis, due to the use of large state spaces for each element in Alloy. One way to overcome this, is to produce a new set of formal template catalogues in a different language that has better dynamic analysis capabilities.

9.4 Future work

There are several directions that can be followed to extend the capability of the TSP framework. They can be divided into two categories: (1) tool support, and (2) formal template extension.

We have briefly discussed an elementary prototype TSP tool in Chapter 4, Section 4.9 for the purpose of maintaining the consistencies of Alloy model produce from TSP model. The advantages of having a better tool to support the TSP framework includes: (1) a visual editor for constructing TSP models; (2) automatic instantiations of templates; (3) potentially tighter integration with the Alloy Analyzer for analysis and feedback; (4) template management for adding or changing the template catalogue; (5) automatic consistency checking for any changes made to a specification; and (6) a traceability comment in the formal specification indicating the source templates. We would also want the tool to be able to generate implementation artefacts, for example, Ecore metamodels from contextualized metamodels, and ETL specification from model transformation specification.

In terms of template extensions, it would be useful to add templates for formalizing OCL patterns for models, metamodels and model transformations. With

templates that can be used to encode and apply OCL, it would then be possible to reason about user-defined *functions* and *constraints*. It would also be possible to develop a new template catalogue that supports other languages for analysing model transformation specification.

9.5 Final remark

This concludes the thesis. In general, a precise model transformation can be obtained from systematically developing model transformation, using a visual representation that has the capability to instantiate templates for producing formal specifications, which are amenable to formal analysis.

Appendix A

Definition of generalization kind and its template instantiations

A.1 Defining generalization

The following define the generalization kind supported by TSP metamodelling language for specifying generalization features.

A.1.1 Complete subclass type partition

A specialization where each individual instances of a class is an instance of its subclasses (where attributes are inherited) called a complete subclass type partition. Figure A.1 shows an example of complete subclass type partition instances of class **Car** is a **LocalMade** or **Imported**.

A.1.2 Incomplete subclass type partition

In a situation where some individual instance of a class is not an instance of any its subclasses and contains only the shared attributes without any specialization, this is called an incomplete subclass type partition. Figure A.2 is an

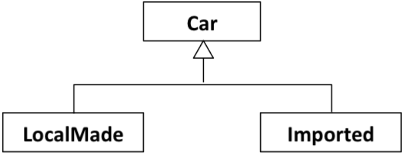


Figure A.1: Complete subclass type partition

example where a **SponsoredStudent** is a **Student** but not every **Student** are a **SponsoredStudent**.

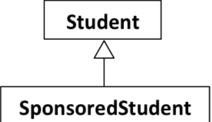


Figure A.2: Incomplete subclass type partition

A.1.3 Disjoint subclass type partition

A disjoint subclass type partition is where an individual class instance is specialized exclusively to one subclass type. For example, a **Lecturer** is a **Permanent** lecturer, or else a **Lecturer** is a **Visiting** lecturer.

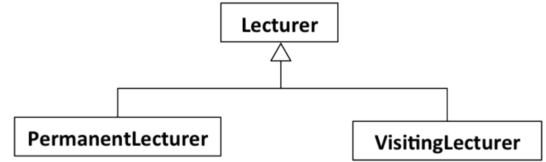


Figure A.3: Disjoint subclass type partition

A.1.4 Overlapping subclass type

The case where an individual class instance can be of multiple type specialization, it is called the overlapping subclass type. Referring again to Figure A.1, a **Car** can be an **Imported** type but also **LocalMade** as it was locally assembled.

A.2 Formalizing generalization

Alloy has a notation for representing generalization, but to address other categories of generalization variants, there will be some additional constraints added to the basic notation. The following describes how the additional constraint is included.

A.2.1 Incomplete, disjoint (Shared)

The semantics provided by default Alloy generalization *extends* can be classified as an *incomplete,disjoint* generalization, ie. parent class can be represented as an atom that represents a valid instance and is not part of its subclasses. For example, Figure A.2 in Section 5.2.4.2, shows an incomplete generalization of *Student* and *SponsoredStudent*. The *incomplete,disjoint* generalization is provided by template **R3: Incomplete, disjoint (Shared)** (Appendix I.4.1.3). If we apply these to the example, the Alloy model is as presented in Listing A.1.

```
1 sig Student{}
2
3 sig SponsoredStudent extends Student{}
```

Listing A.1: R3: Incomplete Disjoint (Shared) (Appendix I.4.1.3) template instantiation

In Figure A.4, Alloy shows a valid instance of a parent class can have an instance along with its subclass instance.

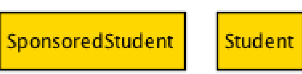


Figure A.4: Results of executing Listing A.1

A.2.2 Complete, Disjoint (Abstraction)

In the case of *complete subclass type partition*, it is a generalization gives all its attributes and to its subclass to be use. Alloy does not have a direct way to define this. Therefore, a scheme that provide the definition has to be created. The solution is to define a superclass that always provides the abstraction and is always realized as one of its subclass instance. For example, in Figure A.1 from Section 5.2.4.2, a Car is LocalMade or Imported, it means that the final instance of a Car is either LocalMade or Imported instances. To capture this behaviour, we have to treat the Car class as abstract, giving generic features for its subclasses to inherit. Listing A.2 is the result of applying template **R1: Complete, Disjoint (Abstraction)** (Appendix I.4.1.1).

```
1 abstract sig Car{}
2
3 sig LocalMade extends Car{}
4
5 sig Imported extends Car{}
```

Listing A.2: R1: Complete Disjoint (Abstraction) (Appendix I.4.1.1) template instantiation

Executing Listing A.2 via *Run* command in Alloy Analyzer shows the valid instances of Car *complete, disjoint* (abstraction) generalization at a given time. We can see that we have given the definition of a *complete, disjoint* by making Car abstract via **R1: Complete, Disjoint (Abstraction)** (Appendix I.4.1.1) template.

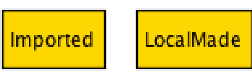


Figure A.5: Result of executing Listing A.2

A.2.3 Complete, disjoint (Refinement)

For *complete, disjoint (Refinement)* generalization, this time, an additional constraint has to be added. Consider Figure A.1 from Section 5.2.4.2 again; this time it is of type *complete, disjoint (Refinement)* generalization. This means that a Car that can be refined as LocalMade-Car or Imported-Car instances. The Alloy model is as presented in Listing A.3 from instantiation of template **R2: Complete, disjoint (Refinement)** (Appendix I.4.1.2).

```
1  sig Car{}
2
3  sig LocalMade in Car{}
4
5  sig Imported in Car{}
6
7  fact DisjointSubClassCar{
8    disj[LocalMade, Imported]
9    Car = LocalMade + Imported
10 }
```

Listing A.3: R2: Complete Disjoint (Refinement) (Appendix I.4.1.2) template instantiation

The ***in*** keywords (line 3 and 5) are used to define a generalization where the subclass completely refines the superclass. But it does not provide the disjointness required for each subclass. The *DisjointSubClassCar* is an additional fact provided by the template that defines disjointness of subclasses, when using the

keyword *in* alone cannot provide the semantic. The execution of Listing A.3 creates valid instances, one of them as showed in Figure A.6.

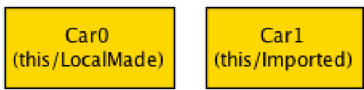


Figure A.6: Result of executing Listing A.3

A.2.4 Complete Overlap

For a complete, overlap type generalization, the Alloy *fact* has to allow some combination of subclass to define its superclass features. The *in* specifically support this definition, but the template provides a constraint that allows some control of the combination classes. To demonstrate, we use the same Car example. Listing A.4 shows the instantiation of **R4: Complete, Overlap** template, where *CombinedLocalMadeImported* can be a combined classes. Figure A.7 shows one of the instance result from the execution that shows a Car is Imported and Local at the same time.

```
sig Car{}

sig LocalMade in Car{}

sig Imported in Car{}

fact CombinedLocalMadeImported{
  some LocalMade & Imported
}
```

Listing A.4: R4: Complete Overlap (Appendix I.4.1.4) template instantiation

Car
(this/Imported, this/LocalMade)

Figure A.7: Run command on Listing A.4

Appendix B

Definition of reflexive association kind

B.1 Defining reflexive association

The following define the reflexive association kind supported by TSP metamodelling language for specifying generalization features.

The following describe the characteristic of each reflexive types of relation $\boldsymbol{r}$ on a class **A**; and a_1, $a_2 ... a_n$ are instances of **A**.

B.1.1 Irreflexive

For every instance of **A** over a relation $\boldsymbol{r}$, there cannot be an instance associated with the same instance. They can be either symmetrical or anti-symmetrical. Acyclic may be a subset of irreflexive but having both defined are redundant, therefore it is either irreflexive or acyclic. Irreflexive type of reflexive association is as shown in Figure B.1.

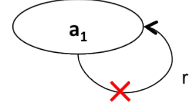


Figure B.1: Irreflexive

B.1.2 Symmetric

If the relation between two instance of **A** is symmetric, a relation $\boldsymbol{r}$ is *bi-directional*. They can be reflexive or irreflexive, and not acyclic. Symmetric type of reflexive association is as shown in Figure B.2.

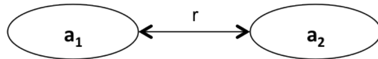


Figure B.2: Symmetric

B.1.3 Anti-symmetric

If the relation between two instance of **A** is anti-symmetric, a relation $\boldsymbol{r}$ between a_1 and a_2 of them implies $a_1 = a_2$. They can be reflexive or irreflexive, and not acyclic. Anti-symmetric type of reflexive association is as shown in Figure B.3.

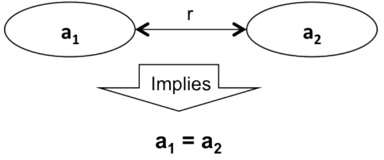


Figure B.3: Anti-symmetric

B.1.4 Asymmetric

If the relation between two instance of **A** is asymmetric, a relation $\boldsymbol{r}$ between a_1 and a_2 is uni-directional. Asymmetric are both irreflexive and anti-symmetric. Acyclic is a subset of asymmetric and having them both defined are redundant. Therefore it is either asymmetric or acyclic. Asymmetric type of reflexive association is as shown in Figure B.4.

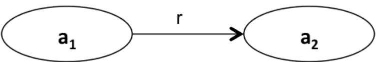


Figure B.4: Asymmetric

B.1.5 Acyclic

For relation $\boldsymbol{r}$ over a_1 and a_2 of **A**, there will be no relation, directly or indirectly, associating back to a_1. Acyclic type of reflexive association is as shown in Figure B.5.

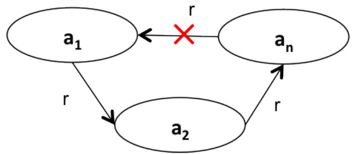


Figure B.5: Acylic

B.2 Formalizing reflexive association

The following shows how templates are instantiated on a reflexive association.

B.2.1 Irreflexive

For reflexive association with irreflexive condition can have three scenario; (1) irreflexive only, (2) irreflexive and symmetrical, and (3) irreflexive and anti-symmetrical. Template **R8: Reflexive- Irreflexive** (Appendix I.4.4.2) provides the instantiation for all scenario. For example, **A** *disallow any two* ***A*** *objects to refer to itself and to each other*, is an irreflexive and anti-symmetric reflexive association type. Generated Alloy is as Listing B.1 and a run instance is as shown in Figure B.6.

```
1 sig A{
2   a: set A
3 }
4
5 fact IrreflexiveAntiSymmetrica{
6   irreflexiveAns[a]
7 }
```

Listing B.1: R8: Reflexive - Irreflexive and Anti-symmetric association (Appendix I.4.4.2) instantiation

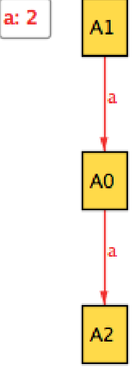


Figure B.6: Result of executing Listing 6.5

B.2.2 Symmetric

For defining that the relation between a ***A*** *object that can refer to itself and each other*, template **R9: Reflexive - Symmetric** (Appendix I.4.4.3) is instantiated. Results of instantiation are as shown in Listing B.2 and Figure B.7 shows an instance of executing the model.

```
1 sig A{
2   a: set A
3 }
4
5 fact Symmetrica{
6   symmetric[a]
7 }
```

Listing B.2: R9: Reflexive - Symmetric association (Appendix I.4.4.3) instantiation

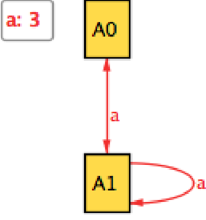


Figure B.7: Result of executing Listing B.2

B.2.3 Anti-symmetric

An ***A*** *object that refers to another* ***A*** *object but not the other way around* means that the reflexive association is anti-symmetric. Listing B.3 is generated as a

result of instantiating template **R10: Reflexive - Anti-Symmetric** (Appendix I.4.4.4).

```
sig A{
  a: set A
}

fact AntiSymmetrica{
  antisymmetric[a]
}
```

Listing B.3: R10: Reflexive - Anti-Symmetric association (Appendix I.4.4.4) instantiation

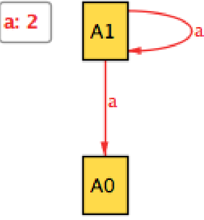


Figure B.8: Result of executing Listing B.3

B.2.4 Asymmetric

An asymmetric relation between an **A** object defines that ***A*** *object is related to another different* ***A*** *object*. It is an anti-symmetric but with irreflexive relation. Template **R11: Reflexive - Asymmetric** (Appendix I.4.4.5) is instantiated, resulting Listing B.4 and instance shown in Figure B.9.

```
sig A{
  a: set A
```

```
3 }
4
5 fact Asymmetrica{
6   asymmetric[a]
7 }
```

Listing B.4: R11: Reflexive - Asymmetric association (Appendix I.4.4.5) instantiation

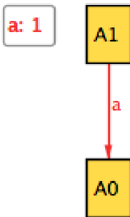


Figure B.9: Result of executing Listing B.4

B.2.5 Acyclic

To any instance of **A**, in *any subsequent relation **a**, there is no reference backward to any of previous **A** instances*. This relation are called acyclic. Template **R12: Reflexive - Acyclic** (Appendix I.4.5.1) generates Listing B.5 and Figure B.10 shows an instance of the execution.

```
1 sig A{
2   a: set A
3 }
4
5 fact AcyclicaA{
6   acyclic[a,A]
```

```
7 }
```

Listing B.5: R12: Reflexive - Acyclic association (Appendix I.4.5.1) instantiation

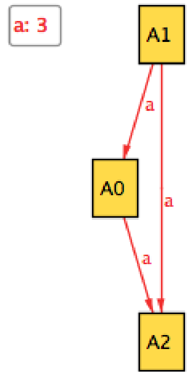


Figure B.10: Result of executing Listing B.5

Appendix C

XML model for Book to Publication transformation example

C.1 Figure 5.10: Book user metamodel

```
1 <user_metamodel name = "Book" source = "True" target = "False"
    bidirectional = "False">
2     <class_element ElmtName = "Book" abstract = "False">
3         <attribute AttrName = "titleB" type = "BookTitle"></
    attribute>
4         <association RoleName = "BookHasChapter" multOf = "1..*"
    ElmtName2 = "Chapter"></association>
5     </class_element>
6     <class_element ElmtName = "Chapter" abstract = "False">
7         <attribute AttrName = "header" type = "ChapHeader"></
    attribute>
```

```
8         <attribute AttrName = "numPages" type = "Int"></attribute>
9     </class_element>
10 </user_metamodel>
```

Listing C.1: XML representation for Figure 5.10: Book user metamodel

C.2 Figure 5.10: Publication user metamodel

```
1 <user_metamodel name = "Book" source = "True" target = "False"
      bidirectional = "True">
2     <class_element ElmtName = "Publication" abstract = "False">
3         <attribute AttrName = "titleP" type = "PublicationTitle"></
      attribute>
4          <attribute AttrName = "totalNumPages" type = "Int"></
      attribute>
5     </class_element>
6 </user_metamodel>
```

Listing C.2: XML representation for Figure 5.10: Publication user metamodel

C.3 Figure 6.20: Positive pattern Book has chapters instantiated from the user metamodel in Figure 5.10

```
1 <model_instance name = "Requirement IM 01" pattern = "Positive">
2     <element_instance ElmtInstName = "abook" ElmtName = "Book">
3         <instance_attribute ElmtAttr = "title" value = "Abook">
```

```
4          </instance_attribute>
5          <relationship ElmtInstSrc = "abook" ElmtNameRel = "
     bookContainChapter">
6              <target ElmtInstNameTrg = "chap1"></target>
7              <target ElmtInstNameTrg = "chap2"></target>
8          </relationship>
9      </element_instance>
10     <element_instance ElmtInstName = "chap1" ElmtName = "Chapter">
11         <instance_attribute ElmtAttr = "header" value = "H1">
12         </instance_attribute>
13         <instance_attribute ElmtAttr = "numPages" value = "4">
14         </instance_attribute>
15     </element_instance>
16     <element_instance ElmtInstName = "chap2" ElmtName =  "Chapter">
17         <instance_attribute ElmtAttr = "header" value = "H2">
18         </instance_attribute>
19         <instance_attribute ElmtAttr = "numPages" value = "5">
20         </instance_attribute>
21     </element_instance>
22 </model_instance>
```

Listing C.3: XML representation for Figure 6.20: Positive pattern Book has chapters instantiated from the user metamodel in Figure 5.10

C.4 Figure 6.22: Negative pattern - Chapter belongs to multiple books

```
1 <model_instance name = "Requirement IM 01" pattern = "Negative">
```

```
2       <element_instance ElmtInstName = "abook1" ElmtName = "Book">
3           <instance_attribute ElmtAttr = "title" value = "Abook1">
4           </instance_attribute>
5           <relationship ElmtInstSrc = "abook1" ElmtNameRel = "
        bookContainChapter">
6               <target ElmtInstNameTrg = "chap1"></target>
7           </relationship>
8       </element_instance>
9       <element_instance ElmtInstName = "abook2" ElmtName = "Book">
10          <instance_attribute ElmtAttr = "title" value = "Abook2">
11          </instance_attribute>
12          <relationship ElmtInstSrc = "abook2" ElmtNameRel = "
        bookContainChapter">
13              <target ElmtInstNameTrg = "chap1"></target>
14          </relationship>
15      </element_instance>
16      <element_instance ElmtInstName = "chap1" ElmtName = "Chapter">
17          <instance_attribute ElmtAttr = "header" value = "H1">
18          </instance_attribute>
19          <instance_attribute ElmtAttr = "numPages" value = "4">
20          </instance_attribute>
21      </element_instance>
22  </model_instance>
```

Listing C.4: XML representation for Figure 6.22: Negative pattern - Chapter belongs to multiple books

C.5 Figure 7.11 and 7.12: Model transformation specification - Defining publication

```
<phase phase_name = "publication_definition" root = "True" phase_type = "1">
    <transformation_rule MappingRel1 = "BookToPublication">
        <source localsrcvar1 = "abook" LocalSrcElmt1 = "Book"></source>
        <target localtrgvar1 = "pub" LocalTrgElmt1 = "Publication"></target>
    </transformation_rule>
    <operation OP_phase_name = "publication_definition">
        <parameter param1 = "localsrcvar1" paramType1 = "LocalSrcElmt1" param2= "localtrgvar1" paramType2 = "LocalTrgElmt1">
        </parameter>
        <state state_name = "Assign publication title">
            <state_op variable = "pub.titleP"></state_op>
            <state_val value = "abook.titleB"></state_val>
        </state>
        <state state_name = "Publication number of pages">
            <state_op variable = "pub.totalNumPages"></state_op>
            <state_val value = "CalculateTotalPages[abook]"></state_val>
        </state>
    </operation>
</phase>
```

Listing C.5: XML representation for Figure 7.11 and 7.12: Model transformation specification - Defining publication

C.6 Figure 7.15: Transformation instance model of transformation from book to publication

```
1 <model_transformation_instance name = "defining_publication" pattern
     = "Positive">
2         <source_element_instance name = "abook"
     user_metamodel_element = "Book">
3             <source_instance_attribute attribute = "title" value = "
     Abook" type = "BookTitle">
4             </source_instance_attribute>
5             <relationship name = "bookContainChapter">
6                 <target>chap1</target>
7                 <target>chap2</target>
8             </relationship>
9         </source_element_instance>
10        <transformation_rule MappingRel1="publication_definition">
11        <target_element_instance name = "pub" user_metamodel_element
     = "Publication"></target_element_instance>
12        </transformation_rule>
13        <source_element_instance name = "chap1"
     user_metamodel_element = "Chapter">
14            <source_instance_attribute attribute = "header" value =
     "H1" type = "ChapHeader">
15            </source_instance_attribute>
```

```
16            <source_instance_attribute attribute = "numPages" value
    = "4">
17            </source_instance_attribute>
18        </source_element_instance>
19        <source_element_instance name = "chap2"
    user_metamodel_element = "Chapter">
20            <source_instance_attribute attribute = "header" value =
    "H2" type = "ChapHeader">
21            </source_instance_attribute>
22            <source_instance_attribute attribute = "numPages" value
    = "5">
23            </source_instance_attribute>
24        </source_element_instance>
25    </source_model_instance>
26 </model_transformation_instance>
```

Listing C.6: XML representation for Figure 7.15: Transformation instance model of transformation from book to publication

Appendix D

Formal specification of Publication User Metamodel

D.1 Formal specification of Publication User Metamodel

Formal specification for Publication model used in the example.

D.1.1 Alloy Model

```
sig Publication{
  titleP : one PublicationTitle,
  totalNumPages : Int
}

sig PublicationTitle{}
```

Listing D.1: User metamodel formal specification for Publication in Figure 5.10

Appendix E

Formal Specification of Relational Database user metamodel

E.1 Formal specification of relational database user metamodel (Target)

Formal specification for relational database model used in the evaluation.

E.1.1 Alloy Model

```
abstract sig DatabaseElement{
  name : one String
}

fact SingleValuename{
  AttrSingleValue[name, String]
}

```

```
9  sig Schema extends DatabaseElement{
10   schemacontainTable1 : set Table
11 }
12
13 sig Table extends DatabaseElement{
14   schemacontainTable2 : one Schema,
15   tablehasForeignKey1 : set ForeignKey,
16   foreignKeyrefertoTable2 : one ForeignKey,
17   tablehasPKeyColumn1 : set Column,
18   tablehasColumn1 : set Column
19 }
20
21 fact BidirectionalMultSchema {
22   Schema <: schemacontainTable1 in (Table) set ->
23   one (Table) and
24   Table <: schemacontainTable2 in (Table) one ->
25   set (Schema) schemacontainTable1 in â¼schemacontainTable2
26 }
27
28 sig ForeignKey extends DatabaseElement{
29   tablehasForeignKey2 : set Table,
30   foreignKeyrefertoTable1 : one Table,
31   columnforForeignKey2 : set Column
32 }
33
34 fact BidirectionalMultTable1{
35   Table <: tablehasForeignKey1 in (ForeignKey) set ->
36   one (ForeignKey) and
37   ForeignKey <: tablehasForeignKey2 in (ForeignKey) one ->
38   set (Table) tablehasForeignKey1 in â¼tablehasForeignKey2
```

```
39 }
40
41 fact BidirectionalMultForeignKey{
42   ForeignKey <: foreignKeyrefertoTable1 in (Table) one ->
43   set (Table) and
44   Table <: foreignKeyrefertoTable2 in (Table) set ->
45   one (ForeignKey) foreignKeyrefertoTable1 in
      â¼foreignKeyrefertoTable2
46 }
47
48 sig Column extends DatabaseElement{
49   type : one Datatype,
50   tablehasPKeyColumn2 : one Table,
51   tablehasColumn2 : one Table,
52   columnforForeignKey1 : set ForeignKey
53 }
54
55 fact BidirectionalMultTable2{
56   Table <: tablehasPKeyColumn1 in (Column) one ->
57   set (Column) and
58   ForeignKey <: tablehasPKeyColumn2 in (Column) set ->
59   one (Table) tablehasPKeyColumn1 in â¼tablehasPKeyColumn2
60 }
61
62 fact BidirectionalMultTable3{
63   Table <: tablehasColumn1 in (Column) one ->
64   set (Column) and
65   ForeignKey <: tablehasColumn2 in (Column) set ->
66   one (Table) tablehasColumn1 in â¼tablehasColumn2
67 }
```

```
68
69 fact BidirectionalMultColumn{
70   Column <: columnforForeignKey1 in (ForeignKey) one ->
71   set (ForeignKey) and
72   Column <: columnforForeignKey2 in (ForeignKey) set ->
73   one (Column) columnforForeignKey1 in â¼columnforForeignKey2
74 }
75
76 sig String{}
77
78 sig Datatype{}
79
80 *Bidirectional fact is included manually.
```

Listing E.1: User metamodel formal specification for relational database in Figure 8.3

Appendix F

XML model for Class to Relational Database transformation example

F.1 Figure 8.2: Class user metamodel

```
1 <user_metamodel name= "Class" source = "True" target = "False"
      bidirectional = "True">
2     <class_element ElmtName = "ModelElement" abstract = "True">
3         <attribute AttrName = "name" type = "String"></attribute>
4     </class_element>
5     <class_element ElmtName = "Package" abstract = "False">
6         <association RoleName = "packagecontainClass1" multOf = "
      1..*" ElmtName2 = "Class"></association>
7         <generalization parent = "ModelElement" type = "
      complete_disjoint_abstraction"> </generalization>
8     </class_element>
```

```
9    <class_element ElmtName = "Class" abstract = "False">
10       <attribute AttrName = "isPersistance" type = "Boolean"></
     attribute>
11       <association RoleName = "packagecontainClass2" multOf = "
     1..*" ElmtName2 = "Package"></association>
12       <association RoleName = "classhasAttribute1" multOf = "1..*"
      ElmtName2 = "Class"></association>
13       <reflexive RoleName = "classisparentClass" type = "acyclic"
     multOf = "zero_to_many"></reflexive>
14       <reflexive RoleName = "classhasrelClass" type = "acyclic"
     multOf = "zero_to_many"></reflexive>
15       <generalization parent = "NamedElement" type = "
     complete_disjoint_abstraction"> </generalization>
16   </class_element>
17   <class_element ElmtName = "Attribute" abstract = "False">
18       <attribute AttrName = "type" type = "Datatype"></attribute>
19       <attribute AttrName = "multivalued" type = "Boolean"></
     attribute>
20       <association RoleName = "classhasAttribute2" multOf = "1..*"
      ElmtName2 = "Class"></association>
21       <generalization parent = "ModelElement" type = "
     complete_disjoint_abstraction"> </generalization>
22   </class_element>
23 </user_metamodel>
```

Listing F.1: XML representation for Figure 8.2: Class user metamodel

F.2 Figure 8.3: Relational Database user metamodel

```
1  <user_metamodel name="Database"source = "False"  target = "True"
       bidirectional = "True">
2      <class_element ElmtName = "DatabaseElement"  abstract = "False">
3          <attribute AttrName = "name"  type = "DBElementName"></
       attribute>
4      </class_element>
5      <class_element ElmtName = "Schema"  abstract = "False">
6          <association RoleName = "schemacontainTable1"  multOf = "1..*
       " ElmtName2 = "Table"></association>
7          <generalization parent = "DatabaseElement"  type = "
       complete_disjoint_abstraction"> </generalization>
8      </class_element>
9      <class_element ElmtName = "Table"  abstract = "False">
10         <association RoleName = "tablehasForeignKey1"  multOf = "1..*
       " ElmtName2 = "ForeignKey"></association>
11       <association RoleName = "foreignKeyrefertoTable2"  multOf = "
       *..1"  ElmtName2 = "ForeignKey"></association>
12       <association RoleName = "tablehasPKeyColumn1"  multOf = "1..*"
       ElmtName2 = "Column"></association>
13       <association RoleName = "tablehasColumn1"  multOf = "1..*"
       ElmtName2 = "Column"></association>
14         <generalization parent = "DatabaseElement"  type = "
       complete_disjoint_abstraction"> </generalization>
15     </class_element>
16     <class_element ElmtName = "ForeignKey"  abstract = "False">
```

```
17          <association RoleName = "foreignKeyrefertoTable1" multOf = "
        1..*" ElmtName2 = "Table"></association>
18        <association RoleName = "tablehasForeignKey2" multOf = "*..1"
        ElmtName2 = "Table"></association>
19        <association RoleName = "columnforForeignKey2" multOf = "*..1"
        ElmtName2 = "Column"></association>
20          <generalization parent = "DatabaseElement" type = "
        complete_disjoint_abstraction"> </generalization>
21      </class_element>
22      <class_element ElmtName = "Column" abstract = "False">
23        <attribute AttrName = "type" type = "Datatype"></attribute>
24          <association RoleName = "tablehasColumn2" multOf = "*..1"
        ElmtName2 = "Table"></association>
25        <association RoleName = "tablehasPKeyColumn2" multOf = "*..1"
        ElmtName2 = "Table"></association>
26        <association RoleName = "columnforForeignKey1" multOf = "*..1"
        ElmtName2 = "ForeignKey"></association>
27          <generalization parent = "DatabaseElement" type = "
        complete_disjoint_abstraction"> </generalization>
28      </class_element>
29  </user_metamodel>
```

Listing F.2: XML representation for Figure 5.10: Publication user metamodel

F.3 Figure 8.4: A positive snapshot for ReqIM1.0

```
1  <model_instance name = "ReqIM1.0" pattern = "Positive">
2      <element_instance ElmtInstName = "Account" ElmtName = "Class">
```

```
3         <instance_attribute ElmtAttr = "isPersistence" value = "True
    ">
4         </instance_attribute>
5         <relationship ElmtInstSrc = "Account" ElmtNameRel = "
    classhasAttribute">
6             <target ElmtInstNameTrg = "accNumber"></target>
7             <target ElmtInstNameTrg = "accBalance"></target>
8         </relationship>
9       <relationship ElmtInstSrc = "Account" ElmtNameRel = "
    classisparentClass">
10            <target ElmtInstNameTrg = "Current"></target>
11            <target ElmtInstNameTrg = "Saving"></target>
12        </relationship>
13    </element_instance>
14    <element_instance ElmtInstName = "accNumber" ElmtName = "
    Attribute">
15        <instance_attribute ElmtAttr = "multivalued" value = "False"
    >
16        </instance_attribute>
17    </element_instance>
18    <element_instance ElmtInstName = "accBalance" ElmtName = "
    Attribute">
19        <instance_attribute ElmtAttr = "multivalued" value = "False"
    >
20        </instance_attribute>
21    </element_instance>
22    <element_instance ElmtInstName = "Current" ElmtName =  "Class">
23        <instance_attribute ElmtAttr = "isPersistence" value = "True
    ">
24        </instance_attribute>
```

```
25          <relationship ElmtInstSrc = "Current" ElmtNameRel = "
       classhasAttribute">
26              <target ElmtInstNameTrg = "annualFee"></target>
27          </relationship>
28      </element_instance>
29      <element_instance ElmtInstName = "Current" ElmtName =  "Class">
30          <instance_attribute ElmtAttr = "isPersistence" value = "True
       ">
31          </instance_attribute>
32          <relationship ElmtInstSrc = "Saving" ElmtNameRel = "
       classhasAttribute">
33              <target ElmtInstNameTrg = "interestRate"></target>
34          </relationship>
35      </element_instance>
36      <element_instance ElmtInstName = "annualFee" ElmtName = "
       Attribute">
37          <instance_attribute ElmtAttr = "multivalued" value = "False"
       >
38          </instance_attribute>
39      </element_instance>
40      <element_instance ElmtInstName = "interestRate" ElmtName = "
       Attribute">
41          <instance_attribute ElmtAttr = "multivalued" value = "False"
       >
42          </instance_attribute>
43      </element_instance>
44  </model_instance>
```

Listing F.3: XML representation for Figure 8.4: A positive snapshot for ReqIM1.0

F.4 Figure 8.6: A positive snapshot pattern for ReqIM2.0(1)

```
1  <model_instance name = "ReqIM2.0" pattern = "Positive">
2      <element_instance ElmtInstName = "Customer" ElmtName = "Class">
3          <instance_attribute ElmtAttr = "isPersistence" value = "True
       ">
4          </instance_attribute>
5          <relationship ElmtInstSrc = "Customer" ElmtNameRel = "
       classhasAttribute">
6              <target ElmtInstNameTrg = "firstName"></target>
7        <target ElmtInstNameTrg = "lastName"></target>
8              <target ElmtInstNameTrg = "personalInterest"></target>
9          </relationship>
10       <relationship ElmtInstSrc = "Customer" ElmtNameRel = "
       classhasrelClass">
11             <target ElmtInstNameTrg = "Account"></target>
12         </relationship>
13     </element_instance>
14     <element_instance ElmtInstName =  firstName" ElmtName = "
       Attribute">
15         <instance_attribute ElmtAttr = "multivalued" value = "False"
       >
16         </instance_attribute>
17     </element_instance>
18     <element_instance ElmtInstName = "lastName" ElmtName = "
       Attribute">
19         <instance_attribute ElmtAttr = "multivalued" value = "False"
       >
```

```
20          </instance_attribute>
21    <element_instance ElmtInstName = "personalInterest" ElmtName = "
        Attribute">
22          <instance_attribute ElmtAttr = "multivalued" value = "True">
23          </instance_attribute>
24     </element_instance>
25     <element_instance ElmtInstName = "Account" ElmtName =  "Class">
26          <instance_attribute ElmtAttr = "isPersistence" value = "True
        ">
27          </instance_attribute>
28          <relationship ElmtInstSrc = "Account" ElmtNameRel = "
        classhasAttribute">
29                <target ElmtInstNameTrg = "accNumber"></target>
30     <target ElmtInstNameTrg = "accBalance"></target>
31          </relationship>
32          <relationship ElmtInstSrc = "Account" ElmtNameRel = "
        classisparentClass">
33                <target ElmtInstNameTrg = "Current"></target>
34          </relationship>
35     </element_instance>
36     <element_instance ElmtInstName = "accNumber" ElmtName = "
        Attribute">
37          <instance_attribute ElmtAttr = "multivalued" value = "False"
        >
38          </instance_attribute>
39     </element_instance>
40     <element_instance ElmtInstName = "accBalance" ElmtName = "
        Attribute">
41          <instance_attribute ElmtAttr = "multivalued" value = "False"
        >
```

```
42          </instance_attribute>
43      </element_instance>
44      <element_instance ElmtInstName = "Current" ElmtName =  "Class">
45          <instance_attribute ElmtAttr = "isPersistence" value = "True
    ">
46        <relationship ElmtInstSrc = "Current" ElmtNameRel = "
    classhasAttribute">
47                <target ElmtInstNameTrg = "annualFee"></target>
48          </relationship>
49          </instance_attribute>
50      <element_instance ElmtInstName = "annualFee" ElmtName = "
    Attribute">
51          <instance_attribute ElmtAttr = "multivalued" value = "False"
    >
52          </instance_attribute>
53      </element_instance>
54  </model_instance>
```

Listing F.4: XML representation for Figure 8.6: A positive snapshot pattern for ReqIM2.0(1)

F.5 Figure 8.9: A negative snapshot for ReqIM2.0(1)

```
1  <model_instance name = "ReqIM2.0(1)" pattern = "Negative">
2      <element_instance ElmtInstName = "Customer" ElmtName = "Class">
3          <instance_attribute ElmtAttr = "isPersistence" value = "True
   ">
```

```
4           </instance_attribute>
5           <relationship ElmtInstSrc = "Customer" ElmtNameRel = "
        classhasrelClass">
6               <target ElmtInstNameTrg = "Account1"></target>
7         <target ElmtInstNameTrg = "Account2"></target>
8           </relationship>
9       </element_instance>
10      <element_instance ElmtInstName = "Account1" ElmtName = "Class">
11          <instance_attribute ElmtAttr = "isPersistence" value = "True
        ">
12          </instance_attribute>
13          <relationship ElmtInstSrc = "Account1" ElmtNameRel = "
        classisparentClass">
14              <target ElmtInstNameTrg = "Current1"></target>
15          </relationship>
16      </element_instance>
17      <element_instance ElmtInstName = "Account2" ElmtName = "Class">
18          <instance_attribute ElmtAttr = "isPersistence"value = "True"
        >
19          </instance_attribute>
20          <relationship ElmtInstSrc = "Account2" ElmtNameRel = "
        classisparentClass">
21              <target ElmtInstNameTrg = "Current2"></target>
22          </relationship>
23      </element_instance>
24      <element_instance ElmtInstName = "Current1" ElmtName = "Class">
25          <instance_attribute ElmtAttr = "isPersistence"value = "True"
        >
26          </instance_attribute>
27      </element_instance>
```

```
28      <element_instance ElmtInstName = "Current2" ElmtName = "Class">
29          <instance_attribute ElmtAttr = "isPersistence"value = "True"
    >
30          </instance_attribute>
31      </element_instance>
32  </model_instance>
```

Listing F.5: XML representation for Figure 8.9: A negative snapshot for ReqIM2.0(1)

F.6 Figure 8.18 and 8.19 : Model transformation specification of the table definition phase with a primary key

```
1   <phase phase_name = "table_definition" root = "True" phase_type = "1
    ">
2       <transformation_rule MappingRel1 = "ClasstoTable">
3           <source localsrcvar1 = "c" LocalSrcElmt1 = "Class"></source>
4           <target localtrgvar1 = "t" LocalTrgElmt1 = "Table"></target>
5       </transformation_rule>
6       <operation OP_phase_name = "table_definition">
7           <parameter
8                   param1 = "localsrcvar1" paramType1 = "LocalSrcElmt1"
9                   param2= "localtrgvar1"  paramType2 = "LocalTrgElmt1">
10          </parameter>
11          <state state_name = "Assign table name">
12              <state_op variable = "t.name"></state_op>
```

```
13              <state_val value = "c.name"></state_val>
14          </state>
15      </operation>
16    <refine_phase refine_phase_name = "define_pKey" >
17      <update_new
18           localtrgvar1 = "t" LocalTrgElmt1 = "Table"
19           nonlocaltrgvar1 = "pKey" NonLocalTrgElmt1 = "Column"
20    </<update_new>
21    <operation OP_refine_phase_name = "refine_define_pKey">
22          <parameter
23                param1 = "localtrgvar1" paramType1 = "LocalTrgElmt1"
24                param2= "nonlocaltrgvar1" paramType2 = "
      NonLocalTrgElmt1">
25          </parameter>
26          <state state_name = "Assign table name">
27              <state_op variable = "pKey.name"></state_op>
28              <state_val value = "c.name"></state_val>
29          </state>
30          <state state_name = "Assign pKey column to table">
31              <state_op variable = "t.tablehasPKeyColumn"></state_op>
32              <state_val value = "pKey"></state_val>
33          </state>
34      </operation>
35    </refine_phase>
36  </phase>
```

Listing F.6: XML representation for Figure 8.18 and 8.19 : Specification of the table definition phase with a primary key

F.7 Figure 8.29: An instance of Class to Table with primary key transformation

```
1 <model_transformation_instance name = "defining_table" pattern = "
    Positive">
2         <source_element_instance name = "Customer"
    user_metamodel_element = "Class">
3         </source_element_instance>
4         <transformation_rule MappingRel1="table_definition">
5         <target_element_instance name = "CustomerTable"
    user_metamodel_element = "Table">
6         </target_element_instance>
7         </transformation_rule>
8         <update_target_element_instance name = "CustomerTable"
    user_metamodel_element = "Table">
9       <non_local_update_new name = "define_pKey">
10        <new_element_instance nonlocaltrgvar = "CustomerTablePK"
    NonLocalTrgElmt = "Column">
11        </new_element_instance>
12      </non_local_update_new>
13    </update_target_element_instance >
14 </model_transformation_instance>
```

Listing F.7: XML representation for Figure 8.29: An instance of Class to Table with primary key transformation

F.8 Figure 8.22 and 8.19: Model transformation specification model for defining multi-valued attribute

```
1  â include Class to Table specification ...
2
3   <refine_phase refine_phase_name = "define_multi_val_col">
4      <transformation_rule MappingRel1 = "Multi_Val_AttToTable">
5           <source localsrcvar2 = "am" LocalSrcElmt2 = "Attribute"></
   source>
6           <target localtrgvar2 = "at" LocalTrgElmt2 = "Table"></
   target>
7        </transformation_rule>
8        <operation OP_phase_name = "define_multi_val_col">
9        <parameter
10             param1 = "localsrcvar2" paramType1 = "LocalSrcElmt2"
11             param2= "localtrgvar2"  paramType2 = "LocalTrgElmt2">
12       </parameter>
13       <state state_name = "Assign multivalued table name">
14           <state_op variable = "at.name"></state_op>
15           <state_val value = "am.name"></state_val>
16       </state>
17    </operation>
18   <refine_phase refine_phase_name = "define_pKey">
19    <update_new
20     localtrgvar2 = "at" LocalTrgElmt2 = "Table"
21     nonlocaltrgvar2 = "pKey" NonLocalTrgElmt2 = "Column"
22    </<update_new>
```

```
23      <operation OP_refine_phase_name = "refine_define_pKey">
24         <parameter
25                param1 = "localtrgvar2" paramType1 = "LocalTrgElmt2"
26                param2= "nonlocaltrgvar2" paramType2 = "
    NonLocalTrgElmt2">
27         </parameter>
28         <state state_name = "Assign value pKey column">
29              <state_op variable = "pKey.name"></state_op>
30              <state_val value = "am.classhasAttribute.name"></
    state_val>
31          </state>
32          <state state_name = "Assign pKey column to table">
33              <state_op variable = "at.tablehasPKeyColumn"></state_op>
34              <state_val value = "pKey"></state_val>
35          </state>
36       </operation>
37    <refine_phase refine_phase_name = "define_val_col">
38      <update_new
39       localtrgvar2 = "at" LocalTrgElmt2 = "Table"
40       nonlocaltrgvar3 = "val" NonLocalTrgElmt3 = "Column"
41      </<update_new>
42    <operation OP_refine_phase_name = "refine_define_pKey">
43          <parameter
44                param1 = "localtrgvar2" paramType1 = "LocalTrgElmt2"
45                param2 = "nonlocaltrgvar3" paramType2 = "
    NonLocalTrgElmt3">
46          </parameter>
47              <state state_name = "Assign table name">
48              <state_op variable = "at.name"></state_op>
```

```
49             <state_val value = "am.classhasAttribute.name"></
    state_val>
50             </state>
51             <state state_name = "Assign value to column">
52             <state_op variable = "val.name"></state_op>
53             <state_val value = "Value"></state_val>
54       <state_op variable = "val.type"></state_op>
55             <state_val value = "am.type"></state_val>
56             </state>
57             <state state_name = "Assign pKey column to table">
58             <state_op variable = "at.tablehasColumn"></state_op>
59             <state_val value = "val"></state_val>
60             </state>
61      </operation>
62   <refine_phase refine_phase_name = "define_fKey">
63     <update_new
64     localtrgvar2 = "at" LocalTrgElmt2 = "Table"
65     localtrgvar1 = "t" LocalTrgElmt1 = "Table"
66     nonlocaltrgvar4 = "fk" NonLocalTrgElmt4 = "Column"
67     </<update_new>
68     <operation OP_refine_phase_name = "define_fKey">
69             <state state_name = "Assign foreign key reference">
70               <state_op variable = "fk.parent"></state_op>
71             <state_val value = "t.pKey"></state_val>
72         <state_op variable = "fk.child"></state_op>
73               <state_val value = "at.pKey"></state_val>
74             </state>
75     </operation>
76     </refine_phase>
77     </refine_phase>
```

```
78          </refine_phase>
79       </refine_phase>
80 </phase>
```

Listing F.8: XML representation for Figure 8.22 and 8.19: Model transformation specification model for defining multi-valued attribute

Appendix G

TSP modelling language notation descriptions

This appendix contain the description of TSP modelling language notations. The modelling language contain six notations, (1) user metamodel, (2) user metamodel instance model, (3) requirements model, (4) rule mapping model, (5) transformation specification model, and (6) transformation instance model.

The following gives the detail of each notations.

G.1 User metamodel notation

This notation is use to represent user metamodel define by TSP metamodelling language (Figure 5.4). Table G.1 and G.2 define the notation for TSP metamodelling language.

G.2 User metamodel instance model notation

User metamodel instance notation is used to define instance pattern for the snapshot analysis of the user metamodel. Table G.3 describes the notations for TSP

Table G.1: TSP metamodelling notation - Part 1

Name	Notation	Description
Abstract Class	*AbstractClass* Attribute: DataType	For defining abstract class concepts. Abstract class can have attributes.
Class	**Class** Attribute: DataType	For defining class concepts. Class can have attributes
Generalization	{relationKind}	For defining generalizations between classes. Generalization is annotated with *generalization kind*.
Bidirectional relation	{relationKind} Relation multiplicityEnd1 multiplicityEnd2	For defining bidirectional relation between classes. Relation includes multiplicity reference for each of the classes. Reflexive relation is annotated with *generalization kind*.

metamodel instance language (Figure 6.18).

G.3 Requirements model notation

The requirements model notation is used to formally represent the model transformation requirements. Figure 7.1 defines the modelling language and Table G.4 describes the notations.

Table G.2: TSP metamodelling notation - Part 2

Name	**Notation**	**Description**
Abstract Class	*AbstractClass* Attribute: DataType	For defining abstract class concepts. Abstract class can have attributes.
Directional relation	{relationKind} Relation multiplicityEnd	For defining directional relation between classes. Relation includes multiplicity reference for target class. Reflexive relation is annotated with *generalization kind*.
Composition relation	multiplicity	For defining composition (strong) relation between *whole* and *part* classes.
Aggregation relation	multiplicity	For defining aggregation (weak) relation between *whole* and *part* classes.

G.4 Rule mapping model notation

The rule mapping model notation is describe by modelling language in Figure 7.3. Table G.5 describes the rule mapping model notations.

G.5 Transformation specification model notation

This notation is used to specify the decomposition of model transformation using the rule define in the mapping model. The transformation specification modelling

Table G.3: TSP metamodelling instance notation

Name	**Notation**	**Description**
Pattern Containment	Pattern type [Pattern name]	A containment for defining pattern for model instance. Pattern type can be *positive* (P) or *negative* (P).
Class Instance	**<<Class>>** ClassName **<<Class.Attribute>>** Value	For defining class instances. Class instances includes the description of its attributes.
Relation Instance	**<<Relation>>** <<RelationName>>	For defining relation instances. Relation instances includes the description of its originating *relation* and relation instance name.

notation is define by TSP model transformation modelling language (Figure 7.5). Table G.6 and G.7 describes the notations.

G.6 Transformation instance model notation

The transformation instance model notation is used to represent the transformation instance pattern for the snapshot analysis. Figure 7.14 define the transformation instance modelling notation describe in Table G.8. Transformation instance notation extends user metamodel instance notations in Section G.2.

Table G.4: TSP requirements model notation

Name	**Notation**	**Description**
Requirement	**<<Requirement>>** Requirement Name **ID:** ID Number **Text:** Description **Source:** Source model/element **Target:** Target model/element	For defining mode transformation requirement. Includes, (1) requirements name, (2) ID number that corresponds to the requirements table and (3) source and target model or elements for the transformation requirement.
Requirement Containment	——⊕	For defining the containment between the requirements.

Table G.5: TSP rule mapping notation

Name	Notation	Description
Mapping Blocks	Source Model → Transformation → Target Model	Rule mapping model consist of three blocks, (1) source model, (2) transformation, and (3) target model. In transformation block, contain the transformation rules, while in source and target model block contains model elements for each of the rules.
Model element	ModelElement	For representing input and output model elements for rules.
Rule	Rule	For representing the transformation rules extracted from the mapping model.
Input / Output Relation	→	For defining input and output relations between, (1) source elements -rule, and (2) rule - target elements, respectively.

Table G.6: TSP transformation specification notation - Part 1

Name	Notation	Description
Phase Block	<<refine?>> Phase <<name>>	Rules within each phase is encapsulate within a phase block.
Condition Definition	Condition <<Expression>>	Condition contains expression that enable a phase to be used.
Refine		Refine phases block that contains refinement rules connected by refine arrows pointing to the main phase.
Rule Mapping	input [<<order>>] output <<RuleMappingName>>	Rule mapping defines the rule used to implement the mapping within a phase. It has input and output port.
Input Element (Local source)	<<InputElement>>	Rule mapping has input element parameter.
Output Element (Local target)	<<<<GenerateType>>>> <<OutputElement>>	Rule mapping produces output element. Output element has categorization of generate type, (1) new, (2) update, and (3) modify.

Table G.7: TSP transformation specification notation - Part 2

Name	**Notation**	**Description**
Non-Local Input Element	<<NonLocalInput>>	Non-local input element is the element required to compute additional information for rule mapping.
Non-Local Output Element	<<<<GenerateType>>>> <<NonLocalOutput>>	Non-local output element is an indirect result of a rule mapping. Non-local output element has categorization of generate type; (1) new, (2) update, and (3) modify.
Assignment Operation	<<Phase>>.<<RuleMappingName>> <<AssignmentOperation>> next	For rule mapping that contain assignment operation, each rule mapping has an assignment operation block that defines the process of assigning features.
Function Definition	<<FunctionName>> <<Expression>>	Function definitions contain function expressions.

Table G.8: TSP transformation instance model notation

Name	Notation	Description
Phase Invocation	<<phase name>>	For representing the invocation of phase by an input element.
Refine Phase Invocation	<<refine phase name>>	For representing the invocation of refine phase by target element.

Appendix H

TSpecProber MTFM Alloy Generics

```
/**Single value attribute*/
 pred AttrSingleValue[r: univ->univ, s: set univ] {
  all x: s | one r.x
}

/**Multivalue attribute*/
pred AttrMultiValue[r: univ->univ, s: set univ] {
  all x: s | lone r.x
}

------

/**Reflexive association - Irreflexive*/
pred irreflexive[r: univ->univ] {
  no iden & r
}
```

```
17
18
19 /**Reflexive association - Irreflexive & Symmetric*/
20 pred irreflexiveSym[r: univ->univ] {
21     no iden & r
22   ~r in r
23 }
24
25
26 /**Reflexive association - Irreflexive & Anti-symmetric*/
27 pred irreflexiveAns[r: univ->univ] {
28     no iden & r
29   ~r & r in iden
30 }
31
32 /**Reflexive association - Symmetric*/
33 pred symmetric [r: univ -> univ] {
34   ~r in r
35 }
36
37
38 /**Reflexive association - Anti-Symmetric*/
39 pred antisymmetric [r: univ -> univ] {
40   ~r & r in iden
41 }
42
43
44 /**Reflexive association - Asymmetric*/
45 pred asymmetric [r: univ -> univ] {
46   ~r & r in iden
```

```
47   no iden & r
48 }
49
50 /**Reflexive association - Acyclic*/
51 pred acyclic[r: univ->univ, s: set univ] {
52   all x: s | x !in x.^r
53 }
```

Listing H.1: Single and multi-value attributes

Appendix I

TSpecProber Template Catalogue

This appendix contain the Alloy TSP templates for formalizing model transformation. The templates are divided into several parts: (1) Module header, (2) User metamodel: Class, (3) User metamodel: Relation, (4) Instance model: Defining model instance, (5) Model transformation specification model, and (6) Instance model : Defining transfomation.

Before we present our templates, the next section describe the templates format.

I.1 Template Format

TEMPLATE ID:
TEMPLATE NAME:
PURPOSE:
SOURCE CONDITION:
TARGET SPECIFICATION:

---

where, ***template ID*** is a unique identifier for a particular template with a format, *character + integer*, ***template name*** is the name of the template, ***purpose*** describes the reason for applying the template, ***source condition*** shows the model fragment it applies and ***target specification*** is the formal statement fragment of the intended language, in this particular case, the Alloy.

All templates instantiation aim to be fully generated and ready for analysis. But in some cases, it may require additional details to be included during instantiation.

I.2 Module Header

The module header templates provide the template to define the links between multiple specification.

I.2.1 M1:TSpecProber Generics

TEMPLATE ID: M1
TEMPLATE NAME: TSpecProber Generics
PURPOSE: Include TSpecProber Generics file
SOURCE CONDITION: Generics file existed within the directory else include directory path.
TARGET SPECIFICATION:

```
open Generics
```

I.2.2 M2: User Metamodel Header

TEMPLATE ID: M2
TEMPLATE NAME: User Metamodel Header
PURPOSE: User metamodel file(s) header
SOURCE CONDITION: (Mandatory)

TARGET SPECIFICATION:

```
module UserModel/≪metamodelName≫
```

I.2.3 M3: (Link) Metamodel to Transformation file

TEMPLATE ID: M3
TEMPLATE NAME: (Link) Metamodel to Transformation file
PURPOSE: Include metamodel file(s)
SOURCE CONDITION: (Mandatory) For multiple source, repeat for every file. At least one source file and target file.
TARGET SPECIFICATION:

```
open UserModel/≪metamodelName≫
```

I.3 User Metamodel: Class

This section provide the templates to instantiate TSP classes.

I.3.1 C1: Abstract Class

TEMPLATE ID: C1
TEMPLATE NAME: Abstract Class
PURPOSE: Defining abstract elements class in user metamodel.
SOURCE CONDITION: When a class is abstract.
TARGET SPECIFICATION:

```
(( one || some ))? abstract sig ≪ElmtName≫ {
   /*If class is with attribute.
   For multiple, iterate for each attribute*/
   ≪AttrName≫:  (( one || some )) ≪Type≫
}
```

```
/*For single value attribute*/
fact SingleValue≪AttrName≫ {
  AttrSingleValue[≪AttrName≫, ≪Type≫]
}
/*For multi-value attribute*/
fact MultiValue≪AttrName≫ {
  AttrMultiValue[≪AttrName≫, ≪Type≫]
}
```

For class with relations, refer to template User Model: Relation.

I.3.2 C2: Class

TEMPLATE ID: C2
TEMPLATE NAME: Class
PURPOSE: Defining element class in user metamodel.
SOURCE CONDITION: When a class is abstract.
TARGET SPECIFICATION:

```
(( one || some ))? sig ≪ElmtName≫ {
  /*If class is with attribute.
    For multiple, iterate for each attribute*/
  ≪AttrName≫: (( one || some )) ≫≪Type≫
}
/*For single value attribute*/
fact SingleValue≪AttrName≫ {
  AttrSingleValue[≪AttrName≫, ≪Type≫]
}
/*For multi-value attribute*/
fact MultiValue≪AttrName≫ {
  AttrMultiValue[≪AttrName≫, ≪Type≫]
}
```

For class with relations, refer to template User Model: Relation. For singleton class the ≪mult≫is ***one***.

I.4 User Metamodel: Relation

This section provide the templates to instantiate relations of a user metamodel.

I.4.1 Generalization

For each class that has *tExtend.isDefined*, the following types can be applied:

1. Complete, disjoint
   - Abstraction
   - Refinement
2. Incomplete, disjoint
   - Shared
3. Complete, Overlap

I.4.1.1 R1: Complete, disjoint (Abstraction)

TEMPLATE ID: R1
TEMPLATE NAME: Complete, disjoint (Abstraction)
PURPOSE: For generalization classes that has the purpose of abstracting features for its subclasses.
SOURCE CONDITION: Class *tExtend.isDefined* and include Generics.
TARGET SPECIFICATION:

```
/*Superclass*/
abstract sig ≪ElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}
/*Subclass (Iterate for every class for the same level subclass element*/
sig ≪ElmtName≫ extends ≪SClassElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}
```

I.4.1.2 R2: Complete, disjoint (Refinement)

TEMPLATE ID: R2
TEMPLATE NAME: Complete, disjoint (Refinement)
PURPOSE: For generalization classes that has the purpose of subclass refining features of the superclass.
SOURCE CONDITION: Class *tExtend.isDefined.*
TARGET SPECIFICATION:

```
/*Superclass*/
sig ≪ElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}
/*Subclass (Iterate for every class for the same level subclass element*/
sig ≪ElmtName≫ in ≪SClassElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}

/*For disjoint sub-class element*/
fact DisjointSubClass≪SClassElmtName≫ {
   disj [≪ElmtName1≫,≪ElmtName2≫..≪ElmtNameN≫]
   ≪SClassElmtName≫ = ≪ElmtName1≫ + ≪ElmtName2≫ + ..  +
      ≪ElmtNameN≫ }
```

I.4.1.3 R3: Incomplete, disjoint (Shared)

TEMPLATE ID: R3
TEMPLATE NAME: Incomplete, disjoint (Shared)
PURPOSE: For generalization classes that has the purpose of superclass sharing features with subclass.
SOURCE CONDITION: Class *tExtend.isDefined.*
TARGET SPECIFICATION:

```
/*Superclass*/
sig ≪ElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}
/*Subclass (Iterate for every class for the same level subclass element*/
sig ≪ElmtName≫ extends ≪SClassElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}
```

I.4.1.4 R4: Complete, Overlap

TEMPLATE ID: R4
TEMPLATE NAME: Complete, overlap
PURPOSE: For generalization classes that has the purpose of superclass sharing features with multiple subclasses.
SOURCE CONDITION: Class *tExtend.isDefined.*
TARGET SPECIFICATION:

```
/*Superclass*/
sig ≪ElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}

/*Subclass (Iterate for every class for the same level subclass element*/
sig ≪ElmtName≫ in ≪SClassElmtName≫ {
   /*If class is with attribute.  Refer Class instantiation*/
}

/*For combined and disjoint sub-class element.Iterate every possible pairs of sub-
classes that are allowed to combined */
fact Combined≪ElmtName1≫≪ElmtName2≫ {
   some ≪ElmtName1≫ & ≪ElmtName2≫
}
```

```
/*For disjoint sub-class element*/
fact DisjointSubClass≪SClassElmtName≫ {
   disj [≪ElmtName1≫,≪ElmtName2≫..≪ElmtNameN≫]
   ≪SClassElmtName≫ = ≪ElmtName1≫ + ≪ElmtName2≫ + .. +
      ≪ElmtNameN≫ }
```

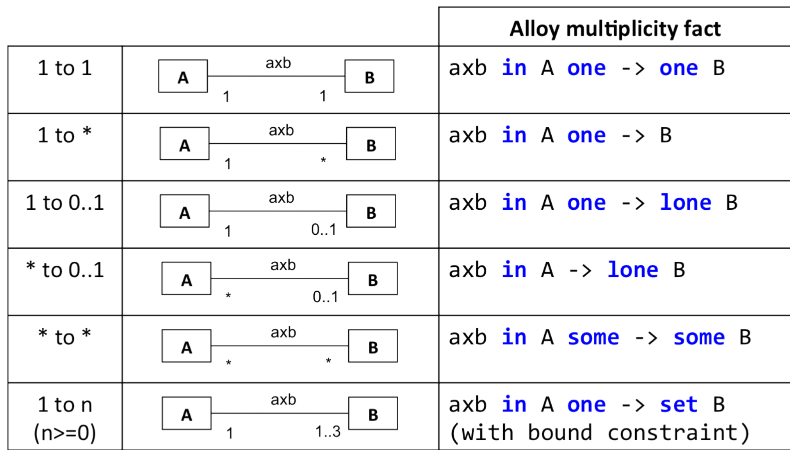
I.4.2 R5: Association (Bi-Directional Only Model)

TEMPLATE ID: R5
TEMPLATE NAME: Association (Bi-directional Only Model)
PURPOSE: For defining relation between two classes of a model that contain bi-directional relations only. Definition includes role name and multiplicity
SOURCE CONDITION: Relation between Class 1 and Class 2 has not been define.
TARGET SPECIFICATION:

```
/*Class End 1 (Element 1)*/
sig ≪ElmtName1≫ {
   /*If class is with attribute.  Refer Class instantiation*/
   /*Iterate for each association attached to Class End 2.
      If not define, instantiate Class End 2 (Element 2)
      with Class instantiation.*/
   ≪RoleName≫:  ≪multOf≫ ≪ElmtName2≫ }

/*Multiplicity facts.*/
fact Multiplicity≪ElmtName1≫≪ElmtName2≫ {
   /*Iterate for each association*/
   ≪RoleName≫:  ≪ElmtName1≫ ≪ofMult≫ -> ≪multOf≫ ≪ElmtName2≫
}

/*Numbered multiplicity facts = n.*/
fact NumberedMultiplicity≪ElmtName1≫≪RoleName≫ {
   all ≪var≫:  ≪ElmtName1≫ | # ≪var≫.≪RoleName≫ ≪CompareOp≫
```



		Alloy multiplicity fact
1 to 1	A —axb— B (1, 1)	axb in A one -> one B
1 to *	A —axb— B (1, *)	axb in A one -> B
1 to 0..1	A —axb— B (1, 0..1)	axb in A one -> lone B
* to 0..1	A —axb— B (*, 0..1)	axb in A -> lone B
* to *	A —axb— B (*, *)	axb in A some -> some B
1 to n (n>=0)	A —axb— B (1, 1..3)	axb in A one -> set B (with bound constraint)

Figure I.1: Multiplicity definition for ≪ofMult≫ and ≪multOf≫.

```
≪n≫
}

/*Numbered multiplicity facts = n1..n2*/
fact NumberedMultiplicity≪ElmtName1≫≪RoleName≫ {
   all ≪var≫:  ≪ElmtName1≫ |
   # ≪var≫.≪RoleName≫ ≪CompareOp≫ ≪n1≫ and
      # ≪var≫.≪RoleName≫ ≪CompareOp≫ ≪n2≫
}
```

I.4.3 R6: Association (Bi-Directional/ Directional)

TEMPLATE ID: R6
TEMPLATE NAME: Association (Bi-Directional using Uni-Directional)
PURPOSE: For defining relation between two classes of a model using two symmetrical uni-directional association. For directional association, only include the allowed path. Definition includes role name and multiplicity
SOURCE CONDITION: Relation between Class 1 and Class 2 has not been define.

TARGET SPECIFICATION:

```
/*Class End 1 → Class 2*/
sig ≪ElmtName1≫ {
   /*If class is with attribute.  Refer Class instantiation*/
   /*Iterate for each association attached to Class End 2.  If Class
2 is not define, instantiate with Class instantiation.*/
   ≪AsscEndName1≫:  ≪multOf≫ ≪ElmtName2≫ }

/*Class End 2 → Class 1*/
sig ≪ElmtName2≫ {
   /*If class is with attribute.  Refer Class instantiation*/
   /*Iterate for each association attached to Class End 1.
   ≪AsscEndName2≫:  ≪multOf≫ ≪ElmtName1≫ }

/*For Bi-directional multiplicity and symmetrical fact*/
fact BidirectionalMult≪ElmtName1≫ {
   ≪ElmtName1≫ <: ≪AsscEndName1≫ in (≪ElmtName1≫) ≪mult≫ ->
      ≪mult≫ (≪ElmtName2≫) and
   ≪ElmtName2≫ <: ≪AsscEndName2≫ in (≪ElmtName2≫) ≪mult≫ ->
      ≪mult≫ (≪ElmtName1≫)
   ≪AsscEndName1≫ in ∼≪AsscEndName2≫
}

/*For Uni-directional multiplicity fact*/
fact DirectionalMult≪ElmtName1≫ {
   ≪ElmtName1≫ <: ≪AsscEndName1≫ in (≪ElmtName1≫) ≪mult≫ ->
      ≪mult≫ (≪ElmtName2≫)
}
```

I.4.4 Reflexive

There are types of reflexive association; irreflexive, symmetric, anti-symmetric, asymmetric and acyclic.

I.4.4.1 R7: Reflexive - Irreflexive

TEMPLATE ID: R7
TEMPLATE NAME: Reflexive - Irreflexive
PURPOSE: For defining reflexive association that does not allow an instance to reference its own self. Association can also be symmetrical.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
sig ≪ElmtName≫ {
   ≪RoleName≫:  set ≪ElmtName≫ }

/*Irreflexive*/
fact Irreflexive≪RoleName≫ {
   irreflexive[≪RoleName≫]
}

/*Irreflexive and symmetric*/
fact IrreflexiveSymmetric≪RoleName≫ {
   irreflexiveSym[≪RoleName≫]
}

/*Irreflexive and anti-symmetric*/
fact IrreflexiveAntiSymmetric≪RoleName≫ {
   irreflexiveAns[≪RoleName≫]
}
```

I.4.4.2 R8: Reflexive - Symmetric

TEMPLATE ID: R8
TEMPLATE NAME: Reflexive - Symmetric
PURPOSE: For defining reflexive association as symmetrical. The association can also be irreflexive.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
sig ≪ElmtName≫ {
   ≪RoleName≫: set ≪ElmtName≫ }

/*Symmetric*/
fact Symmetric≪RoleName≫ {
   symmetric[≪RoleName≫]
}
```

I.4.4.3 R9: Reflexive - Anti-Symmetric

TEMPLATE ID: R9
TEMPLATE NAME: Reflexive - Anti-Symmetric
PURPOSE: For defining reflexive association that are anti-symmetric.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
sig ≪ElmtName≫ {
   ≪RoleName≫: ≪multOf≫ ≪ElmtName≫ }

/*Anti-symmetric*/
fact AntiSymmetric≪RoleName≫ {
   antisymmetric[≪RoleName≫]
}
```

I.4.4.4 R10: Reflexive - Asymmetric

TEMPLATE ID: R10
TEMPLATE NAME: Reflexive - Asymmetric
PURPOSE: For defining reflexive association that are asymmetric.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
sig ≪ElmtName≫ {
  ≪RoleName≫: ≪multOf≫ ≪ElmtName≫ }

/*Asymmetric*/
fact Asymmetric≪RoleName≫ {
  asymmetric[≪RoleName≫]
}
```

I.4.4.5 R11: Reflexive - Acyclic

TEMPLATE ID: R11
TEMPLATE NAME: Reflexive - Acyclic
PURPOSE: For defining reflexive association that does not allow acyclic relation.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
sig ≪ElmtName≫ {
  ≪RoleName≫: set ≪ElmtName≫ }

/*Acyclic*/
fact Acyclic≪RoleName≫≪ElmtName≫ {
  acyclic[≪RoleName≫, ≪ElmtName≫]
}
```

I.4.5 Aggregation

The aggregation is divided into two types, the strong aggregation (composition) and the weak aggregation. The formal definition is similar to defining normal associations. Except for ≪ElmtName1≫ in an aggregation association, is the whole class for ≪ElmtName2≫.

I.4.5.1 R12: Strong Aggregation (Composition)

For each strong aggregation relation, refer to Association instantiation. The following facts are added for defining strong aggregation.

```
/* Strong dependency*/
fact {
   all ≪var1≫:  ≪ElmtName1≫|
      some ≪var2≫:≪ElmtName2≫|
      ≪var1≫.≪RoleName≫ in ≪var2≫
}
/*Disjoint*/
fact {
   all ≪var1≫:≪ElmtName2≫, ≪var2≫,≪var3≫:≪ElmtName1≫|
      ≪var2≫.≪RoleName≫ in ≪var1≫ and
      ≪var3≫.≪RoleName≫ in ≪var1≫
         implies ≪var2≫ = ≪var3≫
}
```

I.4.5.2 R13: Weak Aggregation

For each weak aggregation relation, refer to Association instantiation. The following facts are added for defining weak aggregation.

```
/* Weak dependency*/
fact {
   all ≪var1≫:  ≪ElmtName2≫|
      some ≪var2≫:≪ElmtName1≫|
      ≪var2≫.≪RoleName≫ in ≪var1≫
```

```
}
/*Disjoint*/
fact {
   all ≪var1≫:≪ElmtName2≫, ≪var2≫,≪var3≫:≪ElmtName1≫|
      ≪var2≫.≪RoleName≫ in ≪var1≫ and
      ≪var3≫.≪RoleName≫ in ≪var1≫
         implies ≪var2≫ = ≪var3≫
}
```

I.5 Instance Model: Defining Model Instance

The following templates instantiate model instance snapshots based on user meta-model.

I.5.1 IM1: Element instance definition

TEMPLATE ID: IM1
TEMPLATE NAME: Element instance definition.
PURPOSE: For defining elements instance used to create an instance model.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
one sig ≪ElmtInstName≫ extends ≪ElmtName≫ {}
/*For elements with value attribute. Iterate for each attribute*/
fact ≪ElmtInstName≫AttrValue {
   ≪ElmtInstName≫.≪ElmtAttr≫ = ≪value≫
}
```

I.5.2 IM2: Element instance facts

TEMPLATE ID: IM2
TEMPLATE NAME: Element instance facts.
PURPOSE: For defining elements instance facts used to create an instance model.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
/*For each element, assign instance used in the model*/
fact ElementInstance{
   ≪ElmtName≫ = ≪ElmtInstName1≫ + ≪ElmtInstNamen≫
}
```

I.5.3 IM3: Model instance structure

TEMPLATE ID: IM3
TEMPLATE NAME: Model instance structure.
PURPOSE: For defining model instance structure.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
fact ModelStructure{
   /*For 1..1 relation*/
   ≪ElmtInstNameSrc≫.≪ElmtNameRel≫ = ≪ElmtInstNameTrg≫
   /*For 1..* relation*/
   ≪ElmtNameSrc≫.≪ElmtNameRel≫ = ≪ElmtInstNameTrg1≫ +
      ≪ElmtInstNameTrgn≫
}
```

I.6 Model Transformation Specification Model

This section provide the templates for formalizing model transformation specification.

I.6.1 TM1: Unconditional local-to-local transformation phase

TEMPLATE ID: TM1
TEMPLATE NAME: Unconditional local-to-local transformation phase.
PURPOSE: For defining simple local source to local target transformation phase that does not require any condition.
SOURCE CONDITION:

In the source specification, for each element associated as the source element of the *Mapping Relation*, in the element signature include the following:

```
/*Mapping Relation*/
≪MappingRel≫: one ≪TrgElmt≫,
```

TARGET SPECIFICATION:

```
pred ≪phase_name≫
  (≪localsrcvar_1≫:≪LocalSrcElmt_1≫ ,..,
    ≪localsrcvar_n≫ ≪LocalSrcElmt_n≫,
  ≪localtrgvar_1≫:≪LocalTrgElmt_1≫ ,..,
    ≪localtrgvar_n≫:≪LocalTrgElmt_n≫) {
    ≪localtrgvar_1≫ = ≪MappingRel_1≫[≪localsrcvar_1≫]
      (( and ≪OP_name_1≫[≪param_i≫ ,.., ≪param_j≫))^?]
    /*For subsequent mapping relations*/
    and ≪localtrgvar_n≫ = ≪MappingRel_n≫[≪localsrcvar_n≫]
      (( and ≪OP_name_n≫[≪param_i≫ ,.., ≪param_j≫))^?]
}
```

I.6.2 TM2: Local-to-local transformation phase with condition

TEMPLATE ID: TM2
TEMPLATE NAME: Local-to-local transformation phase with condition.
PURPOSE: For defining local source to local target transformation that requires condition.
SOURCE CONDITION:

In the source specification, for each element associated as the source element of the *Mapping Relation*, in the element signature include the following:

```
/*Mapping Relation*/
≪MappingRel≫:  one ≪TrgElmt≫,
```

TARGET SPECIFICATION:

```
pred ≪phase_name≫
   (≪localsrcvar_1≫:≪LocalSrcElmt_1≫ ,..,
      ≪localsrcvar_n≫:≪LocalSrcElmt_n≫,
   ≪localtrgvar_1≫:≪LocalTrgElmt_1≫ ,..,
      ≪localtrgvar_n≫:≪LocalTrgElmt_n≫) {
   ≪ConditionExp≫ implies
      (≪localtrgvar_1≫ = ≪MappingRel_1≫[≪localsrcvar_1≫]
         (( and ≪OP_name_1≫[≪param_i≫ ,.., ≪param_j≫))?]
      /*For subsequent mapping relations*/
      and ≪localtrgvar_n≫ = ≪MappingRel_n≫[≪localsrcvar_n≫]
         (( and ≪OP_name_n≫[≪param_i≫ ,.., ≪param_j≫))?]
            and Result = Success)
   else
```

```
   ((( Result = Fail | ≪else_phase_name≫ )))
}
```

*Condition definition are as follows:

(1) Extending elements of previous mapping

```
/*For source condition*/
≪SrcElmt≫ in ≪PrevSrcElmt≫.≪Rel≫ and
   /*For target condition*/
   ≪TrgElmt≫ = ≪PrevSrcElmt≫.≪PrevMappingRel≫
```

(2) Querying source element feature

```
≪SrcElmt≫.≪Feature≫ = ≪Expression≫
```

I.6.3 TM3: Global-to-local transformation phase

TEMPLATE ID: TM3
TEMPLATE NAME: Global-to-local transformation phase.
PURPOSE: For defining global source to local target transformation phase. Include non-local source element function query in operation assignment.
SOURCE CONDITION:

In the source specification, for each element associated as the source element of the *Mapping Relation*, in the element signature include the following:

```
/*Mapping Relation*/
≪MappingRel≫:  one ≪TrgElmt≫,
```

TARGET SPECIFICATION:

```
pred ≪phase_name≫
   (≪localsrcvar_1≫:≪LocalSrcElmt_1≫ ,..,
      ≪localsrcvar_n≫:≪LocalSrcElmt_n≫,
   ≪localtrgvar_1≫:≪LocalTrgElmt_1≫ ,..,
      ≪localtrgvar_n≫:≪LocalTrgElmt_n≫) {
      ≪localtrgvar_1≫ = ≪MappingRel_1≫[≪localsrcvar_1≫]
         (( and ≪OP_name_1≫[≪param_i≫ ,.., ≪param_j≫]))?]
      /*For subsequent mapping relations*/
      and ≪localtrgvar_n≫ = ≪MappingRel_n≫[≪localsrcvar_n≫]
         (( and ≪OP_name_n≫[≪param_i≫ ,.., ≪param_j≫]))?]
}
```

I.6.4 TM4: Unconditional non-local transformation phase

TEMPLATE ID: TM4
TEMPLATE NAME: Unconditional non-local transformation phase.
PURPOSE: For defining non-local target elements that does not require any condition.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
pred ≪refine_phase_name≫
   (≪localtrgvar_1≫:≪LocalTrgElmt_1≫ ,..,
   ≪localtrgvar_n≫:≪LocalTrgElmt_n≫,
   ≪nonlocaltrgvar_1≫:≪NonLocalTrgElmt_1≫ ,..,
   ≪nonlocaltrgvar_n≫:≪NonLocalTrgElmt_n≫)
{
      ≪OP_name_1≫[≪param_i≫ ,.., ≪param_j≫]
      /*For subsequent mapping relations*/
      and ≪OP_name_n≫[≪param_i≫ ,.., ≪param_j≫]
}
```

I.6.5 TM5: Non-local transformation phase with condition

TEMPLATE ID: TM5
TEMPLATE NAME: Non-local transformation phase with condition.
PURPOSE: For defining non-local target elements that requires condition.
SOURCE CONDITION:
TARGET SPECIFICATION:

```
pred ≪refine_phase_name≫
   (≪localtrgvar_1≫:≪LocalTrgElmt_1≫ ,..,
   ≪localtrgvar_n≫:≪LocalTrgElmt_n≫,
   ≪nonlocaltrgvar_1≫:≪NonLocalTrgElmt_1≫ ,..,
   ≪nonlocaltrgvar_n≫:≪NonLocalTrgElmt_n≫)
{
   ≪ExpCond≫ implies
      (≪OP_name_1≫[≪param_i≫ ,.., ≪param_j≫]
      /*For subsequent mapping relations*/
      and ≪OP_name_n≫[≪param_i≫ ,.., ≪param_j≫]
         and Result = Success)
   else
   ((( Result = Fail | ≪else_phase_name≫ )))
}
```

I.6.6 TM6: Assignment operation

TEMPLATE ID: TM6
TEMPLATE NAME: Assignment operation
PURPOSE: For defining assignment operation of elements in transformation
SOURCE CONDITION:
TARGET SPECIFICATION:

```
pred ≪OP_phase_name≫
   (≪param_i≫:  ≪paramType_i≫ ,.., ≪param_j≫:  ≪paramType_j≫) {
   /*For each assignment*/
   ≪/*≪assignement task≫*/≫
      /*For each task*/
      ≪param_i≫.≪feature≫ = ≪param_j≫.≪feature≫
   /*For function operation*/
      ≪param_i≫.≪feature≫ = ≪functionName≫[≪paramType_i≫ ,..,
         ≪param_j≫]
}
```

I.7 Instance Model: Defining Transformation Instance

The following templates instantiate transformation instance snapshots. It extends the Defining Model Instance templates (Section I.5)

I.7.1 IM4: Transformation instance mapping relation

TEMPLATE ID: IM4
TEMPLATE NAME: Transformation instance mapping relation.
PURPOSE: For defining transformation instance mapping relation.
SOURCE CONDITION:

TARGET SPECIFICATION:

```
fact Transform{
   /*For each participating phase.  Provide phase parameters*/
   ≪phase_name≫[≪ElmtInsName1≫ ,.., ≪ElmtInsNamen≫]
}
```

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