MODEL TRANSFORMATION BY DEMONSTRATION: A USER-CENTRIC APPROACH TO SUPPORT MODEL EVOLUTION

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ABSTRACT

Domain-Specific Modeling (DSM) is an innovative software development methodology that raises the specification of software to graphical models at a high-level of abstraction using domain concepts available in a language that is defined by a metamodel. Using DSM, models become first-class entities in the construction of software systems, and therefore model evolution becomes as important as code evolution in traditional software development.

Model transformation is a core technology of DSM that converts a source model to a target model, which plays a significant role in supporting model evolution activities. A common approach toward model transformation is to write transformation rules in a specialized model transformation language. Although such languages provide powerful capabilities to automate model transformations, their usage may present challenges to those who are unfamiliar with a specific model transformation language or a particular metamodel definition. In addition, in the collaborative modeling situations when model evolution knowledge needs to be exchanged and reused, most model transformation languages do not support sharing of existing model transformation rules across different editors among different users, so reusing the existing rules to support model evolution activities becomes difficult. Finally, most transformation languages do not have an associated debugger for users to track errors, or the debugger is not at the appropriate level of abstraction for end-users.

This dissertation focuses on three aspects related to supporting model evolution activities: 1) simplify the creation of model transformations in a demonstration-based approach by recording and analyzing the operational behavior exhibited by an end-user as they perform a transformation task manually; 2) improve model evolution knowledge sharing, exchange and reuse through tool support; and 3) enable an end-user centric approach to debug the execution of a model transformation. The overall goal of the research in this dissertation is to enable end-users to create their desired model evolution tasks without any knowledge of model transformation languages or metamodel definitions, share and reuse existing model evolution tasks, and check and trace errors in a user-friendly manner when performing model evolution tasks. Each of these objectives will be explained in detail in this dissertation, combined with case studies from different domains to illustrate how a user-centric approach can support common model evolution activities in practice.

DEDICATION

To Mom and Dad,

for their love and sacrifice.

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LIST OF ABBREVIATIONS

ADC	Analog-to-Digital Converter
AOM	Aspect-Oriented Modeling
AOP	Aspect-Oriented Programming
API	Application Programming Interface
ATL	Atlas Transformation Language
C2M2L	Cloud Computing Management Modeling Language
CASE	Computer-Aided Software Engineering
CDL	Contract Description Language
COM	Component Object Model
CORBA	Common Object Request Broker Architecture
CRUD	Create/Read/Update/Delete
C-SAW	Constraint-Specification Weaver
CWM	Common Warehouse Metamodel
DRE	Distributed Real-time and Embedded
DSM	Domain-Specific Modeling
DSL	Domain-Specific Language
DSML	Domain-Specific Modeling Language
ECU	Electronic Control Unit
ECL	Embedded Constraint Language

EMF	Eclipse Modeling Framework
EmFuncML	Embedded Function Modeling Language
EMP	Eclipse Modeling Project
EQAL	Event Quality of Service Aspect Language
ESML	Embedded Systems Modeling Language
EUP	End-User Programming
FSM	Finite State Machine
GEMS	Generic Eclipse Modeling System
GEF	Graphical Editing Framework
GME	Generic Modeling Environment
GMF	Graphical Modeling Framework
GPL	General-purpose Programming Language
GREAT	Graph Rewrite And Transformation
GUI	Graphical User Interface
HTML	Hypertext Markup Language
J2EE	Java Platform Enterprise Edition
JSF	Java Server Faces
KM3	Kernel Meta-Meta Model
LHS	Left-Hand Side
Live-MTBD	Live-Model Transformation By Demonstration
M2T	Model-to-Text
MDA	Model-Driven Architecture
MDE	Model-Driven Engineering

MOF	Meta-Object Facility
MTBD	Model Transformation By Demonstration
MTBE	Model Transformation By Example
MTL	Model Transformation Language
MT-Scribe	Model Transformation-Scribe
NAC	Negative Application Condition
OCL	Object Constraint Language
OMG	Object Management Group
OSM	Operation Specification Model
PBE	Programming By Example
PIM	Platform-Independent Model
QoS	Quality of Service
QoSAML	QoS Adpation Modeling Language
QVT	Query View Transformations
RHS	Right-Hand Side
RMI	Remote Method Invocation
SLOC	Source Lines Of Code
SRN	Stochastic Reward Net
SRNML	Stochastic Reward Net Modeling Language
TGG	Triple Graphical Grammar
TN	Transformation Net
TTSML	Time-Triggered System Modeling Language
UAV	Unmanned Aerial Vehicle

UML	Unified Modeling Language
VE	Visual Editor
VPL	Visual Programming Language
WCET	Worst Case Execution Time
WYSIWYG	What You See Is What You Get
XML	Extensible Markup Language
XMI	XML Metadata Interchange
XSLT	Extensible Stylesheet Language

CHAPTER 1

INTRODUCTION

Software development is an inherently challenging process, resulting from both essential and accidental complexities [Brooks, 1987]. The essential complexities of software are reflected in the difficulty of understanding the problem, designing and testing the conceptual construct, as well as the characteristics of software, such as invisibility, changeability and conformity. The accidental complexities represent the challenges on the concrete software implementation and testing processes. In the past several decades, much effort has been made to help software developers and engineers address these complexities, in order to increase the productivity, simplicity and reliability of software development.

Among all the effort, one of the most frequently applied and effective approaches is to raise the level of programming language abstraction by capturing only the details relevant to the current computing perspective, but hiding the underlying implementation information [Lenz and Wienands, 2006]. As shown in Figure 1.1, from machine code to assembly language, high-level and object-oriented programming languages, although programmers generally lose fine-grained control of the underlying machine as abstraction increases (e.g., direct memory address control is not feasible using Java while it can be implemented using C effectively), they are enabled to better focus on the specific problems they want to solve, while being isolated from irrelevant low-level implementation details [Greenfield and Short, 2004].

With the complexity and scale of software systems increasing dramatically [Lenz and Wienands, 2006], a new and higher level of abstraction is needed to continue alleviating the difficulties encountered in the complex software development process. A notable and promising approach is Model-Driven Engineering (MDE) [Schmidt, 2006], which decouples the description of the essential characteristics of a problem from the details of a specific solution space (e.g., middleware, programming languages).

MDE promotes the general idea of using models at different levels of abstraction to define systems, and automate the transformation process between different levels of models and the final implementation code. As a concrete and mainstream MDE methodology, Domain-Specific Modeling (DSM) [Gray et al., 2007] uses a Domain-Specific Modeling Language (DSML) [Lédeczi et al., 2001] to declaratively define a software system using specific domain concepts, and automatically generate the desired software artifacts (e.g., programming code, simulation script, XML deployment description) by model transformation engines and code generators. Using DSM, software developers and engineers, or even end-users (e.g., domain experts), are enabled to program in terms of their unique intentions and understanding of a specific problem domain, rather than focusing on solutions that are intertwined with the underlying computing environment [Schmidt, 2006].

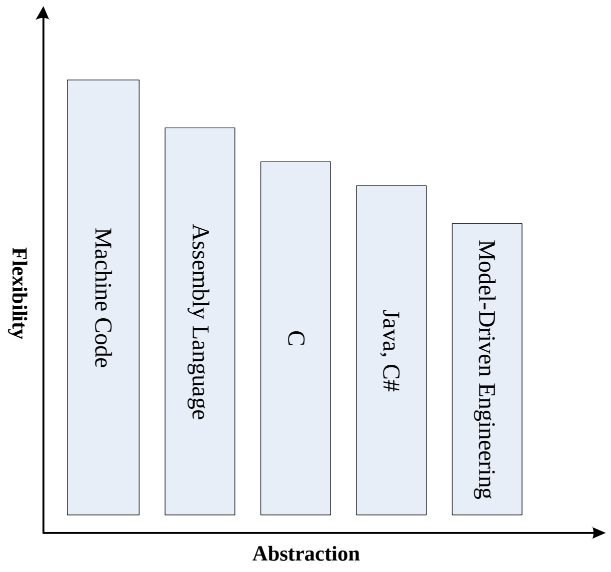


Figure 1.1 – Flexibility versus level of abstraction of programming technologies

1.1 Domain-Specific Modeling (DSM)

DSM reaches a new level of abstraction by focusing on the specific problem domains using DSMLs so that the design space is narrowed down and the associated complexities are reduced. A problem domain can be any of the areas that require software solutions, such as automobile, telecommunication, health care, industry, robotics, energy or finance. It can also vertically include the different aspects of system development, such as user interface, functional properties, non-functional properties, user work flow, or data persistency. Additionally, any of these domains can be divided into smaller problems or tasks, which can be considered as a separate sub-domain.

A DSML is designed for a single problem domain, which only contains the concepts related with the specific problems to solve, rather than the underlying implementation details. The metamodel [Atkinson and Kuhne, 2003] is used to specify the entities, associations and constraints for the DSML, having a similar role as a grammar to specify the syntax for a programming language. The metamodel can be used to generate a modeling environment, in which users are enabled to build concrete models to represent the system for the application domain. The models built by users must conform to the definition of the metamodel. Figure 1.2 shows a DSML called TTSML (Time-Triggered System Modeling Language) [Sun et al., 2011-c] used to specify the data communication system used inside electric automobiles. It provides the basic modeling elements such as *ECU (Electronic Control Unit)*, *Channel*, *Controller*, *Functional Unit*, *Timing Requirement*. Users of TTSML can specify the desired system by constructing the model using these concepts directly. For example, as shown in Figure 1.2, three *ECUs* (i.e., *SimulatorPC*, *DrvierAssistance*, *DriverInferfaceAndSensor*) are connected to both *Channel A* and *Channel B*; different function units (e.g., *BrakeAssistant*, *ReadGasPedalPosition*) are running on these *ECUs* and communicate with each other based on different timing requirements (e.g., *Safety Critical*, *LowSpeedSensor*). The low-level implementation details about how to configure the *ECUs* with the APIs provided by the manufacturer, how to implement the correct data transmission protocol, or how to make the correct function calls to ensure the timing requirements are hidden to users. In other words, users only need to think about the concrete problem space – what system functionalities are needed, what system performance properties are desired, rather than the solution space (i.e., how to implement the actual system).

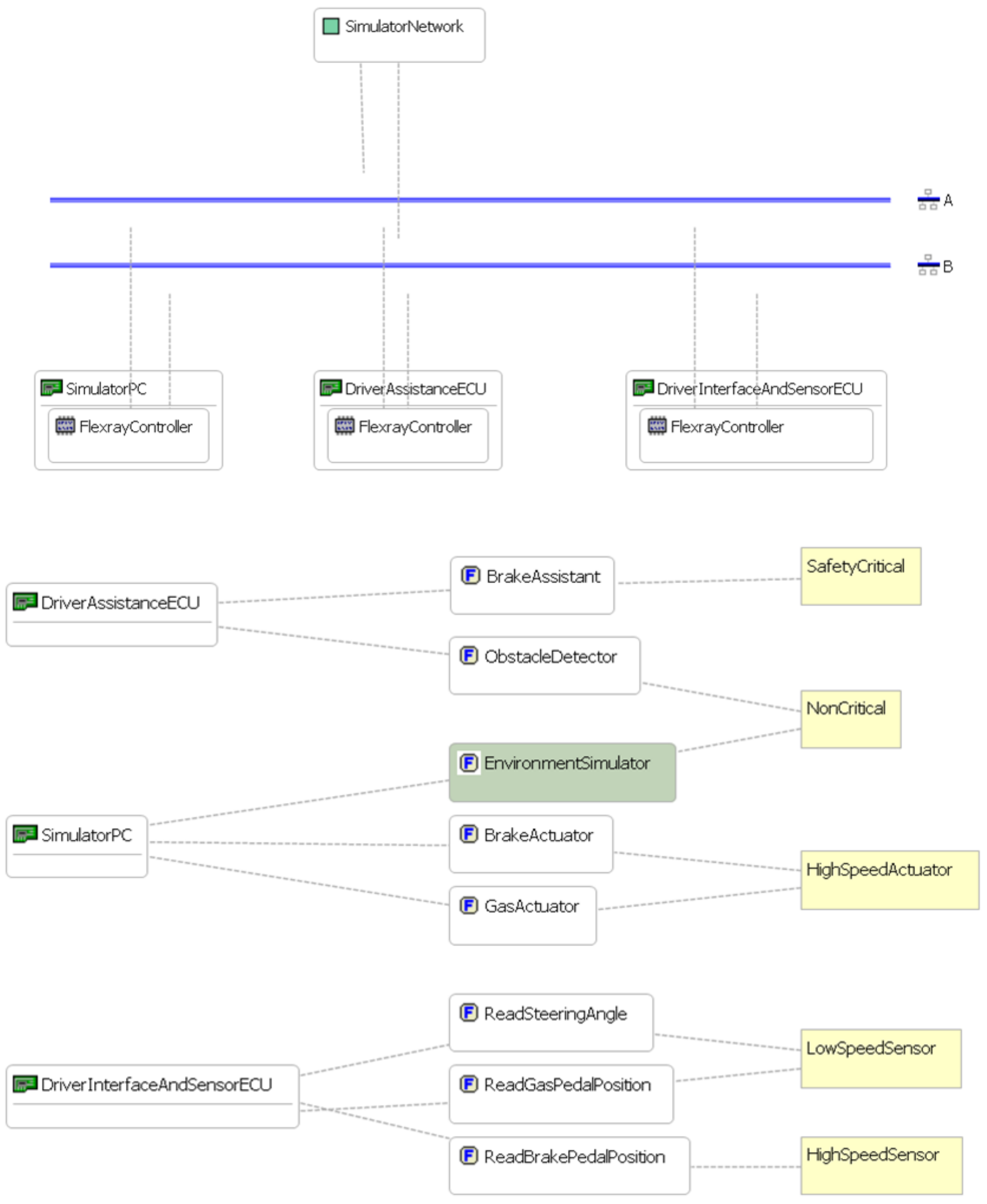


Figure 1.2 – Excerpts of models specified using TTSML

The solution space is handled by code generators associated with the DSML. A code generator [Kelly and Tolvanen, 2008] takes models built by users as input, and produces low-level implementation artifacts as output. Multiple code generators or model interpreters might exist for a single DSML, which can be used to generate the code for different platforms or software artifacts. Taking TTSML as an example, two code generators are available to generate the implementation code for two hardware platforms: Freescale S12 Microcontroller [Freescale, 2011] and Eberspächer FlexRayCard [Eberspächer, 2011]; another generator is used to generate the XML configuration for the protocol implementation. In some other DSM applications, code generators have also been applied to produce HTML files, property files, graphical charts and tables, or even software documents [Kelly and Tolvanen, 2008], as shown in Figure 1.3.

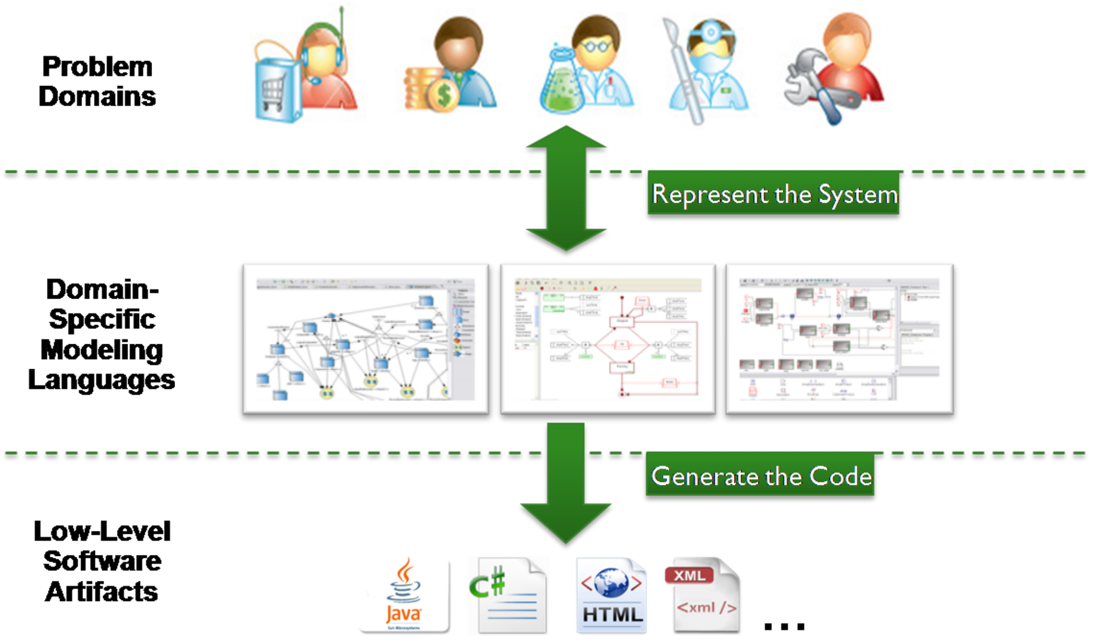


Figure 1.3 – Overview of DSM methodology

The main benefit of DSM comes from its ability to describe the properties of a system at a high-level of abstraction and in a platform-independent notation, and protect key intellectual assets from technology obsolescence, resulting in less effort and fewer low-level details to specify a given system. Compared with the traditional usage of software models and code generation techniques, DSM distinguishes itself by pursuing automated code generation without further modifications, so that users are completely isolated from the low-level implementation details. Otherwise, DSM will not raise the level of abstraction for domain experts. UML [UML, 2011] models, for instance, are often used either as a design blueprint for software developers to write code, or as a basis to generate the initial code framework (e.g., class definitions and method signatures) with the inner implementation part to be filled manually.

Furthermore, by raising the level of abstraction, DSM helps to improve end-user programming [Burnett et al., 2004], and therefore reduces the chance of software failures due to miscommunications between software engineers and end-users. In the traditional software development process, a knowledge and expertise gap between software developers and different domain experts exists, the negative consequence being that developers who are skilled at programming may not fully and correctly understand the user's requirements, while the users who know their problem domain very well may have no idea about how to build the desired software system. However, in DSM, because the system can be represented by high-level and domain-specific models rather than general-purpose programming languages, end-users who have no knowledge or experience in programming are enabled to participate in the software system development process, making more accurate and valuable decisions in software design, implementation, and maintenance [Kelly and Tolvanen, 2008].

1.2 Model Evolution in DSM

Software evolution is an inevitable and essential activity in software development. As noted by Lehman, "Software that is being used must be continually adapted or it becomes progressively less satisfactory" [Lehman, 1978]. In the context of DSM, models replace source code as the first-class entities in the software development process and represent the initial point for the generation of low-level artifacts. Therefore, if a system needs to evolve and adapt to new requirements, instead of changing source code directly, the models representing the system should be evolved first according to the need, which then leads to a re-generation of the low-level code or other artifacts [Lin et al., 2007].

Figure 1.4 shows a model evolution scenario. A metamodel has been defined for a problem domain, and $\texttt{Model}_0$ is the initial model that conforms to the metamodel, which generates the first version of the source code ($\texttt{Code}_0$) for the system. As the new requirements come from the problem domain, $\texttt{Model}_0$ has to be changed and evolved to new versions ($\texttt{Model}_{1,}$ $\texttt{Model}_{2,}$ … $\texttt{Model}_{n,}$) to adapt the new requirements, so that the corresponding changes can be reflected in $\texttt{Code}_1$, $\texttt{Code}_2$, … $\texttt{Code}_n$ by triggering the code generation process from each new model. This dissertation research focuses on addressing the problems and challenges associated with implementing the model evolution process, while involving end-user participation.

A number of scenarios can trigger the evolution of models, such as adding / removing / updating a certain functionality for an existing system [Greenfield and Short, 2004], weaving a new aspect (e.g., logging, constraint checking) into the base system [Elrad et al., 2002; Gray et al., 2006], scaling the system from a base state to a complex state [Lin et al., 2008], and optimizing the internal structure (e.g., refactoring) [France et al., 2003]. Clearly, model evolution is as essential as traditional code evolution in a software development process. In fact, some other model evolution issues also exist in the context of DSM; for instance, evolving a model to a different domain [Jouault and

Kurtev, 2005], metamodel evolution [Sprinkle, 2003; Narayanan et al., 2009], model interpreter evolution [Zhang et al., 2004], and model evolution by changing the corresponding code (i.e., reverse engineering) [Rugaber and Stirewalt, 2004]. However, the research described in this dissertation particularly focuses on model evolution from one state to another and from one version to another version within the same metamodel. The typical evolution activities in this category are model refactoring [Zhang et al., 2005], model scalability [Lin et al., 2008], aspect-oriented modeling [Zhang et al., 2007], model management [Deridder et al., 2008], and model layout configuration [Sun et al., 2011-b].

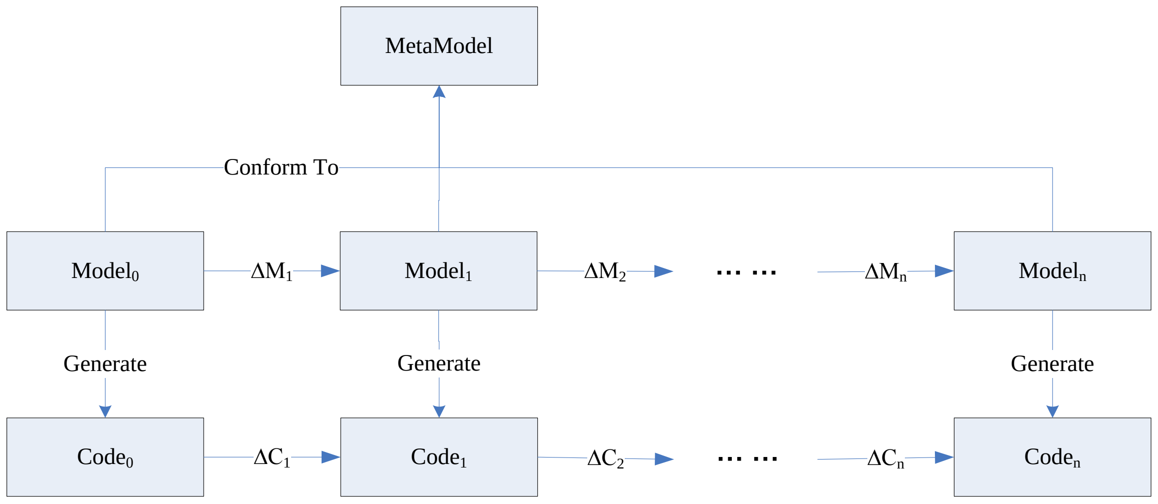


Figure 1.4 – Model evolution in DSM

1.3 Model Transformation and Model Transformation Languages (MTLs)

Model transformation [Sendall and Kozaczynski, 2003] is a core technology in DSM. It receives a source model that conforms to a given source metamodel as input, and produces as output another model conforming to a given target metamodel. When the source and target metamodels are different (i.e., between two different domains), the transformation is called exogenous, as shown in Figure 1.5a (e.g., a UML class diagram model is transformed to a relational data model [Shah and Slaughter, 2003]). If the source and target metamodels are identical, the transformation is called endogenous, as shown in Figure 1.5b (e.g., a UML class diagram model is transformed from one state to another state through a "Pull Up Method" refactoring process [Fowler, 1999]).

Because the essence of model transformation is to transform and change a model, there is a direct connection between model transformation and model evolution. Actually, model evolution tasks as discussed in this dissertation can be regarded as a model transformation process, or more precisely, an endogenous model transformation process, because both the source model (e.g., `Model`$_0$ in Figure 1.4) and the target model (e.g., `Model`$_1$ in Figure 1.4) in a model evolution conform to the same metamodel.

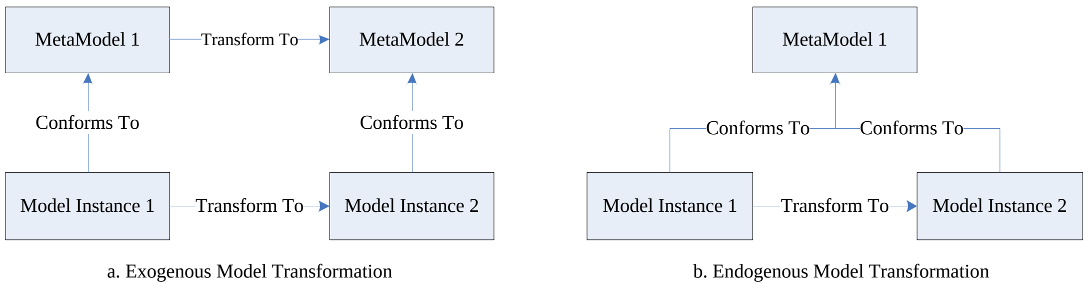


Figure 1.5 – Two types of model transformation – exogenous and endogenous

The benefit of connecting model evolution with model transformation is that a number of model transformation tools and technologies can be utilized to support model evolution tasks. The traditional approach to realize a model transformation is to use an executable model transformation language. A Model Transformation Language (MTL)

[Sendall and Kozaczynski, 2003] is usually a Domain-Specific Language (DSL) [Mernik et al., 2005; Sun et al., 2008] particularly used for model transformation tasks. A set of transformation rules can be defined in a MTL to specify how a source model should be transformed into a target model. More specifically, the rules define how the source model should be mapped to the target model, and the scope where the rules can be applied. These rules are often defined at the metamodel level rather than to a specific model instance, so that they are capable of carrying out the desired transformation process automatically on any model that conforms to the same metamodel.

MTLs can be either graphical or textual, and most of them are at a higher level of abstraction than General-purpose Programming Languages (GPLs), such as Java or C++. MTLs support either an imperative, declarative, or hybrid approach to specify a transformation task. Some popular MTLs in this category are QVT [QVT, 2010], ATL [Jouault et al., 2008], and ECL [Gray, 2002]. Using MTLs, automated model evolution processes can be implemented by specifying and executing the model transformation rules on how to evolve a model from one state to another state, or from one configuration to another.

1.4 Key Challenges in Supporting Model Evolution

As discussed in the previous sections, model evolution is an essential and inevitable activity in DSM. However, the tools to support model evolution have not been well developed. In current DSM practice, model evolution tasks are mainly implemented and automated using MTLs. Although MTLs are powerful and expressive to handle various kinds of model evolution tasks, it is not always the perfect solution due to some challenges related to end-user friendliness, the mechanism of exchanging and reusing model evolution knowledge, and debugging support. The following subsections outline the challenges that this dissertation focuses on with respect to current model evolution practice.

1.4.1 The Difficulty of Learning and Using MTLs for End-Users

Although a number of powerful MTLs have been developed to support various types of model evolution tasks in different modeling tools and platforms, learning and using these languages is by no means an easy task, particularly for general end-users including domain experts and non-programmers who are not familiar with MTLs or GPLs. The emphasis on enabling this group of users to implement model evolution tasks results from the fact that end-users can participate in the software development process using DSM, and in many cases, they know the exact model evolution tasks in need. However, this group of users might be prevented from contributing to these tasks from which they have much domain experience due to the difficulty of learning and using MTLs as described throughout this subsection.

The steep learning curve for MTL adoption. Most MTLs are high-level languages and specific to model transformation tasks, but a steep learning curve is still inevitable due to the complexity of learning the syntax, semantics, special features or concepts, associated libraries, and the editing or execution environment of a MTL. This challenge is particularly true for those who have never had MTL or programming language training.

Moreover, in many cases, in order to correctly use a MTL, users are required to learn not only its basic usage of how to transform models, but also some additional knowledge that is not directly related with model transformations. For example, ECL integrates some general programming concepts, such as variable declarations (e.g., `declare node : object;`), and branch statements (e.g., `if (idx<=max) then`); ATL applies Object Constraint Language (OCL) [OCL, 2010] expressions to give specific constraints on the precondition of model transformations. Learning these may not be very challenging to a computer scientist, a software developer or a model engineer, but it is definitely a hindering barrier to general end-users like domain experts and non-programmers.

In addition, the diversity of MTLs introduces a number of different model transformation design approaches, bringing about a challenge toward achieving a uniform MTL learning process. For instance, with declarative MTLs (e.g., ATL), users can focus on the mapping relationships between the source and target models, ignoring the details underlying those mappings; but many powerful MTLs (e.g., ECL) also support imperative mechanisms, which means that users need to think about how a model should be changed and transformed to the target desired state; some other MTLs (e.g., EMF Tiger [Biermann et al., 2006; EMF Tiger, 2010], GReAT [Agrawal, 03]) are based on graph theory, such as graph matching and graph rewriting, and users are expected to think of model transformation processes in terms of graphs. Thus, even being familiar with a certain MTL cannot guarantee a gradual adoption curve for learning a second MTL.

The difficulty of understanding metamodels. A metamodel, as explained in Section 1.1, serves as the abstract syntax of a DSML, and precisely specifies how the models should be constructed in a particular domain. Using most MTLs, the model transformation rules are often defined at the metamodel level rather than the concrete model instance level. However, developing a deep and clear understanding of a metamodel is challenging, especially for large and complex domains.

The need to define transformation rules at the metamodel level results from the gap existing between the way a user recognizes models and the way a computer does [Wimmer et al., 2007]. Typically, users reason on models that represent real-world examples shown by concrete syntax and mappings between semantically corresponding model elements according to the specific transformation scenarios. However, this way of thinking is not appropriate for precisely defining model transformations with currently available MTLs, because instead of writing transformation rules working for one specific model example, users expect the rules to be generic so that they can be reused on other models for the same transformation purpose. Currently, the most effective way to realize this goal is to define the generic rules in terms of metamodel definitions for the models to be transformed.

Understanding metamodels becomes even more challenging when some concepts in a particular domain are hidden in the metamodel definition and difficult to unveil [Kappel, 2006]. This is because not all concepts in a domain can be represented as first-class constructs in the metamodel. Some domain concepts may be hidden in attributes or association ends in the metamodels. The consequence is that users are required to correctly uncover these hidden concepts and use them in the transformation rules that they write.

Thus, if model transformations can be specified and implemented without explicitly understanding the full details of a metamodel, users could avoid the extra burden of understanding the complex and abstract metamodel definitions.

1.4.2 Limited Tool Support to Exchange and Reuse Model Evolution Knowledge

Similar to traditional software development, specifying a complex system using DSM usually requires collaboration [Redmiles et al., 2004]. A DSML may be used to describe different aspects of a system (e.g., a DSML designed to model embedded systems [Sun et al., 2011-a] enables users to specify the system from the perspectives of both the hardware configuration and the software functional logic), and users might come from different areas with different expertise. Even for the same perspective and the same area, users may have different levels of experience and knowledge (e.g., a senior engineer is more likely to produce higher quality models or provide better modeling solutions in most cases than a junior engineer). When it comes to model evolution tasks in a diverse and collaborative modeling environment, it is essential to enable different users to share, exchange their knowledge and experience, as well as enable the reuse of the knowledge (e.g., a software engineer may need to reuse the hardware engineer's knowledge about evolving a part of the hardware configuration; a junior engineer may need the senior engineer's experience to validate models and fix errors). Unfortunately, tool support in this area is very limited in the current practice.

When using MTLs to implement model evolution tasks, each set of the executable model transformation rules can be regarded as the persistent knowledge for a certain evolution task. Executing the rules on different models actually realizes knowledge reuse. However, for most MTL tools, there is no mechanism to load and execute the transformation rules specified by different users at editing time. For instance, ATL provides an online collection of the commonly used model transformation scenarios

(ATL transformation zoo [ATL Transformation Zoo, 2011]), where users can download the rules and execute them in their own environments. Obviously, this is by no means the desired approach to exchange and reuse knowledge, because a large number of model evolution tasks can be created during the editing time, which at the same time, are needed to be shared and reused by different users. Using a static online collection cannot satisfy the need to acquire the correct evolution knowledge promptly.

Moreover, the presence of reusable model evolution knowledge does not guarantee that it can be reused correctly by users who need them. On one hand, users might not know that certain model evolution tasks they need to accomplish have already been created and shared, so that they might end up manually implementing the task again. On the other hand, even if users know the presence of certain model evolution knowledge that can be potentially reused, how to determine whether it is the right knowledge to reuse or whether it is applicable to their own scenarios is another challenging problem. In the current practice, users may decide to reuse an available model evolution task either by reading and understanding the textual description about the evolution rules, or by directly executing and comparing the results. The negative consequence is that users are very likely to reuse the wrong knowledge due to the misunderstanding of an inaccurate textual description, destroy the current model or import accidental errors by executing the wrong evolution rules. Thus, enabling users to identify the correct and available knowledge to reuse in a timely manner plays an important role in supporting model evolution knowledge exchange and reuse.

1.4.3 The Lack of an End-User Debugging Facility for MTLs

Because model transformation specifications are written by humans and susceptible to errors, the need for testing and debugging mechanisms for MTLs are as important as the similar need with general-purpose programming languages. Although testing offers some confidence about whether the model is in the desired state after being transformed, debugging helps users to examine the transformation process and track potential errors.

Recently, some algorithms and tools have been developed to support model transformation testing by model comparison, which have demonstrated initial results in automating the testing process [Lin et al., 2005; Lin et al., 2007]. However, model transformation debugging is still a weak area with limited results. Most modeling tools or platforms only provide an editing and execution environment for a supported MTL without enabling users to track and monitor the execution of transformation rules and the result. When errors occur, the most common way to fix the error is to check the model after a transformation and locate the erroneous model elements, attributes or connections, and then go back to the corresponding transformation rules to check the potential errors. This process will iterate until the model is transformed to the desired state. Because most MTLs do not support common constructs available in GPLs, the debugging process becomes more challenging if a debugger is not present in the modeling tool or execution engine.

Without the assistance of a debugger, error recovery becomes tedious and error-prone, particularly when the model being transformed is large and a lot of complex transformation rules are involved in the model evolution task. Although some MTL tools already have associated debuggers [Jouault et al., 2008; Balasubramanian et al., 2006-a], the debuggers work by tracking the MTL rules or codes, which are at the same level of abstraction as the MTL and therefore not appropriate for some categories of end-users.

1.5 Research Goals and Overview

To address the difficulty of supporting model evolution using the traditional model transformation approaches that rely on MTLs, and enable a wider range of end-users to participate in model evolution activities through implementing model evolution tasks, exchanging and reusing model evolution knowledge, and debugging model evolution execution process, the research in this dissertation provides a user-centric model transformation approach to implement model evolution tasks with tools to share and reuse evolution knowledge. Furthermore, this research considers the transformation debugging issue to assist in determining the correctness and tracking of model transformation errors. Figure 1.6 shows an integrated view of this research. The overview of the research is described in the following sections.

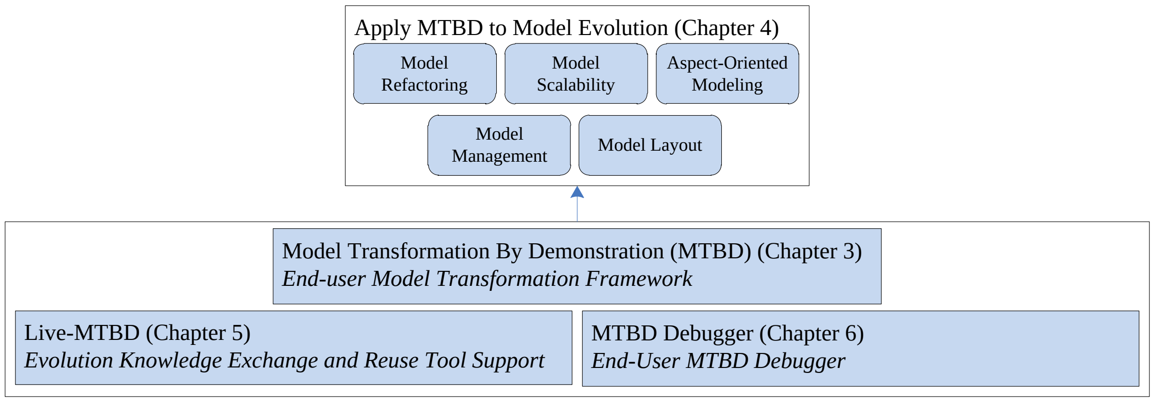

Apply MTBD to Model Evolution (Chapter 4)
Model Refactoring
Model Scalability
Aspect-Oriented Modeling
Model Management
Model Layout
Model Transformation By Demonstration (MTBD) (Chapter 3)
End-user Model Transformation Framework
Live-MTBD (Chapter 5)
Evolution Knowledge Exchange and Reuse Tool Support
MTBD Debugger (Chapter 6)
End-User MTBD Debugger

Figure 1.6 – Research overview

1.5.1 Model Transformation By Demonstration (MTBD) to Simplify Model Transformation

To address the challenges of learning and using MTLs to support model evolution, a new endogenous model transformation framework has been designed and implemented, called Model Transformation By Demonstration (MTBD) [Sun et al., 2009-a], which enables end-users to specify a model transformation by directly performing editing operations on concrete examples (i.e., to give a demonstration), combined with user refinement and automatic inference processes. After a user demonstration, a model transformation pattern is generated as the persistent specification of a model transformation task. MTBD also includes its own transformation pattern execution engine, which executes the inferred transformation by pattern matching and automated operation execution. This framework is different from the traditional MTLs in that no language is involved in the process and the specification of the rules is realized at the model instance level rather than the metamodel level, so that users can be isolated from the language learning curve and the complex metamodel definitions. In other words, the level of abstraction to implement model transformations is raised, so that the end-users (e.g., domain experts and non-programmers) are able to implement the desired model evolution tasks through demonstration without being exposed to the low-level implementation details.

1.5.2 Live-MTBD to Improve Model Evolution Knowledge Exchange and Reuse

The second contribution of this research includes “Live” feature extensions to MTBD (Live-MTBD), which improves the user experience when demonstrating a transformation, and more importantly, supports model evolution knowledge sharing, exchange and reuse. The toolset Live-MTBD contains three components: 1) *Live Demonstration*, provides a more general demonstration environment that allows users to specify editing activities based on their editing history, with the purpose being to encourage users to create more transformation patterns; 2) in order to improve the sharing of editing activity knowledge among different users, *Live Sharing* – a centralized model transformation pattern repository has been built so that transformation patterns can be reused across different editors; 3) a live model transformation matching engine – *Live Matching* has been developed to automatically match the saved transformation patterns at modeling time, and provides editing suggestions and guidance to users during the editing process. Live-MTBD features cooperate seamlessly with MTBD to offer an end-user friendly, collaborative, and intelligent model evolution environment.

1.5.3 MTBD Debugger to Enable End-User Model Transformation Debugging

To support error tracking and execution monitoring, an MTBD debugger associated with the MTBD execution engine has been developed. The debugging tool can offer support for isolating the cause of a transformation error, by enabling users to trace all the matched locations in the model in an execution of a transformation pattern, and step through individual actions of the transformation to display the model data intuitively within the host modeling environment. Users can determine the correctness of the precondition of the inferred pattern from the matching locations, and the correctness of the actions of the inferred pattern by watching each of the execution steps. In addition, to improve end-user friendliness, the MTBD debugger hides the low-level execution information or metamodel definitions and focuses only on information at the model instance level.

1.5.4 Applications of the Research to Support Model Evolution in Practice

The primary purpose of this research is to support various model evolution tasks using a new model transformation approach. Therefore, the power and functionality of the approach should be decided and evaluated by focusing on how it can fulfill the diverse needs of model evolution in practice. The MTBD approach should be applicable to the core types of model evolution tasks, such as model refactoring, model scalability, aspect-oriented modeling, model management, and model layout configuration. Thus, the identification of the special requirements in each type of task and the investigation on how to apply MTBD to these practical applications is another key contribution in this research, and demonstrated by various case studies throughout this dissertation.

1.6 The Structure of the Thesis

This chapter has summarized a subset of the research on model evolution in the context of DSM and the current challenges that exist to support model evolution activities. Research goals that address these problems have been outlined. Chapter 2 describes background information related to the research of this dissertation.

Chapter 3 presents the MTBD model transformation approach, including the description about the main steps and implementation details of the approach and the formal specification of the MTBD functionality. Related work is discussed to highlight the unique features and contributions of MTBD.

Case studies are presented in Chapter 4 to show how MTBD supports various model evolution tasks. In addition, to demonstrate the benefits of this approach, experimental evaluation is discussed, including modeling artifacts, evaluation metrics and experimental results.

Chapter 5 details the live feature extensions of MTBD. The motivation of these features is explained, followed by illustrating its usage through a practical case study.

Chapter 6 describes the debugger for MTBD. This chapter presents the basic debugging features designed for MTBD, as well as how to apply these features to track potential errors. Case studies are also shown to further illustrate the idea.

Chapter 7 outlines future work of the research described in the previous chapters. Chapter 8 concludes the work of this dissertation and summarizes its contributions.

CHAPTER 2

BACKGROUND

This chapter provides background information relevant to the research of this dissertation. First, Model-Driven Engineering (MDE), representing the broad scope of this research, will be introduced, with a further discussion on Domain-Specific Modeling and model evolution. This chapter will also outline the key concepts, techniques and tools in MDE that have been applied in practice. Background information on model transformation and Model Transformation Languages (MTLs) will be given in the third section, which includes the categories of MTLs and a subset of popular languages being used. Finally, because the main contribution of this research focuses on providing an approach centered on end-user model evolution, relevant information about end-user programming will be discussed briefly.

2.1 Model-Driven Engineering (MDE)

The emergence of MDE was triggered by a consistent effort toward raising the level of abstraction in software development. Back in the 1980s when programming languages (e.g., C, Fortran) lacked many of the now common modularity concepts (e.g., objects) to develop increasingly complex software systems, computer-aided software engineering (CASE) [Fuggetta, 1993] was promoted as an approach to assist users in expressing their design decisions above the underlying solution space. CASE applied general-purpose graphical or textual representations to form programs that aimed at reducing the errors incurred using traditional programming languages (e.g., memory leaks and corruption when using C) as well as the development effort. However, CASE finally failed to exert a significant influence on software development, because on one hand, the general-purpose graphical representation used in CASE did not support many application domains effectively; on the other hand, CASE was not generally successful at handling the needs of complex systems development (e.g., concurrent computing is not supported by CASE). In addition, due to a lack of common middleware platforms, generating desired implementation code and integrating it with different platforms is challenging, which undermined the capability of CASE to support multiple platforms.

Since the 1990s, object-oriented programming languages (e.g., Java, C++) have provided more expressive language constructs, and have assisted developers in maintaining and reusing various software systems [Booch, 1997]. Despite a number of advantages, these languages have reached a complexity ceiling due to the fast growth of dependent platforms and middleware complexity, and the inability of expressing domain concepts effectively [Schmidt, 2006].

MDE has emerged as a promising approach to address platform complexity and the need to express domain concepts. Using DSMLs that are designed specifically for application domains, developers can work at a higher-level of abstraction than object-oriented programming languages. In DSM, transformation engines and generators handle the mapping of high-level models to the underlying implementation details, so that developers are fully isolated from the accidental complexities of the solution space. In the past several years, MDE has attracted considerable attention from both academia and industry. A number of concepts (e.g., metamodel [Atkinson and Kuhne, 2003], model transformation [Sendall and Kozaczynski, 2003]), standards (e.g., MDA [MDA, 2011], QVT [QVT, 2011]), tools (e.g., MetaCase+ [MetaCase+, 2011], GMF [GMF, 2011]), and related technologies (e.g., model version control [Lin et al., 2004]) have been created, which have enabled many successful case studies and applications in various areas, such as telephony, information management, bug tracking, stream data processing [Kurtev et al., 2006].

2.1.1 Model-Driven Architecture (MDA)

To better support MDE, the Object Management Group (OMG) launched Model-Driven Architecture (MDA) [MDA, 2011], providing a set of guidelines and specifications to encourage the use of models in software system design and implementation.

The MDA approach specifies a software system using a Platform-Independent Model (PIM), which can then be mapped and transformed to Platform-Specific Models (PSMs). The PIM is based on domain-specific languages for the application domain, but the PSMs can be specified using either a domain-specific or general-purpose language. The OMG provides only the standards and specifications for the basic approach instead of detailed implementations. Some of the standards related with MDA models are listed in the following paragraphs:

Unified Modeling Language (UML). UML is used to describe various types of models in MDA. Although UML was not originally designed for MDA, being the most widely used modeling language, it has become a standard general-purpose modeling language. UML contains a number of diagrams, constructs and views that can be used to represent various perspectives of a system. Thus, UML serves as a standard formalism in MDA for a wide range of application domains.

Meta-Object Facility (MOF). MOF [MOF, 2011] is a meta-metamodel that can be applied to define different metamodels. The definition of UML is based on MOF. Therefore, MOF makes it possible to extend UML or create any other potential languages needed in the future.

XML Metadata Interchange (XMI). XMI [XMI, 2011] defines a standard metadata interchange format for XML documents. This enables models to be shared and exchanged among different tools and platforms. XMI has already been applied as the interchange format for UML models, as well as a number of models built in other tools such as GME [Lédeczi et al., 2001] and EMF [Budinsky et al., 2004].

Common Warehouse Metamodel (CWM). CWM [CWM, 2011] provides interfaces that can be used to enable interchange of warehouse and business intelligence metadata between warehouse tools, warehouse platforms and warehouse metadata repositories. Mappings between two types of metamodels can be defined using CWM, making it possible to build the model transformations in the context of MOF.

In summary, UML, MOF, XMI, CWM and some other standards aim at handling different aspects of the MDA – the creation of models, the extension and definition of models, model interchange, and model transformations.

2.1.2 Domain-Specific Modeling Development Process

While MDA provides a set of standard guidelines to support the vision of MDE, DSM is a concrete MDE methodology that has been applied in a number of domains (e.g., automotive, robotics, mobile computing) successfully. From the example given in Section 1.1, it can be seen that DSM is often based on a graphical DSML designed for a specific problem domain, combined with code generators to produce implementation software artifacts.

In practice, a complete DSM development process follows an iterative process. Model engineers and domain experts need to work together to target the problem domain and understand the necessary domain concepts that will be included in the future DSML. Then, model engineers need to define the DSML precisely by defining the metamodel as well as the needed constraints for the domain. With the complete metamodel, the DSML environment can be generated automatically. In addition, code generators are built by model engineers and software engineers together to map the metamodel concepts to low-level implementation code. With the complete DSML environment and code generators, users can work in the editors to build various model instances when needed and trigger the code generation any time.

The time required to implement a DSM solution varies according to the complexity of each domain. It can take from a few weeks to months [Kelly and Tolvanen, 2008]. No matter what the development period is, the benefits of using DSM can often be seen immediately after users are enabled to create models and generate code [Kelly and Tolvanen, 2008].

2.1.3 Model Evolution in DSM

Model evolution issues in DSM are mainly triggered by two scenarios. First, the metamodel for a certain domain is not unchangeable, because the actual domain in practice evolves and users tend to request new concepts and elements to enhance the expressiveness and power of the DSML. In fact, even model engineers themselves occasionally create new ideas to refine or extend the DSML, when their understanding of a domain improves or when they receive feedback from users. Therefore, evolution of metamodels is inevitable.

When it comes to the model instance level, evolution occurs more frequently. Just like programmers need to change their programs in any phase of software development for different purposes, models are often evolved by users as well. Actually, one of the main advantages of using DSM is reflected in this evolution scenario. Because traditionally, programmers need to understand the source code and make necessary changes according to a new requirement. In the context of DSM, the same change can be realized by modifying models at a high level of abstraction with less effort and then re-generating the code into a new version automatically.

The metamodel evolution problem has been investigated widely [Sprinkle, 2003], but the importance of evolution at the model instance level should not be ignored, because it directly relates to the main benefit of using DSM, and it is targeted for end-users and their usage experience. This dissertation focuses on supporting the evolution problems at the model instance level.

2.2 Metamodeling and Tools

In the previous sections, most of the discussion on MDE and DSM focused on a high level description and background introduction. This section will first present the basic four-layer modeling architecture used in the MDE community, serving as a formal summary of MDE, followed by an introduction to tools that support the MDE and DSM ideas.

2.2.1 Four-Layer Modeling Architecture

The classical architecture of MDE has been defined using four different layers, as shown in Figure 2.1. The topmost layer (i.e., M3 or Meta-metamodel layer) is a core modeling language that conforms to itself, which can be applied to define other modeling languages for different domains (i.e., to define other metamodels). It forms the foundation for the whole MDE architecture. The common modeling languages at this layer are MOF, Ecore, and KM3 [Jouault and Bézivin, 2006]. The second layer is the metamodel layer (or M2). The models at this layer are defined using the modeling language at M3 and therefore are instances of the meta-metamodel. They are defined to precisely specify different application domains. Models at the M1 level will conform to the M2 metamodels. The M1 models represent what users create and manipulate the underlying real system. Each model is built based on a certain metamodel, conforming to all the syntax and static semantics constraints. In many cases, a single system can be specified by multiple models either under the same metamodel or different ones, for the purpose of modeling different components and perspectives. Finally, the real-world system is at the M0 layer, which is mapped and generated from models at M1. One important criterion to evaluate the mappings between M1 and M0 is that for questions about the real-world system at M0, it must be possible to retrieve the answers from models at M1. This is called the substitution principle [Kurtev et al., 2006].

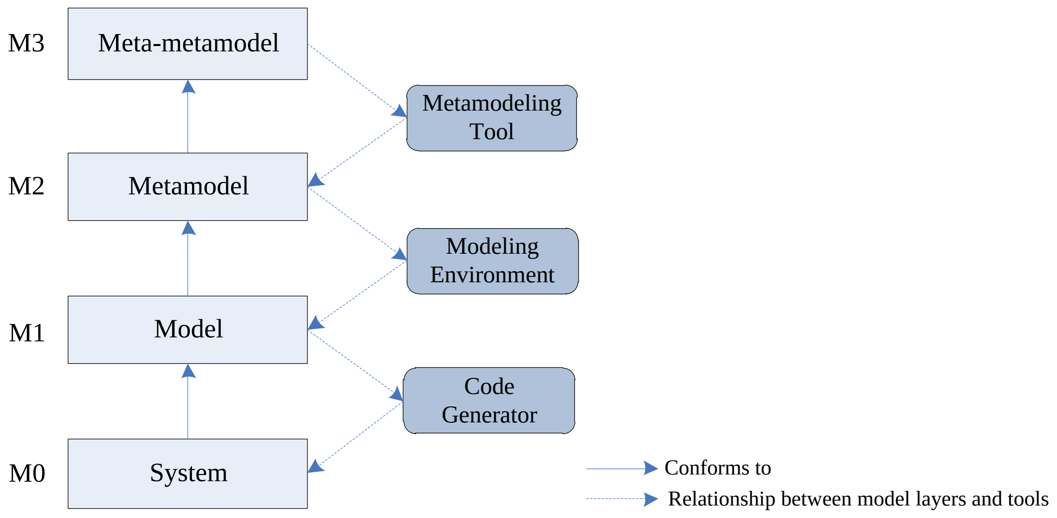


Figure 2.1 – Four layers modeling architecture and tool support

The creation of the final real-world system follows a top-down approach, starting from defining the models at higher layers, to deriving and generating artifacts in the lower layer. To ease the whole workflow, metamodeling tools have been implemented to support the specification of each layer and the transitions as shown in Figure 2.1. Generally speaking, a metamodeling tool has its own M3 modeling language embedded, and provides a metamodeling environment to enable users to create metamodels at the M2 layer. The modeling environment (i.e., end-user modeling editors) at M1 can often be automatically generated from the metamodel. The transition to the final M0 layer is carried out by code generators for each metamodel or model translators embedded in the modeling environment.

2.2.2 Metamodeling Tools

There are several key characteristics that most DSM tools possess, such as generative capabilities (i.e., to automatically generate the model editor or generator from the metamodel), change management (i.e., a runtime facility to support change notifications in models), model serialization (i.e., used to make models persistent), and plug-in capabilities (i.e., to provide an extension mechanism to enrich the functionality of the tool). Examples of metamodeling tools are described in the remainder of this subsection.

Generic Modeling Environment. The Generic Modeling Environment (GME) [Lédeczi et al., 2001] is a metamodeling tool to define DSMLs for different domains. The metamodeling language is based on the UML class diagram notation and OCL constraints. The metamodels specifying the domain concepts are used to automatically generate the target domain-specific environment. The generated domain-specific environment is then used to build domain models that are stored in a model database or in XML format.

GME has an extensible architecture that uses the Component Object Model (COM) [COM, 2011] for integration. External components can be written in any language that supports COM (e.g., C++, Visual Basic, C#). GME has many advanced features. A built-in constraint manager enforces all domain constraints during model building. GME supports multiple viewpoint modeling. It provides metamodel composition for reusing and combining existing modeling languages and language concepts [Karsai et al., 2004]. It also supports model libraries for reuse at the model level. All GME modeling languages provide type inheritance. Model visualization is customizable through decorator interfaces.

Graphical Modeling Framework. The Graphical Modeling Framework (GMF) [Moore et al., 2004; GMF, 2011] is a metamodeling tool based on Eclipse [Eclipse, 2011], which is a part of the Eclipse Modeling Project (EMP) [EMP, 2011]. It includes three key components to define a DSML: the domain model (i.e., the abstract syntax for the domain defined by Ecore [Budinsky et al., 2004]), the graphical definition model (i.e., the concrete syntax for the domain, such as the figures, nodes, and links used to display the models on the diagram), and the tooling definition model (i.e., to specify the palette, creation tools, and actions for the graphical elements in the editor). These three models can be integrated together and used to automatically generate a graphical modeling environment for a particular domain.

Because GMF is part of the EMP, most of the other existing technologies based on EMP can be applied to the models built in GMF. For instance, the M2M project (model to model transformation) [M2M, 2011] and M2T project (model to text transformation) [M2T, 2011] can assist the general model transformation or code generation tasks.

Generic Eclipse Modeling System. The Generic Eclipse Modeling System (GEMS) [GEMS, 2011; White et al., 2007-a] is an open source metamodeling tool in Eclipse. The goal of GEMS is to bridge the gap between the communities experienced with visual metamodeling tools, such as GME, and those built around the Eclipse modeling technologies, such as the Eclipse Modeling Framework (EMF) [Budinsky et al., 04] and GMF. Thus, domain experts that use GEMS can create an Eclipse-based graphical modeling tool without knowing the core components of EMP such as EMF, Graphical Editor Framework (GEF) [GEF, 2011] and GMF. In addition to automatically generating the modeling tool, GEMS also integrates a constraint checking mechanism to enable users to better reason about the models. The layout and appearance of models and the modeling tool can be controlled and customized through stylesheets. Moreover, GEMS provides a facility to capture the events occurring in the model editing process, which is very useful for the work in this dissertation. Extensions can be made to GEMS through the traditional Eclipse plug-in mechanism. The research in this dissertation will be implemented and evaluated in GEMS.

2.3 Model Transformation and Model Transformation Languages

Model transformation has been a core technology since the emergence of MDE and DSM [Sendall and Kozaczynski, 2003]. Examples of model transformation include code generation from models, model synchronization and mapping, model evolution, and reverse engineering. Although the use of a model transformation language has been introduced in Section 1.3 as the main approach to support model transformation processes, other alternatives are also available to implement the same tasks.

The first approach is to manipulate and access the internal structure of a model instance directly using an API provided by a host modeling tool, and encode the transformation procedures in a GPL. This approach is not feasible for end-users who do not have programming experience, because

GPLs lack the high-level abstractions that are needed by end-users to specify transformations. In addition, the power of a transformation is often restricted by the supported API within the modeling tool.

Many modeling tools support importing and exporting model instances in the form of XMI. It is also possible to use existing XML tools (e.g., XSLT [XSLT, 2011]) to perform model transformations outside of a modeling tool using XMI as an intermediate representation. Although XSLT can be used to transform models, it is tightly coupled to XML, requiring experience to define the transformations using concepts at a lower level of abstraction. In addition, transformations performed outside of a modeling tool exert a potential risk that the models being transformed cannot be imported or exported correctly with future versions of the tool.

By comparison, MTLs raise the level of abstraction by providing a set of language constructs specific to the model transformation tasks, playing an increasingly significant role in various model transformation activities.

2.3.1 Categories of Model Transformation Languages

Many MTLs have been invented with different features and characteristics [Mens and Gorp, 2005; Czarnecki and Helsen, 2006]. They can be classified into different categories. Understanding the categories is important for users to choose the most appropriate MTLs for different scenarios. Some main categories will be discussed in the following.

Exogenous versus endogenous. As introduced in Section 1.3, MTLs can be classified into exogenous MTLs and endogenous MTLs based on the difference between the source and target metamodels. Exogenous MTLs can be applied to handle tasks such as model migration (i.e., changing models conforming to the source version of a metamodel into models conforming to an evolved version of the metamodel) and model mapping (i.e., relating and transforming models between two different domains). Endogenous MTLs fit the problems of model refactoring (i.e., optimizing the internal structure of a model) and scalability (i.e., enlarging or reducing the model from a base state) very well. The key characteristic of exogenous MTLs is that the expressive language constructs to define the mappings between two metamodels are always available (e.g., from … to …), so that users can specify the relationships and associations between two domains. For endogenous MTLs, the most important part of the language is the ability to create/read/update/delete models (CRUD). Because endogenous model transformation tasks focus on changing the source model from one state to another state, or from one configuration to another, it is thus very essential to support various language constructs to perform the transformation with complex computation and rich constraints.

Textual versus graphical. Textual MTLs have their own grammar and keywords, and users can write the desired transformation rules in blocks or functions. A typical graphical MTL usually defines a transformation rule as a LHS (left-hand side) graph representing the source model and a RHS (right-hand side) graph representing the target model. Then, the engine automatically matches the LHS graph in a model and changes it into the desired RHS graph. Compared with textual MTLs, it is easier to define specific model patterns using graphs, leading to a simplification of the transformation rules in many cases.

Imperative versus declarative. The imperative style uses highly reusable granular language constructs that are capable of outlining the details of each model transformation step. For example, Aspect-Oriented Modeling (AOM) [Balasubramanian et al., 2006-b; Gray et al., 2001] is an important model transformation scenario, which enhances the modularity at the model level by allowing the separation of concerns (i.e., aspects) from the models representing the base system. To weave an aspect to a base model, a typical imperative MTL enables users to specify precisely where to locate the correct part of the base model that needs the aspect, and how exactly the aspect should be woven step-by-step. Using declarative MTLs, users focus on *what* to do instead of *how*. In other words, declarative MTLs express the logic of a transformation without describing its control flow. The typical example of using a declarative MTL is to specify what kind of elements in a source domain should be mapped to a target domain, without caring about how the mappings and translations are implemented. Although declarative MTLs have many advantages, they are not the best choice for all scenarios (e.g., transforming an attribute based on certain computations is hard to represent declaratively). However, the imperative style should not be discounted entirely. In fact, both styles are not mutually exclusive, and a number of MTLs include both mechanisms to specify transformation rules, offering the appropriate level of granularity as the situation demands.

2.3.2 Examples of MTLs

Three concrete examples of MTLs will be shown in this section, which cover the main categories mentioned in the previous section.

Atlas Transformation Language (ATL). ATL [Jouault et al., 2008] is a textual MTL, designed and implemented under the Eclipse Model-to-Model transformation (M2M) project [M2M, 2011], conforming to the proposed standard by OMG - the Query/View/Transformation (QVT) [QVT, 2011]. Both declarative and imperative language constructs are available in ATL, which makes it a hybrid MTL that can be applied to both endogenous and exogenous model transformation tasks. However, ATL is more appropriate to handle exogenous model transformation scenarios because its execution engine is based on model rewriting rather than in-place changing. Figure 2.2 shows an excerpt of model transformation rules written in ATL. The main blocks in an ATL program are the rules, specifying how to transform a model element from one metamodel to another (e.g., Member2Male). Inside a rule, constraints on the rules (e.g., `not s.isFemale()`) and the specific transformation process (e.g., `fullName <- s.firstName + " " + s.familyName`) are defined. Helpers serve as function calls in an ATL transformation, which can contain the basic logic and control statements.

```
helper context Families!Member def: isFemale() : Boolean =
      if not self.familyMother.oclIsUndefined() then
            true
      else
            if not self.familyDaughter.oclIsUndefined() then
                  true
            else
                  false
            endif
      endif;

rule Member2Male {
      from
            s : Families!Member (not s.isFemale())
      to
            t : Persons!Male (
                  fullName <- s.firstName + ' ' + s.familyName
            )
}
```
Figure 2.2 – An excerpt of an ATL transformation rule

ATL has been implemented in Eclipse with a development toolkit plugin. A library of existing transformations is available to reuse from [ATL Transformation Zoo, 2011], which contains successful transformation scenarios in many domains.

Embedded Constraint Language (ECL). ECL [Gray et al., 2006] was designed and implemented to solve endogenous model transformation problems, supporting the in-place modifications on source models. ECL applies and extends OCL, and supports three types of operations: 1) Model collection can be used to navigate the source model and group the model elements sharing the common features or satisfying the common criteria together. Model collection provides an expressive way to filter desired model elements from a large-scale source model; 2) Model selection operates on the collected model elements and further locates the target model elements to be transformed. The selection process can be based on either the evaluation of a logical expression or the matching of a specified pattern; 3) Model transformation carries out the final transformation task on the selected model elements. The transformation can be applied to both nodes and connections, being capable of adding, removing, and changing the structure and attributes. Figure 2.3 is an excerpt of an ECL example. An aspect in ECL is used to specify a crosscutting concern across a model hierarchy. The *FindData1* aspect collects all the atoms in the model, selects those *Data* atoms with the name being "*data1*" and executes the *AddCond* strategy. A strategy in ECL is a set of transformation operations, which in this example, creates a new *Condition* atom, a new connection, as well as setting up the attributes of each *Condition* atom.

ECL is fully implemented with a transformation engine called the Constraint-Specification Weaver (C-SAW) in GME. Although ECL was originally designed to handle aspect-oriented modeling problems, it has been extended and applied to other general model evolution tasks such as model scalability [Lin et al., 2008] and model refactoring [Zhang et al., 2005]. Because ECL focuses on the same set of model evolution problems as this dissertation research, the comparison between ECL and the result from this research will be made in a future chapter.

```
aspect FindData1(atomName, condName, condExpr : string)
{
      atoms()->select(a | a.kind() == "Data" and
           a.name() == "data1")->AddCond("Data1Cond", "value<200");
}

strategy AddCond(condName, condExpr : string)
{
     declare p : model;
     declare data, pre : atom;

     data := self;
     p := parent();

     pre := p.addAtom("Condition", condName);
     pre.setAttribute("Kind", "PreCondition");
     pre.setAttribute("Expression", condExpr);
     p.addConnection("AddCondition", pre, data);
}
```

Figure 2.3 – An excerpt of an ECL transformation rule

Graph Rewriting and Transformation (GReAT). GReAT [Balasubramanian et al., 2006-a] is a graphical language to specify model transformations. GReAT is a set of three sub-languages: 1) The pattern specification language defines the pattern to be matched in the source model. A pattern consists of nodes and edges that must be present in the model, as well as the associations and containment relationships. Users can also specify negative application conditions that restrict the presence of certain patterns; 2) The transformation rule in GReAT is the basic transformation entity, which contains the pattern to be matched, and a set of actions to be executed. Additionally, guards can be defined as part of the transformation rule to determine whether the actions should be executed based on the evaluation of the logical expression; 3) GReAT also contains a control flow language to handle the larger and more complex transformation scenarios, such as how to sequence the execution of the rules, how to execute the rules in parallel with non-determinism, how to control the hierarchy of the transformation rules using blocks, and how to implement recursion when executing the rules. The execution engine of GReAT is built within GME using graph mapping and rewriting. Figure 2.4 shows an example of a GReAT transformation rule. It binds all the instances of *Class A*, *Class B*, *Class C* that satisfy the given containment relationships (i.e., *Class C* can contain instances of *Class A* and *Class B*, and connections can exist between instances of *Class A* and *Class B*), and creates the new *Item* elements in the container (i.e., *Class C*).

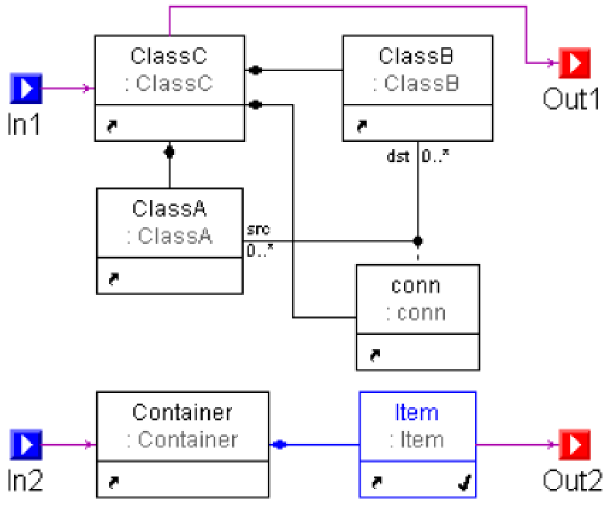


Figure 2.4 – An excerpt of a GReAT transformation rule

2.4 End-User Programming (EUP)

The concept of End-User Programming (EUP) can be traced back to the 1960s [Martin, 1967]. James Martin presented his vision on this topic as, “We must develop languages that the scientist, the architect, the teacher, and the layman can use without being computer experts. The language for each user must be as natural as possible to him. The statistician must talk to his terminal in the language of statistics. The civil engineer must use the language of civil engineering. When a man learns his profession he must learn the problem-oriented languages to go with that profession.” [Martin, 1967]

End-Users are defined as the final users of application programs and software, who have not necessarily been taught or trained how to write code and programs in traditional programming languages. EUP aims at enabling this group of users to use the software in their daily life and work, and also participate in the creation, modification, and maintenance of software applications. The most representative example of EUP is a spreadsheet application [Rothermel et al., 2001]. Users who are not professional developers can process tables of complex data, and create automated calculation behavior without significant knowledge of a programming language.

Supporting EUP exerts a significant influence on the whole software community. According to the research done by the U.S. Bureau of Census and Bureau of Labor [Scaffidi et al., 2005], there are 3 million professional software developers and programmers in the U.S., while over 12 million people say that they do programming at work, and over 50 million spreadsheet and database users exist. Therefore, the total number of end-user programmers in the U.S. alone is several times the number of professional programmers. These end-users’ involvement in programming can contribute substantially to the application domains, because 1) end-users know their domains and problems best, so they can create the specific solutions to solve their own problems without talking or explaining to a programmer, avoiding the potential communication gaps; 2) after end-users receive their own programs and applications, they can also be responsible for the maintenance, rather than simply complaining about the software and seeking help from professional developers, leading to a more general "customer support"; 3) the software systems designed with end-user programming capability can be simpler and less complex, due to the fact that professional programmers only need to focus on implementing the general functions, while the end-users take care of using these general functions to realize their specific needs [Lieberman et al., 2006].

However, the benefits of EUP do not come for free. Problems and cost can also be caused by applying EUP. The first and foremost problem associated with EUP is the quality of the applications built by end-users. Without professional training, end-users are likely to produce errors and bugs, which can have significant impact (e.g., a numerical error in a spreadsheet can lead to fatal failures in many areas). In addition, security cannot be guaranteed in the applications developed by end-users, because they may lack the necessary knowledge on how to test and secure their applications, or in some other cases, the security control is not even exposed to end-users. In some cases, the cost of quality and security issues can weigh much more than the benefits gained from EUP [Harrison, 2004].

In summary, while it is significant and beneficial to support EUP and enable users to participate in software development process, ensuring the quality and security of software applications built by end-users is indispensible.

2.4.1 Examples of EUP

The approach to support model evolution used in this dissertation shares some features of EUP. In this section, we choose some typical and successful examples to further illustrate the idea of EUP.

Programming By Example (PBE). PBE [Cypher, 1993] is a technique for teaching computers new behaviors by demonstrating actions on concrete examples. A program can be generalized from the recorded actions during the demonstration, which is applicable to accomplish the same task to other examples. The goal of PBE is to make programming easier than learning and using traditional programming languages. A popular PBE application domain was robotics [Narayanan et al., 2010]. By moving and operating the robots through a series of teaching, guiding, and play-back steps, the configurations and desired sequential actions for the robot can be completed.

What You See Is What You Get (WYSIWYG). WYSIWYG [Rothermel et al., 2001] represents a technique that enables users to edit certain content (e.g., text, graphs, models) in a form that is exactly the same as it will appear in the final finished version or product. WYSIWYG intends to directly control and manipulate the properties (in most cases the layout) of the final product without learning and using the low-level implementation details. For instance, users can adopt Microsoft Word to configure the layout of a document by checking the final document appearance directly, while the special layout control code has to be inserted into the document using LaTeX [LaTeX, 2011]. Another good example is that a number of Jave GUI editors are available (e.g., NetBeans [NetBeans, 2011], Eclipse Visual Editor [Eclipse VE, 2011]) to handle the Java GUI interface design by dragging and dropping the various GUI control elements on the canvas directly. The underlying executable implementation in Java code is generated automatically. WYSIWYG can also go beyond the layout configuration. Google App Inventor [Google App Inventor, 2011] allows users to create Andriod applications in the same drag-and-drop manner, so that even young people who have no programming experiences can develop mobile applications for their own needs.

Visual Programming Languages (VPL) and DSM. VPLs [Myers, 1986] let users create programs by using graphical elements and constructs rather than textual expressions. Based on the idea that, “A picture is worth a thousand words.” VPLs can make the specification of certain applications more direct and end-user friendly. For instance, the Microsoft Visual Programming Language [MS VPL, 2011] is a graphical development environment designed to create dataflow-based programming models; KTechlab [KTechlab, 2011] uses flowcharts to program microcontrollers graphically; OpenMusic [Agon, 1998] is a visual programming language for music composition applications. DSM, by comparison, shares similar features as VPLs that both rely on the graphical representations. However, although a DSML can be considered a type of VPL, the main difference between a VPL and a DSML is that a DSML raises the level of abstraction by generating the low-level software artifacts, while VPLs are usually independent languages or development environments. When it comes to supporting EUP, both are effective approaches.

CHAPTER 3

MODEL TRANSFORMATION BY DEMONSTRATION: AN END-USER CENTRIC MODEL TRANSFORMATION APPROACH

This chapter presents the main contribution of this dissertation – Model Transformation By Demonstration (MTBD), which is an end-user centric approach to implement model transformation. The basic goals and high-level description of the idea are discussed first, before a detailed explanation of each step and implementation component. A formal description of the approach is also given, which defines the functionality of the approach precisely. In order to highlight the unique features and contribution of MTBD, related work will be discussed and compared, followed by concluding remarks that are presented at the end of the chapter.

3.1 Overview of MTBD

The main difficulty of learning and using MTLs to support model evolution, as discussed in Chapter 1, results from the steep learning curve of MTLs and the challenge of understanding the metamodels correctly. Therefore, the goal of the new model transformation approach presented in this dissertation is to isolate users from learning any MTLs or knowing any metamodels, to make the activity of performing model transformations more end-user centric.

The idea of MTBD derives from PBE. Although PBE focuses on enabling users to teach a computer new behaviors by demonstrating actions on concrete examples, MTBD concentrates on a more specific programming scenario to allow users to implement model transformation tasks by demonstrating how to transform and evolve models on concrete model instances.

The basic idea of MTBD is that instead of manually writing transformation rules in a specific model transformation language, users demonstrate how a model transformation should be done by directly editing (e.g., add, delete, connect, update) a concrete model instance to simulate the desired model transformation process. A recording and inference engine has been developed to capture all user operations performed during the demonstration. After the recording process has completed, the inference engine optimizes the recorded operations and infers a transformation pattern that specifies the precondition of the transformation and the sequence of actions needed to realize the transformation. In order to make the inferred transformation pattern more accurate, users are allowed to make refinements on the pattern through dialogs and wizard interfaces. The finalized pattern is stored in the repository, and can be executed by the execution engine by matching the precondition in a given model instance and then replaying the actions to execute the transformation actions. During the execution of a transformation pattern, constraint checking ensures that the execution does not violate the metamodel definition of the domain.

The design and implementation of MTBD is independent from any MTLs, and metamodel information is not exposed to users during the whole MTBD process, so that users can be isolated from learning MTLs or understanding metamodel definitions. More details about each step of MTBD will be presented in the next sub-sections.

3.2 MTBD Process and Implementation

Figure 3.1 shows the high-level overview of MTBD, which is a complete model transformation framework that allows users to specify a model transformation, as well as to execute the generated transformation pattern in any desired model instances.

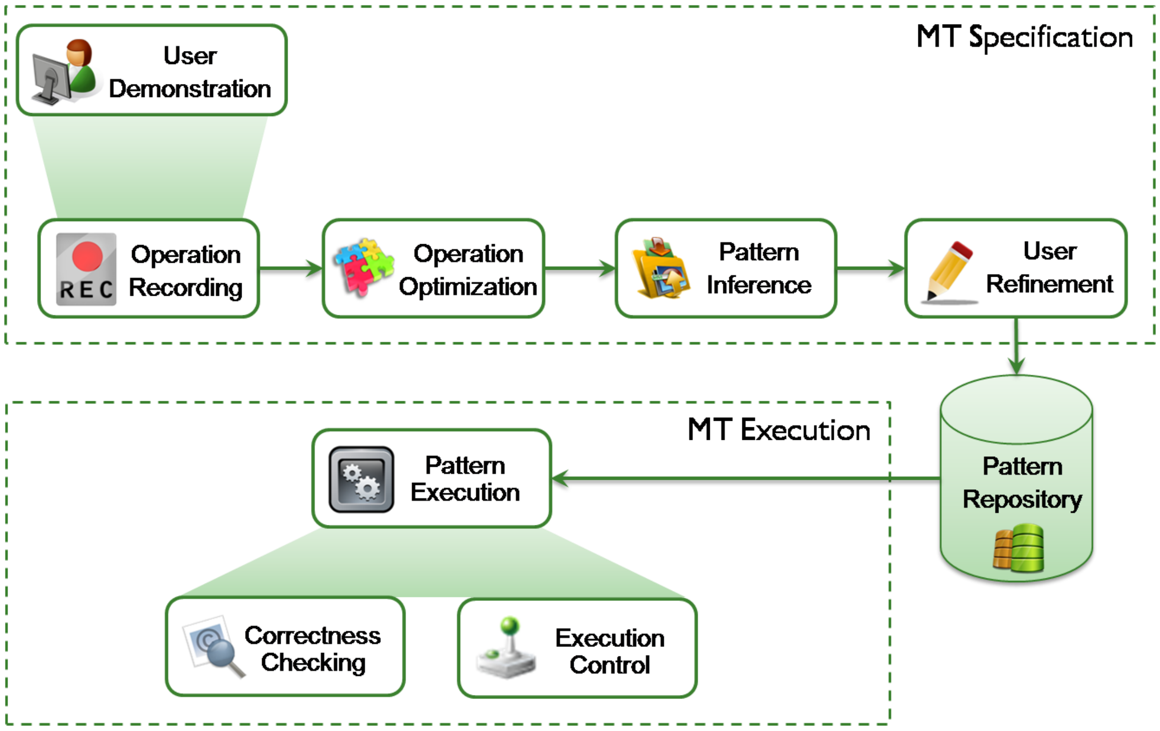


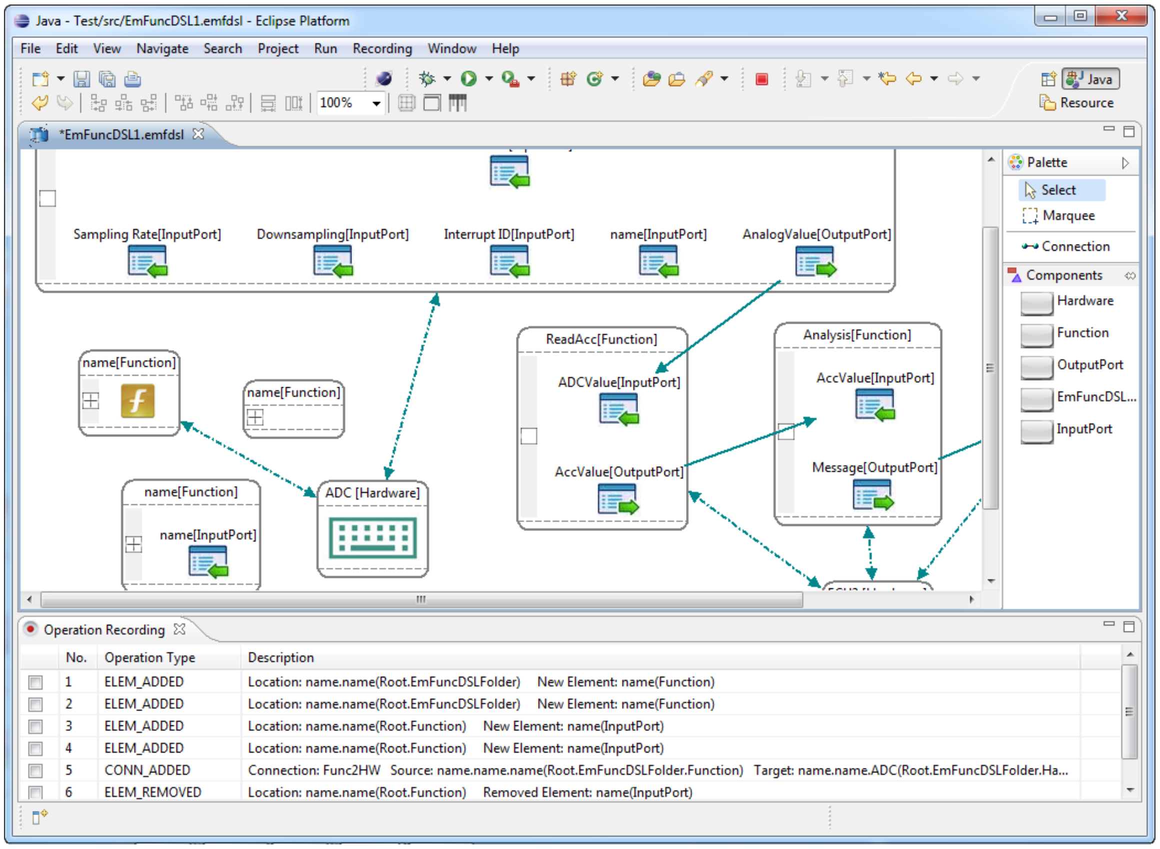
Figure 3.1 – High-level overview of MTBD process

The implementation of MTBD is a plug-in called Model Transformation-Scribe (MT-Scribe) to GEMS in Eclipse. This sub-section will present each of the steps and the associated implementation details.

User Demonstration. A user's demonstration provides the base for transformation pattern analysis and inference, so accurately demonstrating a concrete model transformation process is the first and foremost step. The demonstration is given by directly editing a model instance in the model editor to simulate a transformation task. Six different types of operations can be performed and demonstrated: 1) add a model element (i.e., node), 2) remove a model element, 3) change the attribute of a model element, 4) add a new connection, 5) remove a connection, and 6) change the attribute of a connection. Users can change any model from the source state to the target state using these operations.

The implementation of the demonstration is enabled in the GEMS model editor. Figure 3.2 shows an ongoing demonstration in the modeling language EmFucnML [Sun et al., 2011-a].

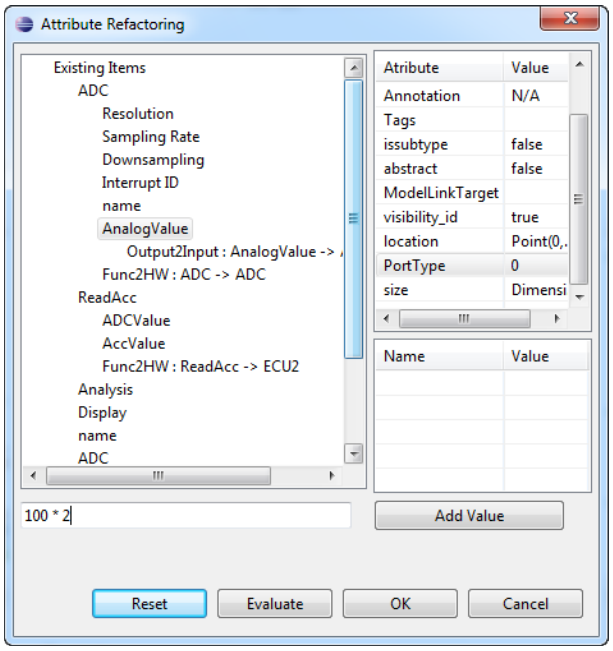
The key of the demonstration is that it should be sufficient to reflect the transformation purpose accurately. For example, if a model transformation scenario requires replacing all model elements of `ElemType1` and `ElemType2` with other types of elements, the demonstration must cover replacing both types of elements, rather than only replacing one of them. On the other hand, over-demonstration should also be avoided. In other words, the demonstration should be as short and concise as possible, which means that it is not necessary to cover multiple instances of the same type of changes needed in the entire model instance. For example, to replace all the elements of `ElemType1` contained in the root of the model, instead of manually deleting every `ElemType1` and adding a new type of element, demonstrating only one replacement is enough, because one replacement already contains the necessary information about how the transformation should be performed in other locations.



	No.	Operation Type	Description
	1	ELEM_ADDED	Location: name.name(Root.EmFuncDSLFolder) New Element: name(Function)
	2	ELEM_ADDED	Location: name.name(Root.EmFuncDSLFolder) New Element: name(Function)
	3	ELEM_ADDED	Location: name.name(Root.Function) New Element: name(InputPort)
	4	ELEM_ADDED	Location: name.name(Root.Function) New Element: name(InputPort)
	5	CONN_ADDED	Connection: Func2HW Source: name.name.name(Root.EmFuncDSLFolder.Function) Target: name.name.ADC(Root.EmFuncDSLFolder.Ha...
	6	ELEM_REMOVED	Location: name.name(Root.Function) Removed Element: name(InputPort)

Figure 3.2 – An ongoing demonstration and the Operation Recording view

During the demonstration, users are expected to perform operations not only on model elements and connections, but also on their attributes, so that the attribute transformation can be realized. In most model evolution activities, attribute transformation is an essential task, because the attributes in the target model are often based on the computation using one or more attributes in the source model. To support this type of scenario, an attribute refactoring editor has been developed. As illustrated in Figure 3.3, the attribute refactoring editor enables users to access all the attributes in the current model editor and specify the desired transformation expressions (e.g., string and arithmetic computation). During the demonstration, a user specifies the attribute computation with the concrete values and obtains the concrete results, but the generic and metamodel level transformation rules can be inferred from it later. The computation can either be based on single attribute value assignment, or the combination of multiple attribute values from different model elements and connections. The attribute refactoring editor also provides a mechanism to let users create a temporary data pair, with a given name and a value. The creation of the temporary data pair is actually used to simulate the user input process, and the data can be used in any attribute configuration and computation process through the entire demonstration. The creation of the temporary data will be generalized as a user input action and will display an input box when the final pattern is executed.



```
Existing Items
    ADC
        Resolution
        Sampling Rate
        Downsampling
        Interrupt ID
        name
        AnalogValue
            Output2Input : AnalogValue ->
        Func2HW : ADC -> ADC
    ReadAcc
        ADCValue
        AccValue
        Func2HW : ReadAcc -> ECU2
    Analysis
    Display
    name
    ADC
```

Atribute	Value
Annotation	N/A
Tags	
issubtype	false
abstract	false
ModelLinkTarget	
visibility_id	true
location	Point(0,.
PortType	0
size	Dimensi

Name	Value

100 * 2

Figure 3.3 – The attribute refactoring editor

Because the demonstration is based on the concrete model instances, users are fully isolated from metamodel definitions and MTL concepts, which allow them to think about the transformation or evolution problem using the concepts they are most familiar with.

Operation Recording. User demonstration reflects the intention of the transformation. To infer this intention accurately, the detailed information about each operation performed during the demonstration should be recorded accordingly. The information to be recorded includes the elements and connections being involved directly during the demonstration, but also the context information. Therefore, an event listener has been developed to monitor all the operations occurring in the model editor and collect the information for each operation in sequence. In GEMS, an extension point is available to capture all the events occurring in the editor. The event listener extends this extension point and stores all the needed information, and displays it in the *Operation Recording* view (the bottom part of Figure 3.2), where users can track all the operations being recorded during the demonstration. Table 3.1 shows the six types of operations that a user may perform and the related information that needs to be recorded. Each recorded operation is encapsulated into an object, similar to the Command pattern [Gamma et al., 1995]. The final list of these objects represents the sequence of operations the user performed during the demonstration.

Operation Optimization. The list of recorded operations indicates how a transformation should be performed. However, not all operations in the list are meaningful. Users may perform useless or inefficient operations during the demonstration. For instance, without a careful design, it is possible that a user first adds a new element and modifies its attributes, and then deletes it in another operation later, with the result being that all the operations regarding this element actually did not take effect in the transformation process and therefore are meaningless. The presence of meaningless operations not only has the potential to make the inferred transformation preconditions inaccurate, but also exerts a negative influence on the performance of a transformation, especially when it executes on a large model instance. Thus, an optimization that eliminates all meaningless operations is automatically done after the recording. An optimization algorithm has been designed and implemented to detect the meaningless operations and eliminate them, which will be presented in Section 3.3.

Table 3.1

The types of operations and the related context information recorded

Operation Type	**Information Recorded**
Add an Element	Location of the parent element and its meta type The newly added element and its meta type
Remove an Element	Location of the element being removed and its meta type
Modify an Element	Location of the element being modified and its meta type The attribute name, the old value and the new value
Add a Connection	Location of the parent source and target elements and their meta types The newly added connection and its meta type
Remove a Connection	Location of the connection being modified and its meta type
Modify a Connection	Location of the connection being modified and its meta type The attribute name, the old value and the new value

Pattern Inference. With an optimized list of recorded operations, the initial transformation can be inferred. Because the MTBD approach does not rely on any MTLs, it is not necessary to generate specific transformation rules, although that is possible. Instead, a general transformation pattern is inferred, which is invisible to end-users so that they are fully isolated from knowing MTLs or any implementation details. The transformation pattern describes the precondition of a transformation (i.e., *where* the transformation should be performed) and the actions of a transformation (i.e., *how* the transformation should be realized). The precondition is defined by specifying the required model elements and connections, with the constraints on them (e.g., the type of the element must be `ElemType1`). The actions specify the sequence of operations to be executed on the elements and connections identified in the precondition. By analyzing the recorded operations, the related meta-information of model elements and connections is extracted to construct the precondition, and the actions are generated by generalizing the recorded operation sequence.

The pattern inferred in this step is an initial version, which means that the precondition is the weakest precondition for the transformation and the set of actions is specific to the operations performed during the demonstration. For instance, if a user performed an operation to remove an element of `ElemType1` from the root of the model instance, and another operation to add a new element of `ElemType2` in the root, the inferred precondition is that the model instance should contain at least an element of `ElemType1` in the root so that the delete operation could be executed on it. In other words, satisfying the weakest precondition means that a model instance contains the minimally sufficient elements for each operation to be executed correctly. Obviously, such kind of precondition is not restrictive enough in practice. In many cases, more specific constraints are needed for the precondition from the aspects of both structure and attribute, which cannot be inferred directly from the demonstration. For instance, the element of `ElemType1` should be removed only when a certain attribute value (e.g., `load`) is less than `100`, or only when it is connected to another element of `ElemType1`. Similarly, the initially inferred transformation actions are just the same as the operations in the recorded operation set. However, sometimes this kind of repetition is not generic enough to reflect the user's real intention. Thus, a user refinement step comes after the inference of the initial transformation pattern to let users make the pattern more accurate.

User refinement. The initial pattern inferred is specific to the demonstration and is usually not practical and accurate enough, due to the limitation on the expressiveness of the user demonstration. Thus, MTBD allows users to refine the inferred transformation by providing more feedback for the desired transformation scenario. Three types of refinement can be performed: 1) refinement on the structural precondition, 2) refinement on the attribute precondition, and 3) refinement on the transformation actions. In order to keep users at the appropriate level of abstraction without knowing MTLs or metamodel definition, all the refinements can be done through interfaces that only expose information from the demonstration on the concrete model instances.

The refinement on the structural precondition aims to restrict the required model elements and connections to be included when matching a model transformation pattern. From the example mentioned in the previous sub-section, after a user demonstrates removal of an element of `ElemType1`, the structural precondition inferred only contains one `ElemType1`. If the desired transformation scenario is to remove this element only when it is connected to another `ElemType1` trough a connection, users can refine the inferred transformation pattern by including the additional required elements or connections. The refinement can be done directly in the model editor, by selecting the concrete elements or connections and confirming their containment using a one-click pop-up menu in the editor, as shown in Figure 3.4.

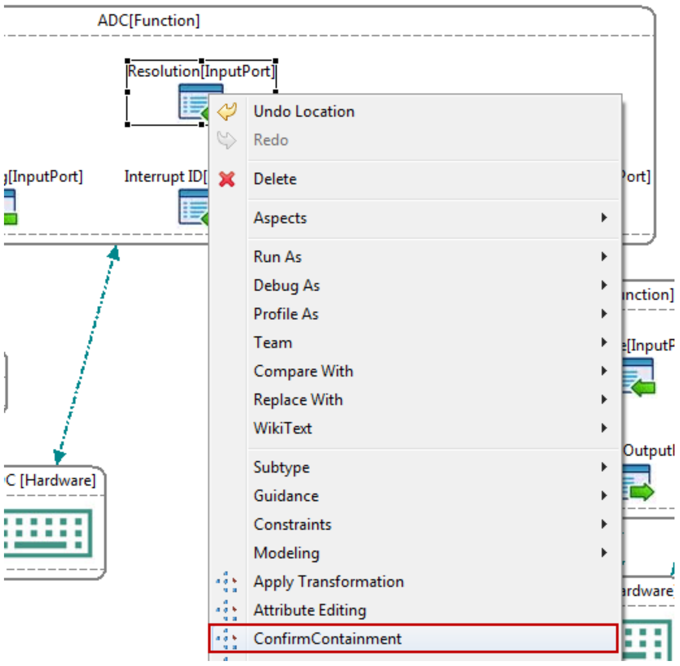
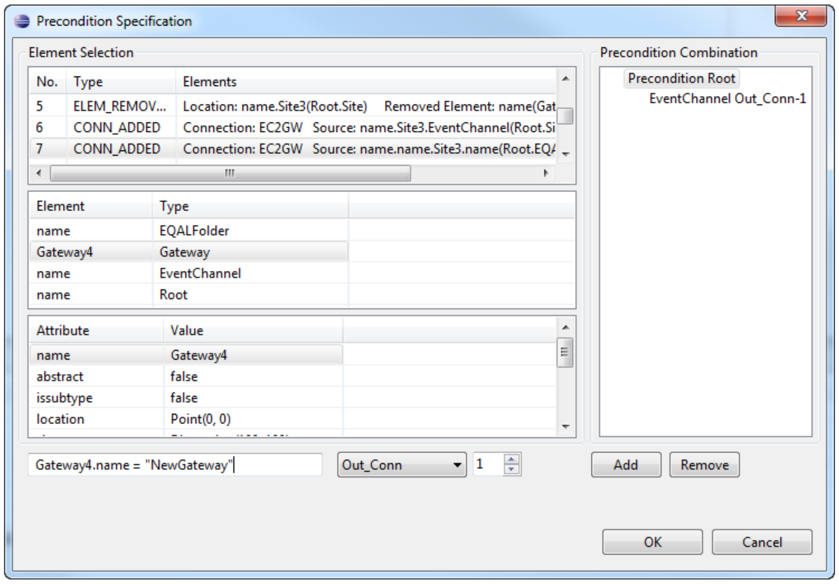


Figure 3.4 – Refine structural precondition by confirming containment

The refinement on an attribute precondition enables users to give constraints on the attributes of model elements and connections specified in the structural precondition. When matching a transformation pattern in a model instance, after the structure is matched, all the constraints on the attributes must be satisfied as well. The constraints on attributes are specified using logical expressions. For instance, if the desired model transformation scenario is to remove `ElemType1` only when `load < 100`, users can find out the element of `ElemType1` in the precondition specification dialog, select the attribute “`load`,” followed by giving the expression “`< 100`.” The constraint can be based on multiple attributes on different model elements and connections. For example, if `ElemType1`, `ElemType2`, and `ElemType3` are involved in the precondition, the constraint can be made by specifying “`ElemType1.load + ElemType2.load ==`

`ElemType3.load`." The refinement is done in a dialog as shown in Figure 3.5. The upper-left lists all the recorded operations in the demonstration. By clicking on a specific operation, all the model elements involved will be listed, so that a user can locate the elements for which they want to provide more constraints. Similarly, by clicking on a certain element, all its attributes and associated values are listed. Users can select certain attributes and type the necessary restrictions. Also, constraints can be given on the attributes that are not defined in the metamodel, such as the number of outgoing or incoming connections. Through this interface, users continue to work at the model instance level to give specific preconditions on the elements they considered in the demonstration. The meta-information and generic computation will be inferred and stored in the transformation pattern automatically, with the information on the low-level implementation and metamodel definition being hidden.

The inferred sequence of transformation actions also can be refined by users. The most typical scenario is to identify the generic operations that should be repeated according to the available model elements and connections. An illustrative example of this refinement is when a user wants to remove all the elements of `ElemType1` in the root of the model instance. Instead of demonstrating the removal of all the elements, the demonstration is done by only removing one of them. In the initially inferred transformation actions, only a single operation (i.e., remove `Elem1`) is included. Without refinement, the execution of the transformation pattern will only trigger the removal of a single `ElemType1`, rather than deleting all of those contained in the root of the model as expected. Therefore, users can refine the transformation actions, by marking the operation generic. A generic operation means that during an execution of a transformation pattern, the operation should be executed repeatedly by matching the related precondition in the current model until no more matches can be made. The identification of generic operations can be accomplished by marking the list of transformation actions in a dialog, as shown in Figure 3.6.



No.	Type	Elements
5	ELEM_REMOV...	Location: name.Site3(Root.Site) Removed Element: name(Gat
6	CONN_ADDED	Connection: EC2GW Source: name.Site3.EventChannel(Root.Si
7	CONN_ADDED	Connection: EC2GW Source: name.name.Site3.name(Root.EQ/

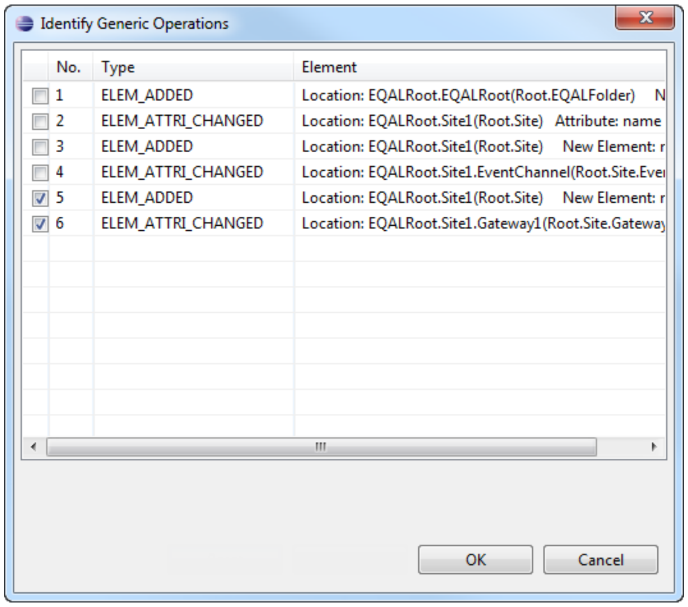
Element	Type
name	EQALFolder
Gateway4	Gateway
name	EventChannel
name	Root

Attribute	Value
name	Gateway4
abstract	false
issubtype	false
location	Point(0, 0)

Gateway4.name = "NewGateway"

Figure 3.5 – Precondition specification dialog

Pattern Repository. After the user refinement, the transformation pattern will be finalized and stored in the pattern repository for future use. Because the transformation pattern is represented by different types of objects (i.e., precondition objects, transformation action objects), the current implementation of MTBD serializes all the objects in a transformation pattern and stores them locally.



	No.	Type	Element
☐	1	ELEM_ADDED	Location: EQALRoot.EQALRoot(Root.EQALFolder) N
☐	2	ELEM_ATTRI_CHANGED	Location: EQALRoot.Site1(Root.Site) Attribute: name
☐	3	ELEM_ADDED	Location: EQALRoot.Site1(Root.Site) New Element: r
☐	4	ELEM_ATTRI_CHANGED	Location: EQALRoot.Site1.EventChannel(Root.Site.Eve
✓	5	ELEM_ADDED	Location: EQALRoot.Site1(Root.Site) New Element: r
✓	6	ELEM_ATTRI_CHANGED	Location: EQALRoot.Site1.Gateway1(Root.Site.Gatewa

Figure 3.6 – Generic operations identification dialog

Pattern Execution. The final generated patterns in the repository can be executed on any model instances. Because a pattern consists of the precondition and the transformation actions, the execution starts with matching the precondition in the new model instance and then carries out the transformation actions on the matched locations of the model. The precondition matching is done by traversing the model instance to search all locations that satisfy both the structural and attribute preconditions. Because both the precondition and the model instance can be regarded as graphs, the precondition matching problem could be solved by using graph matching theories [Varró et al., 2005]. A backtracking algorithm has been developed to match a precondition in a given model instance, as presented in Section 3.3. A notification is given if no matching locations are found. In MTBD, a matching location is defined as a part or substructure of a model that contains all the model elements and connections required in the precondition that satisfies all the constraints given in the user's refinement.

After a matching location is found, the transformation actions can be executed with the matched model elements and connections. If operations are identified as generic, the execution engine will rematch the related part of the precondition, and execute these operations as long as additional matching can be made.

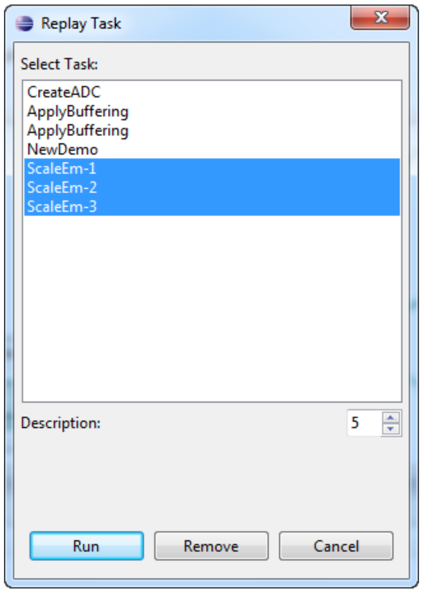


Figure 3.7 – Execution controller dialog

Execution Control. Users can select the pattern in the execution controller dialog shown in Figure 3.7 to execute an inferred transformation pattern from the repository. Users can select multiple patterns to execute in sequence, which is particularly useful when a model transformation task is divided by sub-tasks and specified by different demonstrations. In addition, the total times for executing the selected pattern(s) can be specified, because in some use cases (e.g., model scalability), a transformation pattern(s) needs to be executed multiple times to transform the model to a specific state and configuration. Moreover, users can customize part of the model instance to execute the pattern. By default, a transformation pattern will be executed in the root of the current model instance and matched in the whole model. Users are also allowed to select a partial model as an input base to match a transformation pattern.

Correctness Checking. The location matching the precondition guarantees that all transformation actions can be executed with necessary operands with satisfied constraints. However, it does not ensure that executing them will not violate the metamodel definition or external constraints, because the implementation of executing the actions is based on the low-level model manipulation APIs provided by GEMS that could be applied without the monitoring of the GEMS checking mechanism. Therefore, the execution of each transformation action will be logged and the model instance correctness checking is performed after every execution. If a certain action violates the metamodel definition, all executed actions are undone and the whole transformation is cancelled, with the model instance being rolled back to the initial state. Because the transformation actions have been encapsulated as objects in the Command pattern, the undo process is implemented directly.

3.3 Formal Specification of MTBD

As a new model transformation approach that is at a higher level of abstraction than MTLs, MTBD provides an end-user centric solution to handle model transformation problems. Different from MTLs that have well-defined language syntax and semantics to precisely reflect the power and functionality, the usage and power of MTBD cannot be expressed directly in a similar way. Therefore, a formal specification of MTBD is presented in this section, for the purpose of accurately describing the process of MTBD and defining its power and full functionality.

Using the description of MTBD provided in Section 3.2, a formal model of the MTBD has been built as a 5-tuple:

$$MTBD = \left\langle \vec{\Delta}_m, TG(M_i, \vec{\Delta}_m), \varpi(M_i, \vec{\Delta}_m), \phi(\vec{P}, \vec{T}), \xi(M_j, \vec{P}', \vec{T}') \right\rangle \qquad (1)$$

where:

- M_i is a model conformant to the metamodel $Meta_i$
- M_j is a model also conformant to the metamodel $Meta_i$
- $\vec{\Delta}_m$ is a sequence of model modifications recorded during a user demonstration of a transformation on the model, M_i.
- $TG(M_i, \vec{\Delta}_m)$ is a generalization function that produces an initial set of model transformation actions, $\vec{T}$, that can be applied to any model conformant to $Meta_i$. The transformation is produced by generalizing the series of modifications, $\vec{\Delta}_m$, that were applied to M_i.
- $\varpi(M_i, \vec{\Delta}_m)$ is an inference function that extracts a set of preconditions, $\vec{P}$, needed in order to generalize and apply the modifications, $\vec{\Delta}_m$, to another model.
- $\phi(\vec{P}, \vec{T})$ is an optional manual transformation and precondition refinement function that allows the domain expert to modify the transformation and preconditions inferred by *TG* and ϖ. This function produces a refined transformation, $\vec{T}'$, and set of preconditions $\vec{P}'$.
- $\xi(M_j, \vec{P}', \vec{T}')$ is a transformation function that applies the refined generalized transformation, $\vec{T}'$, to a model, M_j, if the preconditions $\vec{P}'$ are met by M_j.

3.3.1 Operation Demonstration and Recording

The goal of MTBD is to allow users to express domain knowledge regarding a function, $K(M_i)$. That is, the user is describing a domain-specific function that can be applied to a model in order to achieve a domain-specific goal. A critical component of MTBD is that the domain function (transformation) is expressed in terms of the notations in the modeling language and not the notations used to describe the metamodel, $Meta_i$.

MTBD captures domain functions as transformations that can be applied to models that adhere to the metamodel, $Meta_i$, of the target domain. The first step in MTBD is for a user to apply the domain function, $K(M_i)$ to a model, so that the MTBD engine can capture the set of model modifications, $\vec{\Delta}_m$. The process begins by the user or an external signal initiating a recording process. During the recording process, the user applies the domain function, $K(M_i)$, to the model, M_i:

$$K(M_i) \Rightarrow M_j \qquad (2)$$

$$K : Meta_i \longrightarrow Meta_i \qquad (3)$$

The domain function takes an initial model, M_i, as input, and produces a new model, M_j, as output. Although it is possible that M_i and M_j are not conformant to the same metamodel, $Meta_i$, this dissertation explicitly focuses and enforces this assumption. Equation 3 shows that the domain function must represent an endogenous model transformation that maps a model in one metamodel to a model in the same metamodel.

3.3.2 Operation Optimization

The set of modifications $\vec{\Delta}_m$ potentially can contain meaningless operations due to a users' careless design of a demonstration. An algorithm has been developed to remove these meaningless operations and optimize $\vec{\Delta}_m$, as shown in Algorithm 1. The algorithm traverses the whole recorded operation list, and seeks the meaningless operation pairs on the same model element or connection, such as removing after adding, or multiple modifications without making changes between source and target states.

```
for each op in the input operation list
  switch (op.type)
    case ADD_ELEM:
      for each op_temp after the current op in the list
        if op_temp.type == REMOVE_ELEM and op_temp removes what op added

          and the element was not referred in between
            then remove both op and op_temp from the list
      end for
    case MODIFY_ELEM:
      traverse the final model instance and search the element being modified
      if not found then remove op from the list
      if found then compare the attribute value with the value stored in op
        if different then remove op from the list
    case ADD_CONN:
      for each op_temp after the current op in the list
        if op_temp.type == REMOVE_CONN and op_temp removes what op added
          and the element was not referred in between
            then remove both op and op_temp from the list
      end for
    case MODIFY_CONN:
      traverse the final model instance and search the connection being modified
      if not found then remove op from opList
      if found then compare its attribute value with the value stored in op
        if different then remove op from opList
end for
```

Algorithm 1 – Optimize Operation List

3.3.3 Pattern Inference

After the recording process, the MTBD engine possesses a series of optimized model modifications $\vec{\Delta}_m$, that express the application of the domain function $K(M_i)$, to a specific model. The next step of MTBD is to use pattern inference to generalize and describe the domain function as a model transformation. A critical aspect of this process is that the transformation must be expressed in terms of the general metamodel notations captured in $Meta_i$, rather than a specific model's elements, M_i. The inference step produces a model transformation, which we describe as a tuple:

$$Transformation = \left\langle \vec{P}, \vec{T} \right\rangle \tag{4}$$

where $\vec{P}$ is a set of preconditions that must be met in order to apply the transformation produced by function ϖ , and $\vec{T}$ is the set of generalized model modifications that transform the source model to the desired target model, produced by function TG. In terms of the domain function, $\vec{P}$ describes the domain knowledge regarding the circumstances in which $K(M_i)$ can be applied, and $\vec{T}$ defines what to do when these circumstances are met. For example, in the previous example from Section 3.2, $\vec{P}$ is the precondition that the element must be connected to another element and the load attribute is above a set threshold, where $\vec{T}$ represents the modifications needed in order to remove or replace the element.

As mentioned in the previous sub-section, the preconditions can be subdivided into two types:

Structural preconditions that govern the types of elements, the containment relationships, and connection relationships that must exist within the model. The structural preconditions take the form of assertions on the hierarchy or connection relationships that must be present in the model. A hierarchical precondition, Pe_i, is described as a vector:

$$Pe_i = T_0, T_1, \ldots, T_n \tag{5}$$

where T_0 is the type of an element that is directly modified by one or more operations in

$\vec{\Delta}_m$, T_1 is the type of the parent of T_0, T_2 is the type of the parent of T_1, and so forth to the root element. In order for this precondition to hold in an arbitrary model, M_j, an instance of the type T_0, contained within an element of type T_1, must exist. More formally, given an element, e_i, in a model M_j that conforms to the metamodel $Meta_i$, a hierarchical precondition, Pe_i, is satisfied by e_i if:

$$V(e_i, T_i) = (type(e_i) == T_i) \wedge (V(e_{i+1}, T_{i+1})) \tag{6}$$

$$Pe_i(e_i) = \begin{cases} (V(e_i, T_0) == true), \ true \\ otherwise, \ false \end{cases} \tag{7}$$

A connection precondition is another form of a structural precondition. Connection preconditions dictate the associations that must be present in the model. A connection precondition, Pc_i, is defined as a 3-tuple:

$$Pc_i = <Pe_j, Pe_k, T_l> \tag{8}$$

where Pe_j specifies a structural precondition that must be met for an element to be considered the source element of a connection to be modified; Pe_k is a precondition that must be met for an element to be considered the target element of the connection; and T_l is the type of connection that must exist between the elements that satisfy the source and target structural preconditions. In order for a connection, c_i, between two elements, e_i and e_j, to satisfy Pc_i:

$$Pc_i = \begin{cases} Pe_j(e_i) \wedge Pe_k(e_j) \wedge (type(c_i) == T_l), \ true \\ Pe_j(e_j) \wedge Pe_k(e_i) \wedge (type(c_i) == T_l), \ true \\ otherwise, \ false \end{cases} \tag{9}$$

The inference $\varpi(M_i, \vec{\Delta}_m)$ function evaluates each change in Δ_m that occurred. From these changes, structural preconditions are extracted as follows:

- *Added Elements*. For each model element e_j that is added to the model as a child of e_i, a precondition Pe_i is created. The type vector for Pe_i captures the types of elements that are visited from traversing from e_i to the root of the model. T_0 is set to the type of e_i.

- *Removed Elements*. If an element e_i is removed from the model, a precondition Pe_k is created. The type vector for Pe_k captures the types of elements that are visited from traversing from e_i to the root of the model. T_0 is set to the type of e_i.
- *Added Connections*. Each new connection, c_j, that is added from model element e_i to e_j produces a new precondition Pc_i. The type vector for the source element Pe_j captures the types of elements that are visited from traversing the source element to the root of the model. The type vector for the target element Pe_k captures the types of elements that are visited from traversing the target element to the root of the model. T_l is set to 0 to indicate that no existing connection is required between the elements that satisfy Pe_j and Pe_k.
- *Removed Connections*. Each deleted connection, c_j, that previously started from model element e_i and ended at model element e_j produces a new precondition, Pc_i. The type vector for the source element Pe_j captures the types of elements that are visited from traversing the source element to the root of the model. The type vector for the target element, Pe_k, captures the types of elements that are visited from traversing from the target element to the root of the model. T_l is set to the type of c_j.

- *Changed Element Attributes*. If an element e_i, has an attribute value changed, a pre-condition Pe_k, is created. The type vector for Pe_k captures the types of elements that are visited from traversing from e_i to the root of the model. T_0 is set to the type of e_i.
- *Changed Connection Attributes*. If a connection, c_i, has an attribute value changed, a precondition Pc_k is created. The type vector for the source element Pe_j captures the types of elements that are visited from traversing the source element to the root of the model. The type vector for the target element Pe_k captures the types of elements that are visited from traversing the target element to the root of the model. T_l is set to the type of c_j.

Attribute preconditions specify the required values of attributes on the model elements that a transformation will apply. The attribute preconditions, *Ac*, are specified as tuples:

$$Ac_i = <Pe_i, Expr> \tag{10}$$

where Pe_i is a structural precondition specifying the source model element to which the attribute precondition must be checked. The *Expr* component specifies a mathematical expression over the attributes of an element that satisfy Pe_i. Currently, the attribute must be a primitive value and any logical and arithmetic expressions are supported.

Complete structural and attribute preconditions are difficult to infer automatically. Simple algorithms can extract preconditions that specify the minimum number of required model elements and connections, and an exact value of one or more element attributes. However, these algorithms are often too exclusive and generate preconditions that require exact matching of the structure and all attribute values. Ideally, attribute preconditions are specified as expressions from domain knowledge covering the affected elements. Manual inference refinement is used to capture this type of precondition.

With the inferred precondition, the transformation action $\vec{T}$ can be constructed by listing all the recorded operations *op* in the demonstration, associating with the elements and connections in the precondition $\vec{P}$.

3.3.4 User Refinement

The goal of MTBD is to generate a transformation, $\vec{T}$, that faithfully represents the domain function $K(M_i)$. However, in many circumstances, the model that the function is demonstrated on, M_i, may lack sufficient information to infer preconditions accurately. In this type of situation, the domain expert must be able to refine the inferred preconditions in order to ensure that $\vec{T}$ accurately captures $K(M_i)$. The optional user refinement function, $\phi(\vec{P},\vec{T})$, allows the user to view and modify the inferred transformation and preconditions produced by *TG* and ϖ. The following three types of refinement are supported:

- Refinement on structural precondition is a function $\phi_s(\vec{P})$ to include additional element $Pe_i = T_0, T_1,...,T_n$ or connection $Pc_i = <Pe_j, Pe_k, T_l>$ to the initial precondition $\vec{P}$, and produces an updated precondition $\vec{P}'$.
- Refinement on attribute precondition is a function $\phi_a(\vec{P})$ to include an additional attribute constraint $Ac_i = <Pe_i, Expr>$ to the initial precondition $\vec{P}$, and produces an updated precondition $\vec{P}'$.
- Refinement on transformation actions is a function $\phi_t(\vec{T})$ to update a set of *op* in $\vec{T}$ to be *op'* as generic, and produces an updated transformation action $\vec{T}'$.

3.3.5 Pattern Execution

The pattern execution function $\xi(M_j, \vec{P}', \vec{T}')$ takes an input model M_j, and matches the precondition $\vec{P}'$. Transformation actions $\vec{T}'$ are executed on all the matched locations. The matching algorithm is based on a backtracking algorithm as shown in Algorithm 2. The algorithm works by first constructing the candidate object list used for matching the preconditions. Then, all combinations of the candidate objects in the list are tried to match all preconditions. Failing to satisfy any of the preconditions will lead to the next combination in a backtracking manner. Once the precondition $\vec{P}'$ can be matched, transformation actions $\vec{T}'$ can be guaranteed to be executed with the sufficient operands.

```
Initialize a candidate object list $L$ containing all the elements and connections in $M_j$
for each entry $p$ in the precondition $\vec{P}'$
  for each $obj$ in the candidate object list $L$
    if $obj$ matches $p$ then assign $obj$ to $p$ and break
    if $obj$ does not match $p$ then continue
  end for
  if $p$ is assigned and is the last entry in the list $L$ then matching succeeds
  if $p$ has not been assign then backtrack to the previous $p$ and continue
  if no further backtracking is allowed then matching fails and break
end for
```

Algorithm 2 – Precondition matching using a backtracking algorithm

3.4 Related Work

The general area of related work concerns new model transformation approaches that aim at simplifying the implementation of model transformation tasks. Some innovative model transformation approaches have been proposed and developed as alternatives to MTLs. These new approaches share a similar goal of making the specification of model transformation easier and more user friendly, requiring less knowledge of MTLs and metamodels. These innovations provide strong potential to simplify the automation of model scalability tasks.

Model Transformation By Example (MTBE) [Varró, 2006] is an innovative approach to address the challenges inherent from using model transformation languages. Instead of writing transformation rules manually, MTBE enables users to define a prototypical set of interrelated mappings between the source and target model instances, and then the metamodel-level transformation rules can be inferred and generated semi-automatically. In this context, users work directly at the model instance level and configure the mappings without knowing any details about the metamodel definition or the hidden concepts. With the semi-automatically generated rules, the simplicity of specifying model transformations is greatly improved. As first introduced by Varró [Varró, 2006], the prototypical transformation rules of MTBE can be generated partially from the user-defined mappings by conducting source and target model context analysis. Varró later proposed a way to realize MTBE by using inductive logic programming [Balogh and Varró, 2009]. Similarly, Strommer and Wimmer implemented an Eclipse prototype to enable generation of ATL rules from the semantic mappings between domain models [Strommer et al., 2007; Strommer and Wimmer, 2008]. Instead of using logic programming engines, the inference and reasoning process is based on pattern matching.

However, the current state of MTBE research still has some limitations in terms of automating model scalability tasks. The semi-automatic generation often leads to an iterative manual refinement of the generated rules; therefore, the model evolution designers are not isolated completely from knowing the transformation languages and the metamodel definitions. In addition, the inference of transformation rules depends on the given sets of mapping examples. In order to obtain a complete and precise inference result, one or more representative examples must be available for users to setup the prototypical mappings, but seeding the process with the proper scalability examples is not always an easy task. Furthermore, current MTBE approaches focus on mapping the corresponding domain concepts between two different metamodels without handling complex attribute transformations. Therefore, it is challenging to automate the configuration of attributes in the scaling process, which is commonly required in practice. Finally, most MTBE approaches fit the exogenous model transformation concept very well to map the concepts one-to-one between two different domains, but they are not very practical when it comes to endogenous model transformations where one-to-multiple or multiple-to-multiple mappings between the source and target models are involved, which presents limitations in supporting model scalability evolution activities.

Brosch et al. introduced a method for specifying composite operations within the user's modeling language and environment of choice [Brosch et al., 2009-a; Brosch et al., 2009-b]. The user models the composite operation by-example, changing a source model into the desired target model. By comparing the source and target states, the specific changes can be summarized by a model difference algorithm. After giving additional specification of the pre-condition and post-condition, an Operation Specification Model (OSM) can be generated that represents the composite operation scenario and can be used to generate other transformation artifacts. Similar to MTBE, users can work on the concrete model instance level without knowing about the metamodel to define composite operations through examples. Although user refinement (e.g., specification of pre- and post- conditions) is also needed to make the generated transformation complete and accurate, the refinement is done at the example level through the given interfaces, rather than at the generated transformation rule when using MTBE. In addition, the composite operation focuses on endogenous model transformation, which potentially could be used to support automating model scalability tasks. However, the major limitations with this approach are: 1) Even though the refinement process is not on the level of generated model transformation rules, some programming concepts are involved (e.g., `includesAll()`, `isEmpty()`, and some iteration control), making this process dependent on technical skills that some domain experts may not possess; 2) Attribute transformation has not been considered and implemented, which shares the same problem as MTBE; 3) In the generation of artifacts for a certain scenario, a manual binding process is required to map the elements in the OSM to the new concrete model. Although a user friendly interface has been developed to simplify the procedure, the manual binding process would become challenging when a large number of model elements and connections are present in a scaling scenario.

EMF Refactor [Arendt et al., 2009; EMF Refactor, 2011] is a new open source component under the Eclipse EMFT project [Eclipse EMFT, 2011] to provide tool support for generating and applying refactorings for models based on EMF Ecore models. EMF Refactor is based on EMF Tiger, an Eclipse plug-in that performs in-place EMF model transformations using a graphical MTL. The model transformation concepts of EMF Tiger are based on algebraic graph transformation concepts. Model refactorings are designed by ordered sets of rules. Each rule describes a conditional statement on model changes. If the pattern specified in the LHS exists, it is transformed into another pattern defined in the RHS. Additionally, several negative application conditions (NACs) can be specified which represent patterns that prevent the rule from being applied. A complete set of artifacts can be generated from the rules as a refactoring operation applicable to EMF models.

EMF Refactor enables an automatic generation of refactoring operations, simplifying the process of adding new refactoring functions to support model evolution activities in model editors. However, the initial definition of the refactoring rules is based on EMF Tiger. As pointed out in Section 1.3, a graphical MTL also presents challenges to end-users. In fact, defining LHS, RHS, and NAC graphs may be as difficult as writing textual rules for those users who have no model transformation or programming experience. Moreover, EMF Refactor is restricted to support model refactoring without the capability of enabling other types of model evolution activities such as model scalability, aspect-oriented modeling.

Although our contribution focuses on model transformations, a similar work has been done to carry out program transformations by demonstration [Robbes and Lanza, 2008]. To perform a program transformation, users first manually change a concrete program example, and all the changes will be recorded by the monitoring plug-in. Then, the recorded changes will be generalized in a transformation. After editing and specifying the generated transformation, it can be applied to other source code locations. Although it also supports the specification of how variable values are computed, it is in a separate step with much manual editing involved. MTBD automates this step in the demonstration process and is focused on demonstrating changes on model instances, not source code.

3.5 Summary

The goal of the research described in this chapter is to provide an end-user centric model transformation approach to support model evolution. The new approach presented in this chapter is MTBD that extends the idea of PBE to allow users to specify a model transformation by demonstrating the process on concrete examples. The detailed MTBD process and components are presented, with its formal specification being defined. MTBD has been implemented as a plug-in to GEMS in Eclipse, which can support these model evolution activities on any DSML defined in GEMS.

Chapter 4 will provide case studies of using MTBD on the typical model evolution tasks, such as model scalability, model refactoring, aspect-oriented modeling, model management, and model layout.

CHAPTER 4
MTBD IN ACTION:
USING MTBD TO SUPPORT MODEL EVOLUTION

The final goal of MTBD is to support model evolution activities in practice. Five types of model evolution tasks will be described in this chapter to demonstrate a wide range of evolution tasks that are possible with MTBD. For each type of model evolution, background information will be given followed by the key techniques needed. Then, a case study will be presented to illustrate how to use MTBD to address the problem in each type of evolution. Furthermore, to demonstrate the benefits of this approach, experimental evaluation is provided at the end of the chapter.

4.1 Model Refactoring

Refactoring refers to the process of changing the internal structure of a software system without modifying its external functional behavior or existing functionality [Fowler, 1999]. Traditionally, refactoring focused on the implementation stage to optimize the structure of program code [Mens and Tourwé, 2004]. In MDE and DSM, applying refactoring to models is as important as to code [Zhang et al., 2005], because models have become first-class entities to construct a software system. Also, optimizing model structures at the design stage may result in a potential reduction of the cost during future maintenance [Zhang et al., 2005].

A model refactoring process is a typical example of an endogenous model transformation, where a source model in a non-optimized state is transformed to the target model with the structure being optimized. For example, Figure 4.1 shows a refactoring example on a UML state diagram for a simple telephone object. The initial model is in a messy state (i.e., because one can hang up at any time during communication, transitions have been drawn to the *Idle* state from every other state in the diagram), but can be transformed to a model with an optimized structure (i.e., all the other states have been moved into a new parent state called *Active*, and only one set of incoming and outgoing transitions from *Idle* is needed). Both models are in the same domain and conform to the same metamodel, and the refactoring did not change the functions of the model.

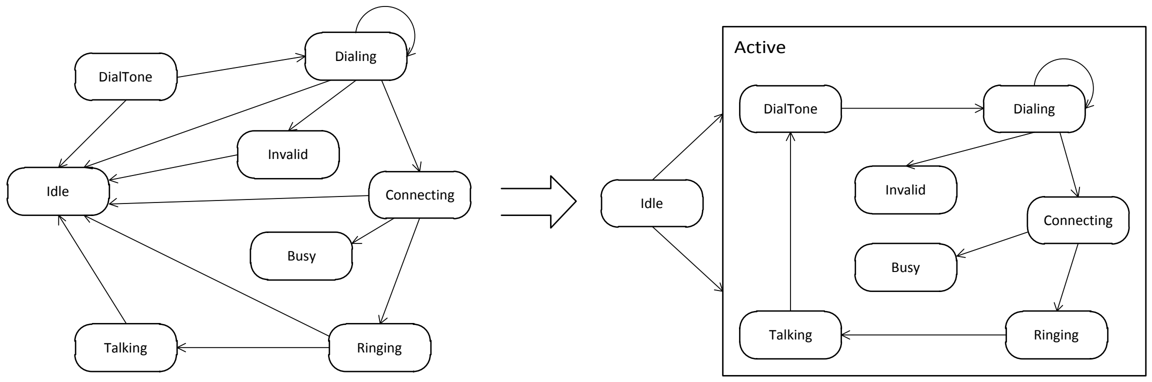


Figure 4.1 – Model refactoring for state diagram (adapted from [Suny é et al., 2001])

To use model transformation to implement model refactoring tasks in a practical way, the following features are frequently required:

- The final model transformation must be generic, not specific to a model instance (e.g., the transformation should be capable of moving not only seven states to the *Active* state, but also any number of states to the *Active* state).
- A precise precondition specification must be enabled to restrict the subpart of the model that is to be refactored.
- When executing a model transformation, users should be able to select the subparts of the model manually to perform a refactoring, or automatically match the precondition in the whole model.
- User input must be enabled to specify the attributes for different scenarios. In the example of Figure 4.1, the newly created surrounding state is called *Active*. However, in other scenarios, the name could be something else. Therefore, users should be able to specify the name according to their needs.

MTBD supports the requirements above by enabling the precondition and generic operation refinement. The execution controller enables users to flexibly choose where to execute the transformation pattern. The user input can be realized by using the artificial attribute pair, which will be presented in the case study.

4.1.1 Case Study – Background

UML class diagrams have been used widely to design and visualize software architecture. Similar to software source code refactoring, a number of refactoring rules can be applied to UML class diagrams at the modeling level. Because UML class diagrams are more intuitive as a graphical notation than the source code, it provides a way to enable software developers to discover the refactoring hot spots earlier in the lifecycle, as well as evaluating the impact after the refactoring.

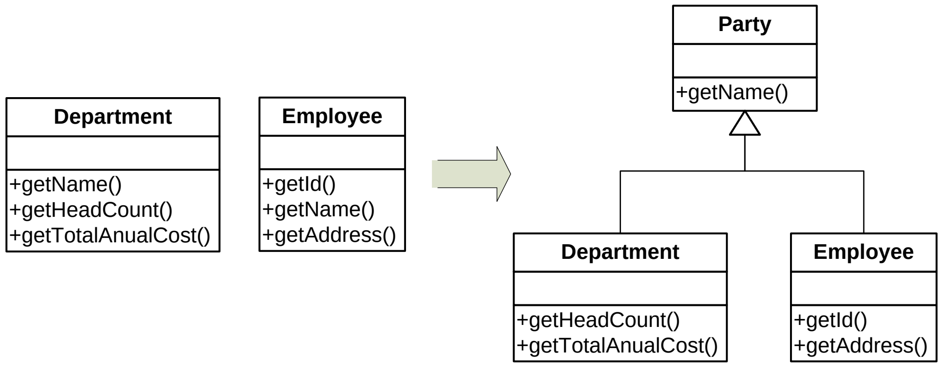


Figure 4.2 – UML refactoring - Extract Superclass

One classical UML class diagram refactoring is *Extract Superclass*, which is defined as "when you have two classes with similar features, create a superclass and move the common features to the superclass." [France et al., 2003] The main purpose of this refactoring is to remove the duplicate common behaviors from different classes. For instance, as shown in Figure 4.2, both *Department* and *Employee* share the same method *getName()*, so a new parent class *Party* is created containing the common method *getName()*, followed by making *Department* and *Employee* extensions of the super class and removing the original *getName()*. Of course, extract superclass can be applied to more than two classes based on the same principle.

4.1.2 Case Study – Solution

Using MTBD to specify model refactoring starts from demonstrating the refactoring process on the concrete example followed by refining and generating the generic transformation pattern. We take the example in Figure 4.2 as our base model for the demonstration. List 4.1 shows the operations performed during the demonstration. The demonstration starts by creating the new parent class. Because in different scenarios, the name of the new parent class varies, so an artificial name is created and then used to set the name of the new class. The artificial name will become a user input box when the final transformation pattern is executed, so that users can have a chance to input their desired attribute values. In the newly created parent class, a method is added, which represents the common behavior to extract. The name of the method should be the same as the one to be removed in the subclasses. The attribute refactoring editor can be used to access the method *getName()* in *Department* and set the name of the new method to be the same. After the method is created in the parent classes, we can then remove the original method in the subclass, and finally make a generalization connection. After this point, the extract process in one of the subclasses has been done. We continue to demonstrate extraction of the behavior in *Employee* class. Because the parent class has been created already, we simply remove the method *getName()* in *Employee* and make the generalization connection.

The correct transformation pattern cannot be generated without user refinement in this case. On one hand, the precondition has to be defined to restrict the extract process only to the method with the same name, as shown in Operation 10 in List 4.1. On the other hand, the number of subclasses varies, so we must make sure that the same process can be applied to all those classes that having the same behavior, by identifying Operations 8 and 9 as generic.

List 4.1 – Operations for demonstrating Extract Superclass
(* represents generic operations to be identified)

Sequence	**Operation Performed**
1	Add a *Class* in *UMLRoot*
2	Create an artificial name with the value: *ClassName = “Party”*
3	Set *UMLRoot.Class.name = ClassName = “Party”*
4	Add a *Method* in *UMLRoot.Party*
5	Set *UMLRoot.Party.Method.name = UMLRoot.Department.getName = “getName”*
6	Remove *getName* in *UMLRoot.Department*
7	Connect *UMLRoot.Department and UMLRoot.Party* with generalization
8*	Remove *getName* in *UMLRoot.Employee*
9*	Connect *UMLRoot.Employee and UMLRoot.Party* with generalization
10	Add precondition *UMLRoot.Department.getName.name == UMLRoot.Employee.getName.name*

With the finalized transformation pattern, users can apply it to any UML class diagram model either by automatically matching the pattern, or manually selecting part of the model to receive the refactoring.

4.2 Model Scalability

Model scalability is defined in [Gray et al., 2005] as the ability to build a complex model from a base model by adding or replicating its model elements, connections or substructures. In the context of MDE and DSM, analyzing and testing the scalability of models becomes essential in every phase of software development. For instance, feature models [Kang et al., 1990] are used as design models in software product lines to configure the components of a software system, such that adding new product functionality often consists of adding new feature elements to a model. Domain-specific models can be built to specify software systems and generate implementation code, which means that expanding the implementation of a software system is based on scaling the corresponding domain-specific models. Moreover, when a software system is about to be deployed, deployment models can be used to specify how to allocate software to the underlying hardware infrastructure [White et al., 2007-b] and to monitor and control the infrastructure at runtime [Sun et al., 2009-b]. In order to allocate additional infrastructure to handle larger workloads, the underlying deployment models must be scaled.

To support model scalability, the following four features are important when using model transformation approaches:

- The finalized model transformation must be capable of scaling up a model independently of the number of base degrees. In other words, it must be very generic (e.g., the transformation should work for the tasks to scale up the model from 4 to 5, 9 to 10, 99 to 100, or even back down from a larger model to a smaller one).
- Because it is very common to compose an attribute (e.g., name) in the complex model using the attribute in the based model, a rich set of attribute transformations should be supported (e.g., string concatenation, substring matching).
- Manually scaling a model by executing a model transformation one-by-one is tedious. When executing a transformation, users should be able to specify the number of times the selected transformation will be executed.
- Sometimes, a single scaling process can be done by several separated tasks with several model transformation processes, so users should also be allowed to select multiple model transformations in a certain sequence to execute.

MTBD is designed and implemented to support the features listed above. To make the generated transformation pattern generic for different model instances, users could first identify the process of scaling the model by one degree. Then, by demonstrating this smaller scaling transformation on a concrete model, the generic pattern can be inferred by identifying the generic operations in the user refinement step. Executing the pattern multiple times (users can customize the execution times in the execution controller) may result in scaling the model for multiple degrees, without being dependent on the existing number of model elements and connections. For those complex model scalability scenarios, a single task can be divided and accomplished by multiple demonstrations. The execution control also enables users to select multiple transformation patterns in a specific execution sequence. Finally, complex attribute transformation is supported in the attribute refactoring editor.

4.2.1 Case Study – Background

Stochastic Reward Nets (SRNs) [Muppala et al., 1994] can be used for evaluating the reliability of complex distributed systems. The Stochastic Reward Net Modeling Language (SRNML) [Kogekar et al., 2006] was developed to describe SRN models of large distributed systems [Lin et al., 2008], in order to design and model performance-based system properties such as schedulability, performance, and time profiles. For example, the SRN model defined by SRNML in Figure 4.3 depicts mechanisms to handle synchronous event demultiplexing and dispatching when applying the Reactor pattern [Schmidt et al., 2000] in middleware for network services.

The reactor pattern handles service requests to a service handler from one or multiple input events concurrently. Whenever an event comes in, the service handler demultiplexes the incoming event to its associated event handler. Thus, an SRN model consists of two parts: the event types handled by a reactor and the associated execution snapshot. The execution snapshot depicts the underlying mechanism for handling the event types included in the top part, so any change made to the event types will require corresponding changes to the snapshot. In Figure 4.3, the original model has two event types, *1* and *2*, each from its arrival (e.g., *A1*), to queuing (e.g., *Sn1*) and finally service (e.g., *Sr1*) through the immediate transitions (e.g., *B1*, *S1*). It also models the process of taking successive snapshots and non-deterministic service of event handles in each snapshot through some snapshot transitions and places (e.g., *StSnpSht*, *TStSnp1*, *TProcSnp1,2*).

The scalability challenges of SRN models are triggered when new event types and the corresponding connections with event handlers are added. As shown in the bottom of Figure 4.3, when two new event types (*3* and *4*) need to be modeled, two new sets of event types and connections (i.e., from *A3* to *Sr3*, from *A4* to *Sr4*) should be added. Also, the snapshot model should be scaled accordingly by adding new snapshot places (i.e., *SnpLnProg3*, *SnpLnProg4*), transitions from starting place to end place (i.e., *TStSnp3*, *TEnSnp3*, *TStSnp4*, *TEnSnp4*), transitions between each new place and each existing place (i.e., *TProcSnp3,1*, *TProcSnp1,3*, *TProcSnp3,2*, *TProcSnp2,3*, *TProcSnp4,1*, *TProcSnp1,4*, *TProcSnp4,2*, *TProcSnp2,4*, *TProcSnp3,4*, *TProcSnp4,3*), as well as all the needed connections between places and transitions.

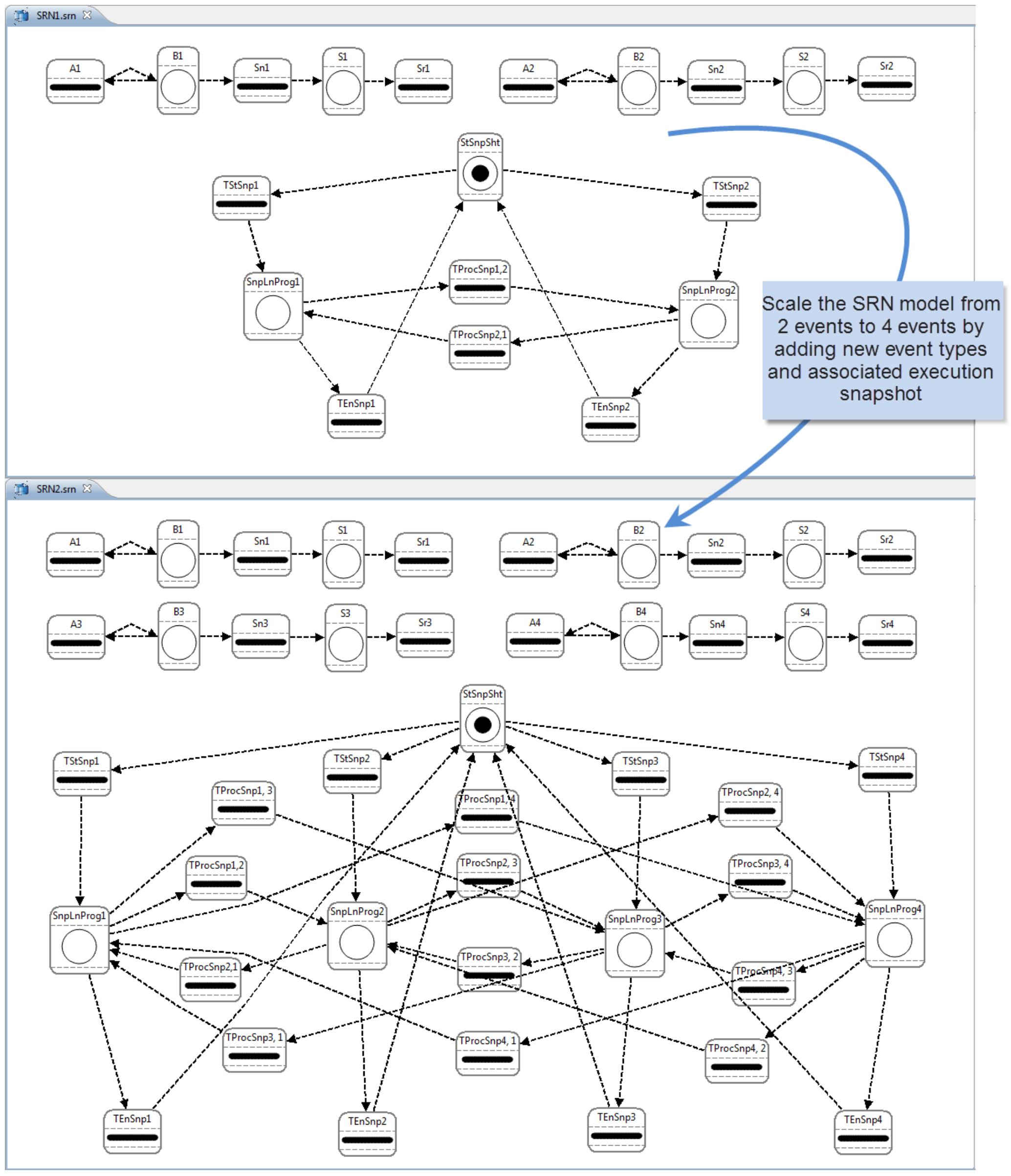


Figure 4.3 – An SRN model before (top) and after (bottom) scaling

4.2.2 Case Study – Solution

Using MTBD to address the model scalability problem starts with analyzing the scalability scenario. The task of adding one more event types to an existing SRN model can be divided into the following three sub-tasks, as shown in Figure 4.4:

t1. Create a new set of places, transitions and connections for the new event type. Specify proper names for them based on the name of the event.

t2. Create the *TStSnp* and *TEnSnp* snapshot transitions and the *SnpInProg* snapshot place, as well as the associated connections.

t3. For each pair of <existing snapshot place, new snapshot place>, create two *TProcSnp* transitions and connect their *SnpInProg* places to these *TProcSnp* transitions.

To demonstrate scalability as an evolution task, we choose the 2-event SRN model as shown in the top of Figure 4.3. Then, we manually edit the model and demonstrate the three sub-tasks. To demonstrate t1, the operations identified in List 4.2 are performed.

List 4.2 – Operations for demonstrating Sub-task t1 of model scalability example

Sequence	**Operation Performed**
1	Add a *Place* in *SRNRoot*
2	Create an artificial name with the value: *EventName = "3"*
3	Set *SRNRoot.Place.name = "A" + EventName = "A3"*
4	Add a *Transition* in *SRNRoot*
5	Set *SRNRoot.Transition.name = "B" + EventName = "B3"*
6	Add a *Place* in *SRNRoot*
7	Set *SRNRoot.Place.name = "Sn" + EventName = "Sn3"*
8	Add a *Transition* in *SRNRoot*
9	Set *SRNRoot.Transition.name = "S" + EventName = "S3"*
10	Add a *Place* in *SRNRoot*
11	Set *SRNRoot.Place.name = "Sr" + EventName = "Sr3"*
12	Connect *SRNRoot.A3* and *SRNRoot.B3*
13	Connect *SRNRoot.B3* and *SRNRoot.A3*
14	Connect *SRNRoot.B3* and *SRNRoot.Sn3*
15	Connect *SRNRoot.Sn3* and *SRNRoot.S3*
16	Connect *SRNRoot.S3* and *SRNRoot.Sr3*
17	Connect *SRNRoot.A3* and *SRNRoot.B3*

Operation 2 is used to create a name for a certain value manually, which can be reused later in the rest of the demonstration to setup the desired name for each element (e.g., the new event is called "*3*", so the places and transitions are named as "*A3*", "*B3*", "*Sn3*"). The operation also indicates that the value of this name should be given by the user, which will invoke an input box when the final generated transformation pattern is executed on other model instances. When setting up the attribute in operations 3, 5, 7, 9, 11, users just need to give the specific composition of the attributes by using the artificial names and constants, or simply select an existing attribute value in the attribute refactoring editor. After applying these operations, the top model will have a new event type, as shown in Figure 4.4 (Sub-task 1).

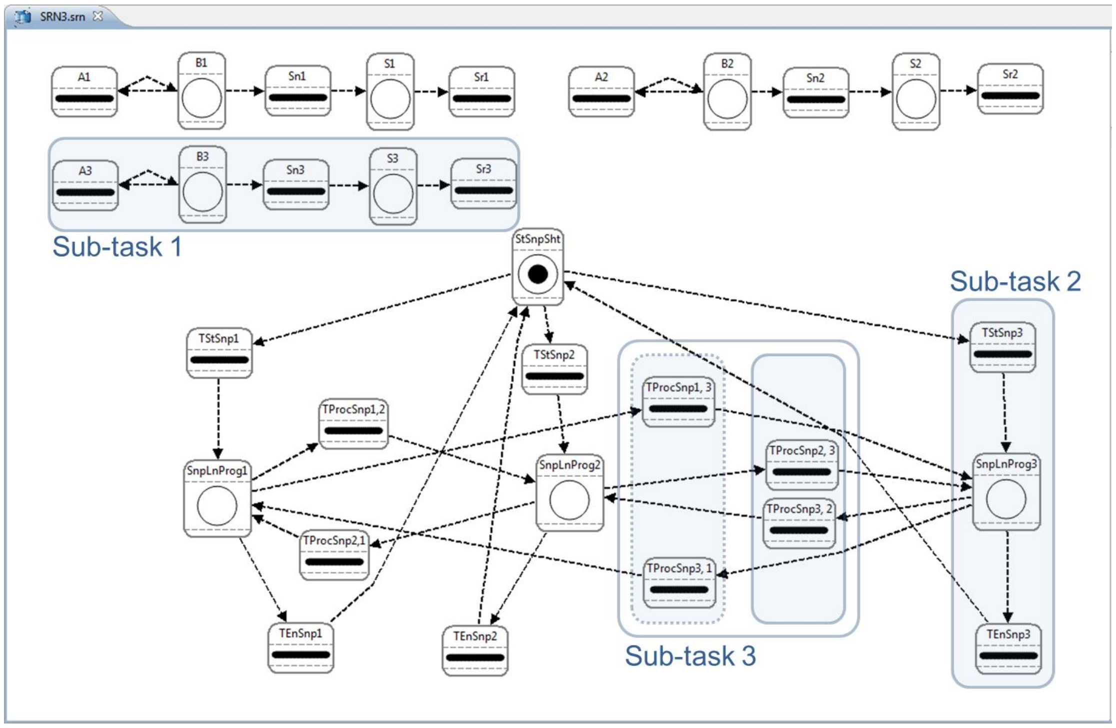


Figure 4.4 – The process of scaling a SRN model from two events to three events

To demonstrate t2, the necessary snapshot places and transitions in sub-task 2 are added for the new event type by performing the operations indicated in List 4.3. Figure 4.4 (Sub-task t2) shows the model after these operations.

List 4.3 – Operations for demonstrating Sub-task t2 of model scalability example

Sequence	Operation Performed
18	Add a *SnpPlace* in *SRNRoot*
19	Set*SRNRoot.SnpPlace.name= "SnpLnProg"+EventName = "SnpLnProg3"*
20	Add a *SnpTransition* in *SRNRoot*
21	Set *SRNRoot.SnpTransition.name = "TStSnp" + EventName = "TStSnp3"*
22	Add a *SnpTransition* in *SRNRoot*
23	Set *SRNRoot.SnpTransition.name = "TEnSnp" + EventName = "TEnSnp3"*
24	Connect *SRNRoot.StSnpSht* and *SRNRoot.TStSnp3*
25	Connect *SRNRoot.TStSnp3* and *SRNRoot.SnpLnProg3*
26	Connect *SRNRoot.SnpLnProg3* and *SRNRoot.TEnSnp3*
27	Connect *SRNRoot.TEnSnp3* and *SRNRoot.StSnpSht*

To demonstrate t3, two snapshot transitions for each <*existing snapshot place, new snapshot place*> are created. This sub-task involves using generic operations, because the number of existing snapshot places may vary in different model instances. This number will also increase after each scaling process. Therefore, in the demonstration, users only need to create two snapshot transitions for just one set of <*existing snapshot place, new snapshot place*>, followed by identifying these operations as generic after the demonstration, so that the engine will generate the correct transformation pattern to repeat these operations when needed. The operations performed are shown in List 4.4. We select *SnpLnProg2* as the existing snapshot place, and demonstrate the creation of snapshot transitions *TProcSnp2,3* and *TProcSnp3, 2*.

List 4.4 – Operations for demonstrating Sub-task t3 of model scalability example (* represents generic operations to be identified)

Sequence	**Operation Performed**
28*	Add a *SnpTransition* in *SRNRoot*
29*	Set *SRNRoot.SnpTransition.name = "TProcSnp" + SRNRoot.SnpLnProg2.name.subString(9) + "," + EventName = "TProcSnp" + "2" + "," + "3" = "TProcSnp2,3"*
30*	Add a *SnpTransition* in *SRNRoot*
31*	Set *SRNRoot.SnpTransition.name = "TProcSnp" + EventName + "," + SRNRoot.SnpLnProg3.name.subString(9) = "TProcSnp" + "3" + "," + "2" = "TProcSnp3,2"*
32*	Connect *SRNRoot.SnpLnProg2* and *SRNRoot.TProcSnp2,3*
33*	Connect *SRNRoot.TProcSnp2,3* and *SRNRoot.SnpLnProg3*
34*	Connect *SRNRoot.SnpLnProg3* and *SRNRoot.TProcSnp3,2*
35*	Connect *SRNRoot.TProcSnp3,2* and *SRNRoot.SnpLnProg2*

When specifying the name attributes, complex String composition can be given, as done in operations 29 and 31. After the demonstration is completed and generic operations are identified in the user refinement step, the inference engine automatically infers and generates the transformation pattern. After the inferred transformation is saved, a user may select any model instance and a desired transformation pattern, and the selected model will be scaled by adding a new event type. The execution of the pattern multiple times can be realized using the execution control. The bottom of Figure 4.3 is the result of adding two event types using the inferred pattern.

4.3 Aspect-Oriented Modeling

In DSM, constraints may be specified throughout the nodes of a model to stipulate design criteria and limit design alternatives. A lack of support for separation of concerns with respect to constraints can cause difficulties when creating models [Gray et al., 2001]. The scattering of constraints throughout various levels of a model makes it hard to maintain and reason about their effect and purpose [Zhang, 2009].

Similar to the idea of traditional Aspect-Oriented Programming (AOP) [Kiczales et al., 1997], Aspect-Oriented Modeling (AOM) [Balasubramanian et al., 2006-b] enhances modularity at the model level by allowing the separation of concerns. The same concepts in AOP can also be applied in AOM [Gray et al., 2001].

A typical AOM process weaves the aspect models (i.e., the crosscutting concerns that are scattered across a model) into the base model (i.e., the main model without crosscutting behaviors). The model weaving process is accomplished by locating specific locations in the base model according to some pattern of model properties, and composing the necessary aspect models at these locations. An AOM task specifies where and how to weave new concerns into the base model.

To support typical AOM functions using model transformation approaches, two points should be taken into consideration:

- The mechanism to specify the precondition of a model transformation is essential to locate the correct locations for weaving an aspect. Thus, it must support a desired granularity and diversity on the specification of a precondition.
- In some AOM tasks, constraints need to be weaved into the base model [Gray et al., 2001]. These constraints are often specified in OCL, which contains complex string formatting. Therefore, long string construction and computation should be supported.

MTBD can be applied to address AOM challenges because the specification of preconditions on both the structure and attribute are supported, with the granularity on any model element, connection and all of their attributes. The specific aspect can be represented by the sequence of transformation actions. Long string computation is possible using the attribute refactoring editor. Using MTBD, users can demonstrate where and how to weave an aspect into one of the desired locations in the base model, followed by weaving the aspect to the rest of the model instance by executing the generated transformation pattern.

4.3.1 Case Study – Background

The development of distributed real-time and embedded (DRE) systems is often challenging because of the consideration of different Quality-of-Service (QoS) constraints that might conflict with each other and must be treated as trade-offs among a series of alternative design decisions [Gray et al., 2009]. The QoS Adpation Modeling Language (QoSAML) was designed to address the challenges of using an MDE approach, which uses a Finite State Machine (FSM) representation extended with hierarchy and concurrency mechanisms to model the QoS adpative behavior of the system [Gray et al., 2009].

One successful usage of QoSAML is to specify the QoS properties for an Unmanned Aerial Vehicle (UAV) [Karr et al., 2001]. A UAV is an aircraft that is capable of surveying dangerous terrain and territories. The UAV continuously sends video streams to a central distributor, so that operators can observe the video and give futher commands to the UAV. In order to reach a precise and timely response from operations, a smooth video stream must be guaranteed, which means that the video must not be stale, or be affected by jittering. However, due to the changing conditions in the surveillance environment, the fidelity of the video stream must be maintained by adjusting the QoS parameters. In good conditions where a realiable network transmission is avaible, a smooth video stream can be kept using a high video *Size* and a high video *FrameRate*, while in a poor environment, both video *Size* and *FrameRate* should be reduced in order to keep the same video transimission latency.

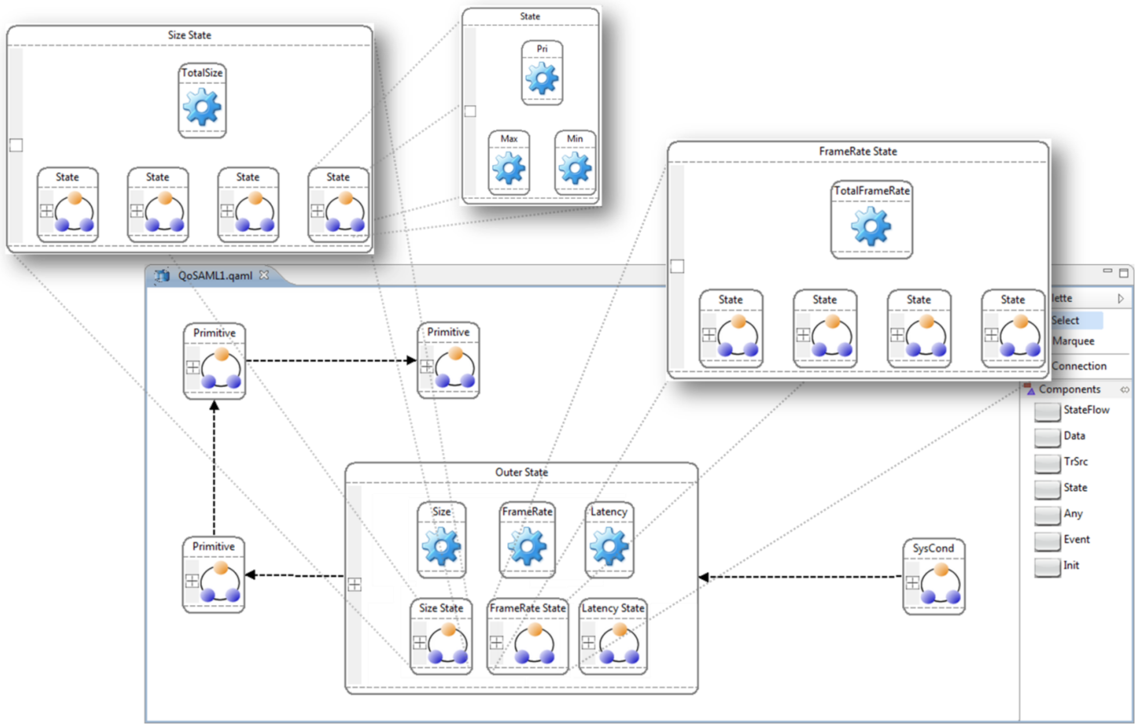


Figure 4.5 – QoSAML model

Figure 4.5 is part of a QoSAML model that specifies the QoS properties for a UAV application. In this model, the latency is a dependent variable input to a hierachical state machine called *Outer State*. Inside the *OuterState*, there are state machines that describe the adaption of identified independent control parameters, such as *Size State*, *FrameRate State*. In each of the state machines, several *States* are included to represent the options for the corresponding control parameter. A state specifies three *Data* for the option: *Pri* defines the priority of this option; *Max* defines the maximum value that can be used for this parameter; and *Min* defines the minimum value for the parameter. Model translators have been developed to generate Contract Description Language (CDL) [Karr et al., 2001] from the QoSAML models automatically, which can be integrated into the runtime kernel of the system.

The AOM scenario in QoSAML results from the configuration of the transition strategies. The model in Figure 4.5 is not complete, because the transitions between different states have not been specified. A transition connects a source state to a target state, representing how a control parameter can be changed and adapted. To give the transitions, there are two different strategies that can be used, as illustrated in Figure 4.6. The left side of

Figure 4.6 specifies a protocol that changes one parameter (*Size*) before trying to adjust another independent paramenter (*FrameRate*). In other words, the *FrameRate* parameter has a higher priority so that it is not reduced until there is no further reduction possible to the *Size*. By contrast, the strategy in the right side of Figure 4.6 is more equitable, with a zig-zag pattern suggesting that the reduction of one parameter is staggered with the reduction of another. From this scenario, it can be seen that weaving the strategy protocols becomes a challenging task when more control parameters are invovled, or a large number of intermediate states are included in the state.

As the case study for supporting AOM, we choose the task of weaving the priority exhaustive protocol to the QoSAML model, which is defined as follows:

In a given state machine, for each pair of two states included in the state machine, if their priority data are less than 5, and if the priority data of one state is one less than the other, add a transition between the two states from the state with the lower priority (SourceState) to the one with the higher priority (TargetState). In addition, set up the attibutes for the transition: the Guard of the transition should be given from the users input, and the Action of the transition should be in the format of "ControlParameterName = (SourceState.Max + TargetState.Max) / 2)."

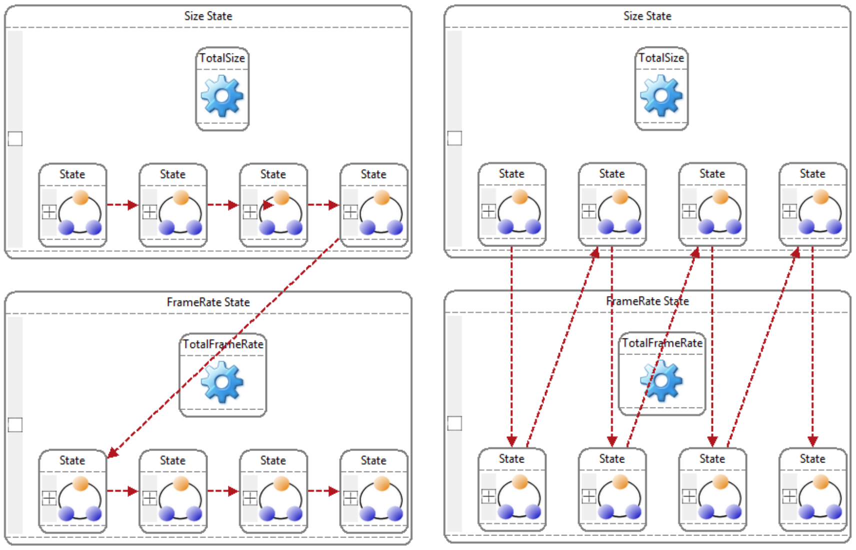
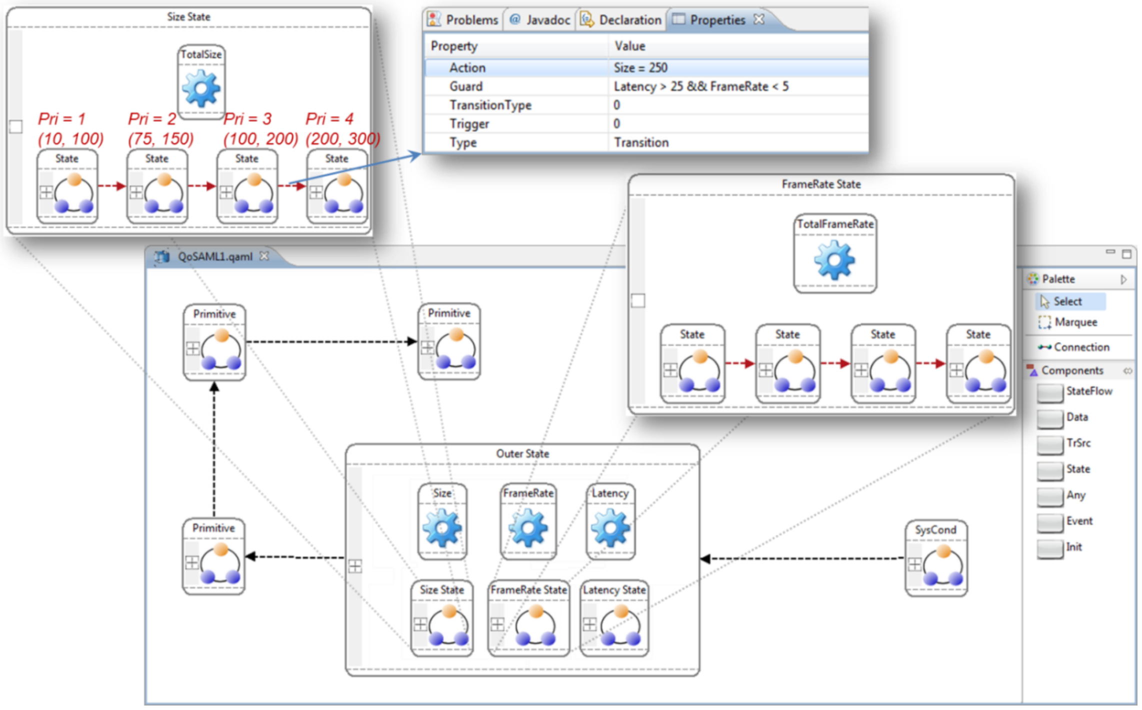


Figure 4.6 – Two state transition protocols to adapt to environment - Priority Exhaustive (left) and Zig-zag (right) (adapted from [Gray, 2002])

For example, Figure 4.7 shows the model after applying the priority exhaustive protocol to *Size State* and *FrameRate State*. The challenges of this task result from locating all pairs of the states that consist of the qualified priority data (i.e., *SourceState.Priority* = *TargetState.Priority* – *1*, *SourceState.Priority* < *5*, *TargetState.Priority* < *5*), performing the repeated computation to get the average value from the two Max data, as well as enabling user input.



Property	Value
Action	Size = 250
Guard	Latency > 25 && FrameRate < 5
TransitionType	0
Trigger	0
Type	Transition

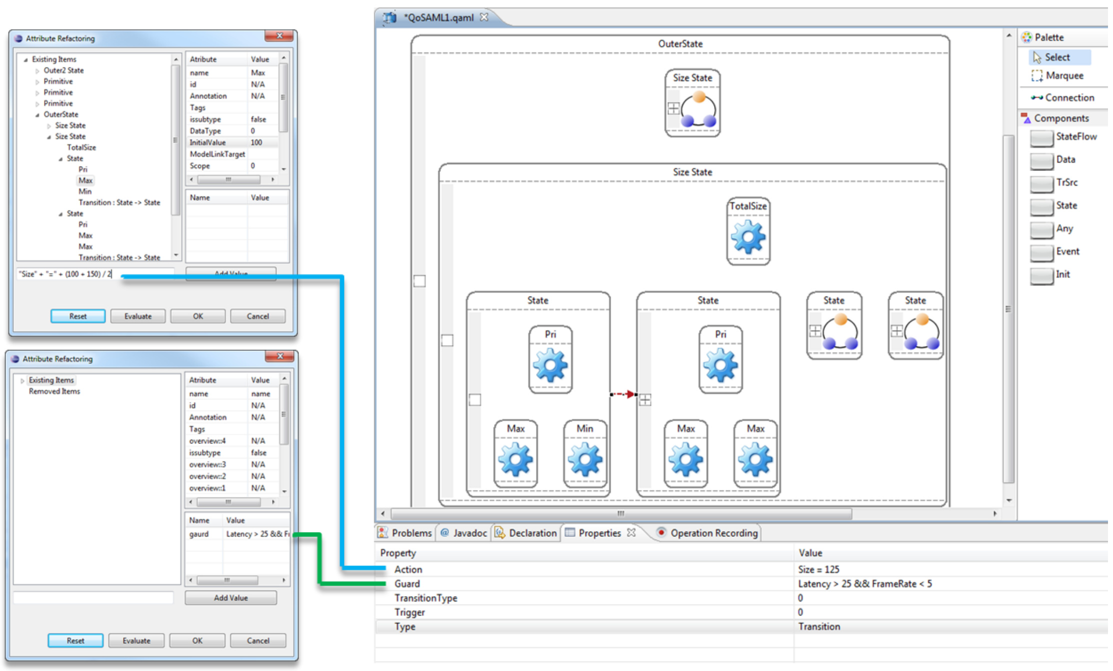
Figure 4.7 – A QoSAML model after applying the Priority Exhaustive protocol

4.3.2 *Case Study – Solution*

The demonstration of adding a QoS transition strategy is performed on the selected *Size State*, as shown in Figure 4.8. Inside the *Size State*, we locate the two *States* with the proper *Pri* values, and perform the operations in List 4.5. The *Action* attribute configuration by operation 2 is conducted through the attribute refactoring editor.

List 4.5 – Operations for demonstrating weaving protocol aspects

Sequence	Operation Performed
1	Add a *Transition* between *QoSAMLRoot.OuterState.SizeState.State1* and *QoSAMLRoot.OuterState.SizeState.State2*
2	Set Transition.Action = *QoSAMLRoot.OuterState.SizeState.name + " = " + (QoSAMLRoot.OuterState.SizeState.State1.Max.value + QoSAMLRoot.OuterState.SizeState.State2.Max.value) / 2 = "Size = 75"*
3	Create a temporary data pair (Name: *guard*, Value: "*Latency > 25 &&FrameRate< 5*")
4	Set *Transition.Guard* = *guard.value* = "*Latency > 25 &&FrameRate< 5*"



Atribute	Value
name	Max
id	N/A
Annotation	N/A
Tags	
issubtype	false
DataType	0
InitialValue	100
ModelLinkTarget	
Scope	0

Name	Value

"Size" + "=" + (100 + 150) / 2

Atribute	Value
name	name
id	N/A
Annotation	N/A
Tags	
overview::4	N/A
issubtype	false
overview::3	N/A
overview::2	N/A
overview::1	N/A

Name	Value
gaurd	Latency > 25 && Fr

Property	Value
Action	Size = 125
Guard	Latency > 25 && FrameRate < 5
TransitionType	0
Trigger	0
Type	Transition

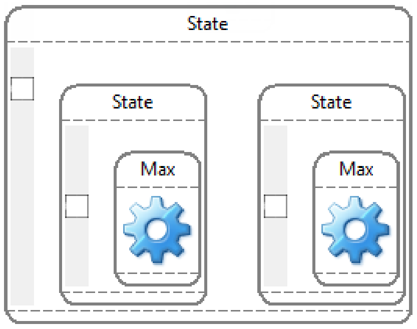
Figure 4.8 – Demonstration of adding a transition and setting up the attributes for the new transition

The initial pattern generalized from the demonstration is shown in Figure 4.9 (the transformation pattern is invisible to end-users, and the figure shows an abstract representation of the pattern for the purpose of illustrating how the pattern is specified and stored). It can be seen that the precondition is not accurate enough, because the relationship between the two *Pri* values are not reflected in the demonstration. Moreover, although the two *Max* elements are included in the pattern, they share the same type as *Min* and *Pri* (their meta types are all *Data*), the consequence being that it is possible that the execution engine incorrectly uses *Min* or *Pri* to calculate the average value, or uses *Max* or *Min* to compare the *Pri* relationship. Thus, it is necessary to futher restrict the *Data* involved in the pattern with their names. The following operations in List 4.6 are performed in the user refinement step. Operations 5 – 10 confirm the required *Pri* data elements and their relationships, while operations 11 – 12 ensures that *Max* data elements exist in the two *States*. Figure 4.10 shows the final generated transformation pattern.

List 4.6 – Refinement operations performed in the demonstration of weaving aspects

Sequence	**Operation Performed**
5	Confirm the containment of *QoSAMLRoot.OuterState.SizeState.State1.Pri*
6	Confirm the containment of *QoSAMLRoot.OuterState.SizeState.State2.Pri*
7	Specify precondition *QoSAMLRoot.OuterState.SizeState.State1.Pri.name = "Pri"*
8	Specify precondition *QoSAMLRoot.OuterState.SizeState.State2.Pri.name = "Pri"*
9	Specify precondition *QoSAMLRoot.OuterState.SizeState.State1.Pri.value* = *QoSAMLRoot.OuterState.SizeState.State2.Pri.value* - 1
10	Specify precondition *QoSAMLRoot.OuterState.SizeState.State2.Pri.value < 5*
11	Specify precondition *QoSAMLRoot.OuterState.SizeState.State1.Max.name == "Max"*
12	Specify precondition *QoSAMLRoot.OuterState.SizeState.State2.Max.name == "Max"*

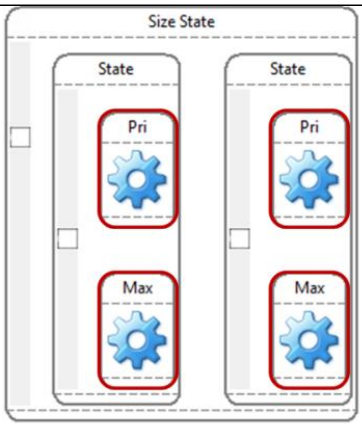
Executing the pattern on any selected *States* will make the execution engine automatically traverse the state and locate all the pairs of included *States* that satisfy the *Pri* relationship constraint and contains needed *Max* elements, so that the *Transition* can be added correctly combined with a user input *Guard* value.

Precondition	
elem1.elem2.elem3.elem4 elem1.elem2.elem3.elem5 elem1.elem2.elem3.elem4.elem6 elem1.elem2.elem3.elem5.elem7	
elem1: QoSAMLRoot elem2: State elem3: State elem4: State elem5: State elem6: Data elem7: Data	

Actions

1. Add a *Transition* between *elem4* and *elem5*
2. Set *Transition.Action* = *elem3.name* + "=" + (*elem6.value* + *elem7.value*) / *2*
3. Create a data pair (*guard* = "*Latency > 25 &&FrameRate< 5*")
4. Set *Transition.Guard* = *guard.value*

Figure 4.9 – The initial generalized transformation pattern

Precondition		
elem1.elem2.elem3.elem4 elem1.elem2.elem3.elem5 elem1.elem2.elem3.elem4.elem6 (elem6.name == "Max") elem1.elem2.elem3.elem5.elem7 (elem7.name == "Max") elem1.elem2.elem3.elem4.elem8 (elem8.name == "Pri") elem1.elem2.elem3.elem5.elem9 (elem9.name == "Pri") (elem8.value == elem9.value – 1) (elem9.value < 5)		
elem1: QoSAMLRoot elem2: State elem3: State	elem4: State elem5: State elem6: Data	elem7: Data elem8: Data elem9: Data

Actions

5. Add a *Transition* between *elem4* and *elem5*
6. Set *Transition.Action* = *elem3.name* + "=" + (*elem6.value* + *elem7.value*) / *2*
7. Create a data pair (*guard* = "*Latency > 25 &&FrameRate< 5*")
8. Set *Transition.Guard* = *guard.value*

Figure 4.10 – The final generated transformation pattern after user refinement

4.4 Model Management

Apart from model refactoring, model scalability and AOM, other model editing tasks are often needed during model evolution for the purpose of maintenance. These kinds of tasks are classified as model management [Deridder et al., 2008; Sun et al., 2009-b].

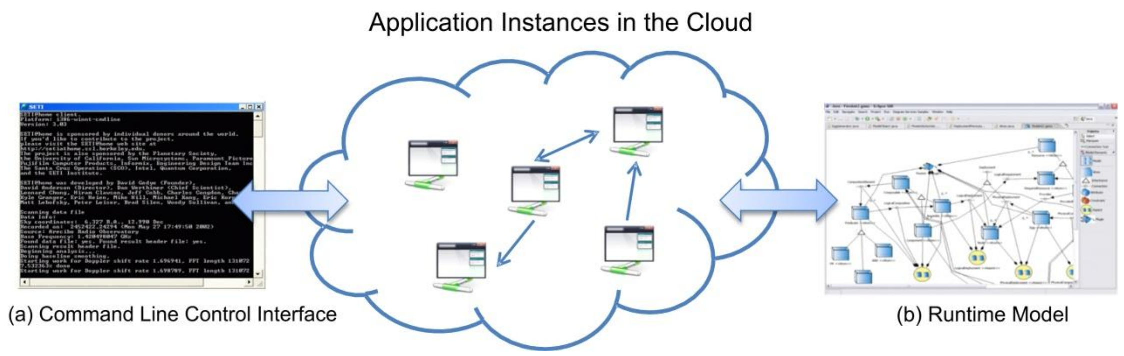
The need for model management often emerges from the change of system requirements, the need to detect and recover erroneous models, the regular update of model status, or the test of an alternative system design. In addition, model management becomes more important and useful when applied to the runtime model of an application [Blair et al., 2009]. Models at runtime extend the applicability of model-driven engineering techniques to the runtime environment. A runtime model usually provides current and exact information about the system to drive subsequent adaptation decisions. A causal connection exists between the models and the applications so that adaptations can be made at the model level rather than at the system level. Runtime model management is significant, because a fast response is always needed in the management tasks in order to reach acceptable performance. Relying on manual model management may be undesirable in some cases, especially when a large number of applications exist.

Realizing the model management tasks also relies on the power of supporting the specification of precondition constraints as well as generic operations. An additional requirement is a mechanism to select and execute certain transformation patterns regularly (e.g., whenever a change happens in the model, the error recovery pattern will be executed to see if the error exists and recovery will occur, if needed).

4.4.1 *Case Study – Background*

In the cloud computing paradigm [Hayes, 2008], the large number of running nodes increases the number of potential points of failure and the complexity of recovering from error states. For instance, if an application terminates unexpectedly, it is necessary to search quickly through the large number of running nodes to locate the problematic nodes and states. Moreover, to avoid costly downtime, administrators must quickly remedy the problematic node states to avoid further spread of errors.

Although many cloud computing platforms provide a user-friendly and simple interface to manage and control the application instances (Figure 4.11a), administrators must still be experienced with the administrative commands, the configuration of each application, as well as some domain knowledge about each running instance. Administrators must therefore be highly trained to handle error detection and error recovery effectively. The complexity of managing a large cloud of nodes can increase maintenance costs, especially when personnel are replaced due to turnover or downsizing.


Application Instances in the Cloud
SETI
(a) Command Line Control Interface
(b) Runtime Model

```
SETI@home client.
Platform: i386-winnt-cmdline
Version: 3.03

SETI@home is sponsored by individual donors around the world.
If you'd like to contribute to the project,
please visit the SETI@home web site at
http://setiathome.ssl.berkeley.edu.
The project is also sponsored by the Planetary Society,
the University of California, Sun Microsystems, Paramount Picture
Fujifilm Computer Products, Informix, Engineering Design Team Inc
The Santa Cruz Operation (SCO), Intel, Quantum Corporation,
and the SETI Institute.

SETI@home was developed by David Gedye (Founder),
David Anderson (Director), Dan Werthimer (Chief Scientist),
Leonard Chung, Hiram Clawson, Jeff Cobb, Charles Congdon, Cha
Kyle Granger, Eric Heien, Mike Hill, Michael Kang, Eric Kor
Matt Lebofsky, Peter Leiser, Brad Silen, Woody Sullivan, an

Scanning data file
Data Info:
Sky coordinates:  6.327 R.A., 12.998 Dec
Recorded on:  2452422.24294 (Mon May 27 17:49:50 2002)
Source: Arecibo Radio Observatory
Base Frequency: 1.420498047 GHz
Found data file: yes. Found result header file: yes.
Scanning result header file.
Beginning analysis...
Doing baseline smoothing.
Starting work for Doppler shift rate 1.696941, FFT length 131072
7.532363% done
Starting work for Doppler shift rate 1.698789, FFT length 131072
```

Figure 4.11 – Two options to control application instances

To address the challenges of traditional cloud computing application management, the Cloud Computing Management Modeling Language (C2M2L) is a DSML developed to define the running status of a specific cloud application. C2M2L can be used to construct a runtime model that serves as a graphical monitoring interface to reflect the running nodes and states of an application. Figure 4.12 is an excerpt of a C2M2L runtime model instance, which specifies the PetStore (a sample J2EE application brought by Java BluePrints program using Ajax with Java, JSF, and Java Persistence APIs) application node – *PetStore Web Tier Instance 1*, including four services being applied. Whenever errors appear in the cloud, they are also reflected in the model (i.e., models are relevant at runtime). A causal connection is established such that correcting errors in the runtime model triggers the same corresponding changes in the cloud. Because models are a high-level abstraction of the application instances, administering changes by editing the models (Figure 4.11b) is easier and more direct to most general end-users than using the traditional command-line interface (Figure 4.11a). The correction of errors in the cloud can then be accomplished by modifying the runtime models.

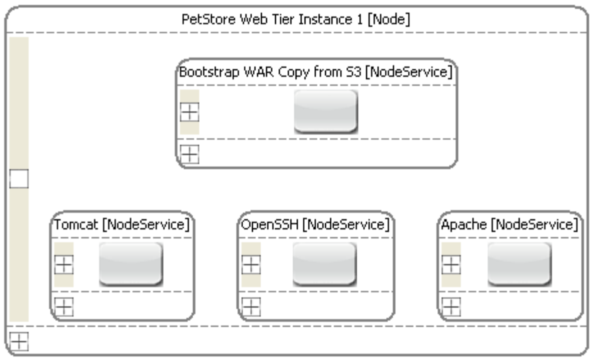

PetStore Web Tier Instance 1 [Node]
Bootstrap WAR Copy from S3 [NodeService]
Tomcat [NodeService]
OpenSSH [NodeService]
Apache [NodeService]

Figure 4.12 – Pet Store Web Tier 1 node

One model management scenario in C2M2L comes from handling the overloaded application nodes. If the *CPULoad* of a *Node* exceeds *20*, and *CPULoadRateofChange* exceeds *5*, the Node is overloaded. Table 4.1 shows a *Node* in the erroneous overloaded state. The solution to this scenario is to replace the *Node* with two identical *Nodes*, and split the *CPULoad* equally to the two new *Nodes*. In other words, set the *CPULoad* attribute of each new *Node* to be half of the original *Node*.

Table 4.1

Attributes of PetStore Web Tier Instance 1 (Overloaded Node)

Attribute Name	**Value**
IsWorking	True
AMI	ami-45e7002c
CPULoad	22.0
CPULoadRateOfChange	5.5
HeartbeatURI	http://ps01.aws.amazon.com/hb
HostName	http://ps01.aws.amazon.com/hb
Name	PetStore Web Tier Instance 1

4.4.2 Cast Study – Solution

Using MTBD to specify the error recovery solution, we first select a *Node* and perform the demonstration. As shown in List 4.7, after adding the two new *Node* elements, the attributes are initialized as usual. In order to split the original *CPULoad* into two equal parts, the attribute editor is applied. For example, if the original *CPULoad* is *25*, we can set *NewNode.CPULoad = 25 / 2 = 12.5* through an attribute editor dialog, which can be internally recorded as *NewNode.CPULoad = PetStore Web Tier Instance 1.CPULoad / 2*. The attribute editor enables users to specify the attribute computation at the instance level in a demonstration process, but infer the transformation rules at the metamodel level, so that when the value changes at the next time (e.g., *50*, not *25*), it can still compute the correct value.

List 4.7 – Operations for demonstrating model management example
(* represents generic operations to be identified)

Sequence	Operation Performed
1	Remove *PetStore Web Tier Instance 1*
2	Add a new *Node*
3–8	Set the attributes of the new *Node* to be those in the old one (6 attributes)
9	Set the *CPULoad* attribute of the new *Node* to be half in the old one
10*	Add a new *NodeService*
11–13*	Set all the attributes of these *NodeService* to be those in the old one (3 attributes)
14	Add a another new *Node*
15–21	Set the attributes of the new Node to be those in the old one (6 attributes)
22	Set the *CPULoad* attribute of the new *Node* to be half in the old one
23*	Add a new *NodeService*
24–26*	Set all the attributes of these *NodeService* to be those in the old one (3 attributes)

The original inferred transformation pattern also needs to be refined. In this scenario, the precondition should be all the *Nodes* whose *CPULoad* is greater than *20* and *CPULoadRateofChange* is greater than *5*. Therefore, we added one restriction on the precondition: *PetStore Web Tier Instance 1.CPULoad > 20 && PetStore Web Tier Instance 1.CPULoadRateofChange > 5*. In addition, because the number of *NodeServices* in a *Node* is not fixed, replicating *NodeServices* needs to be demonstrated on a single case followed by identifying the operations as generic.

Executing this transformation will automatically find all of the *Nodes* that are overloaded, and split the load into two new *Nodes*. If the load in the new *Node* is still over the limit, it can be split again by invoking the transformation repeatedly until the values satisfy the precondition.

4.5 Model Layout

The model evolution activities in the previous subsections focus only on the semantic aspects of the evolution (e.g., adding or removing necessary model elements and connections, modifying attributes of model elements), but the layout of models (e.g., positions of model elements, font, color and size used in labels) is rarely considered in the traditional model evolution process [Sun et al., 2011-b]. For instance, executing a set of model transformation rules to add model elements and connections will sometimes lead to placing all the newly created elements in a random location in the model editor.

Ignoring the desired layout after model evolution has a strong potential to undermine the readability and understandability of the evolved model, and may even unexpectedly affect the implicit semantics under certain circumstances. For example, users may accidentally misunderstand the system because of a disordered layout. Furthermore, the positions of model elements and connections may correspond to special coordinates in the real-world, such that an unoptimized layout could lead to unexpected problems for the actual system. It may be possible to incorporate the layout information related with the implicit semantics into the metamodel as part of the abstract syntax, but a change to the metamodel may trigger further model migration problems. Although it is very direct to adjust the layout manually, it becomes a tedious, timing-consuming task when a larger number of model elements are involved in the model evolution process. Therefore, while the semantic concerns of model evolution have been implemented and automated, it is indispensible to realize the automatic configuration of the layout as part of the model evolution process, as a type of “Pretty Printing” for models.

The most commonly used approach to automatically arrange the layout of models is to apply layout algorithms [Battista et al., 1994; Misue et al., 1995] after the evolution process. A number of modeling tools (e.g., GMF, GEMS, GME, MetaCase+ [MetaCase+, 2011]) provide automatic layout functionality in their model editors using specific algorithms. They can rearrange the layout of the models and make them more readable by avoiding the overlaps of model elements and connections, adding blank spaces among model elements, or grouping the same type of elements together. However, most of these algorithms do not consider the implicit semantics of the model elements and connections; the result being that a readable model does not necessarily result in an optimized system if part of the system implementation depends on the layout configuration. Furthermore, fixed layout algorithms usually cannot consider the underlying mental map of individual users (i.e., a user's understanding of the relationship between the entities in a diagram) [Misue et al., 1995] into consideration. Although a user might prefer to see different types of model elements grouped closely, the automatic layout algorithm might destroy the user's mental map by separating them.

An alternative to configuring the layout is to change the layout properties as part of the model evolution using a model transformation process. When specifying model transformation rules to evolve the semantic aspect of the model, extra rules may be given to handle the layout configuration. Although this offers a flexible way to enable users to customize the preferred implicit semantics and mental maps, it is tied to MTLs. In addition, testing and debugging the layout configuration are done by running the transformation and checking the final model, which is not direct and convenient.

Therefore, a desirable approach to configure the model layout concerns in model evolution tasks should include the following features:

- It should enable users to customize the layout configuration flexibly in order to realize their desired implicit semantics and mental maps.
- It should be separated clearly from the semantic aspect of the model evolution.
- It should enable end-users to configure and test the result using the notation related to their domain.
- It should be at a level of abstraction that is appropriate for end-user adoption, and not tied to low-level accident complexities of the transformation process.

Using MTBD to Support Model Layout. After demonstrating the semantic concerns of model evolution using MTBD, users can continue to select target model elements and place them at the correct positions as a demonstration of the layout transformation. At the same time, the underlying MTBD engine records all of the user’s operations and then generates a transformation pattern that incorporates both the semantic evolution and the layout configuration [Sun et al., 2011-b].

Various options can be applied when specifying the positions, as presented in the following:

- *Absolute coordinates*. The most direct and simplest layout configuration is to use absolute coordinates. Users can demonstrate where to place each element exactly in the editor. As shown in List 4.8, two kinds of operations are added to the editor to support locating and choosing the absolute coordinates of a certain element. When the transformation is executed, the chosen model elements will be placed in the exact same location as in the demonstration. For example, in the top of Figure 4.13, the *Node* in the lower-right corner is selected and confirmed with an absolute coordinate for both X and Y in the demonstration. When the generated transformation pattern is executed, the *Node* is configured with the same coordinate values automatically as shown in the bottom of Figure 4.13.

List 4.8 – Layout configuration operations using absolute coordinates

Operation Type	**Description**
Set *X* as Current	Set *X* in the current coordinates as the desired *X*
Set *Y* as Current	Set *Y* in the current coordinates as the desired *Y*

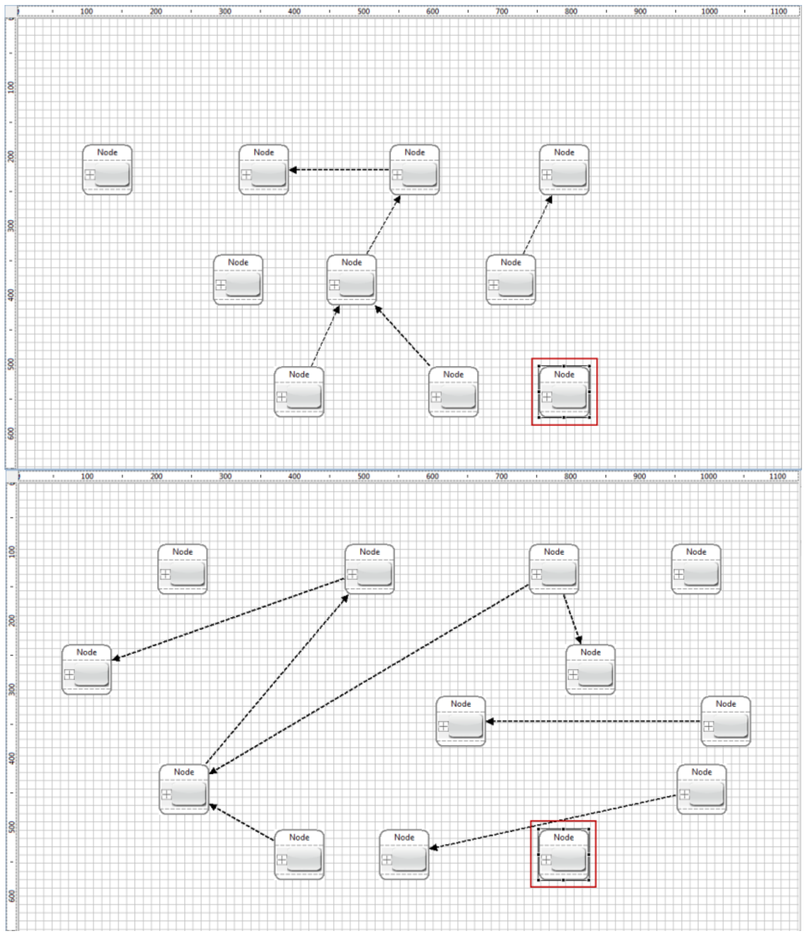


Figure 4.13 – Using absolute coordinates in the demonstration (top) to place the element in the same location in every model evolution scenario (bottom)

- *Relative coordinates to model boundary*. Using relative coordinates requires a reference point. One type of reference is to consider all the model elements and connections as a whole rectangle (i.e., the minimum rectangle that includes all the current model elements and connections), and use the boundary of the rectangle as the reference. The coordinates can be relative to each side of the rectangle from either inside or outside. Thus, a total of eight operations can be extended, as shown in List 4.9. For instance, in the top of Figure 4.14, *Node1* and *Node2* are two newly created model elements. When configuring the layout in the demonstration, *Node1* is specified using *Set X Relative to Rightmost Outside*, and *Set Y as Current*, while *Node2* applies *Set X Relative to Leftmost Inside* and *Set Y Relative to Lowermost Inside*. The result is that when applying the transformation in other models, *Node1* will always be placed right to the existing model, but at the same vertical level as in the demonstration; and *Node2* will always appear on the left-lower corner of the existing model, as shown in the bottom of Figure 4.14.

List 4.9 – Layout configuration operations using relative coordinates to model boundary

Operation Type	**Description**
Set *Y* Relative to Uppermost	Set the desired *Y* to be the current *Y* relative to the uppermost boundary of the current model from inside or outside
Set *Y* Relative to Lowermost	Set the desired *Y* to be the current *Y* relative to the lowermost boundary of the current model from inside or outside
Set *X* Relative to Leftmost	Set the desired *X* to be the current *X* relative to the leftmost boundary of the current model from inside or outside
Set *X* Relative to Rightmost	Set the desired *X* to be the current *X* relative to the rightmost boundary of the current model from inside or outside

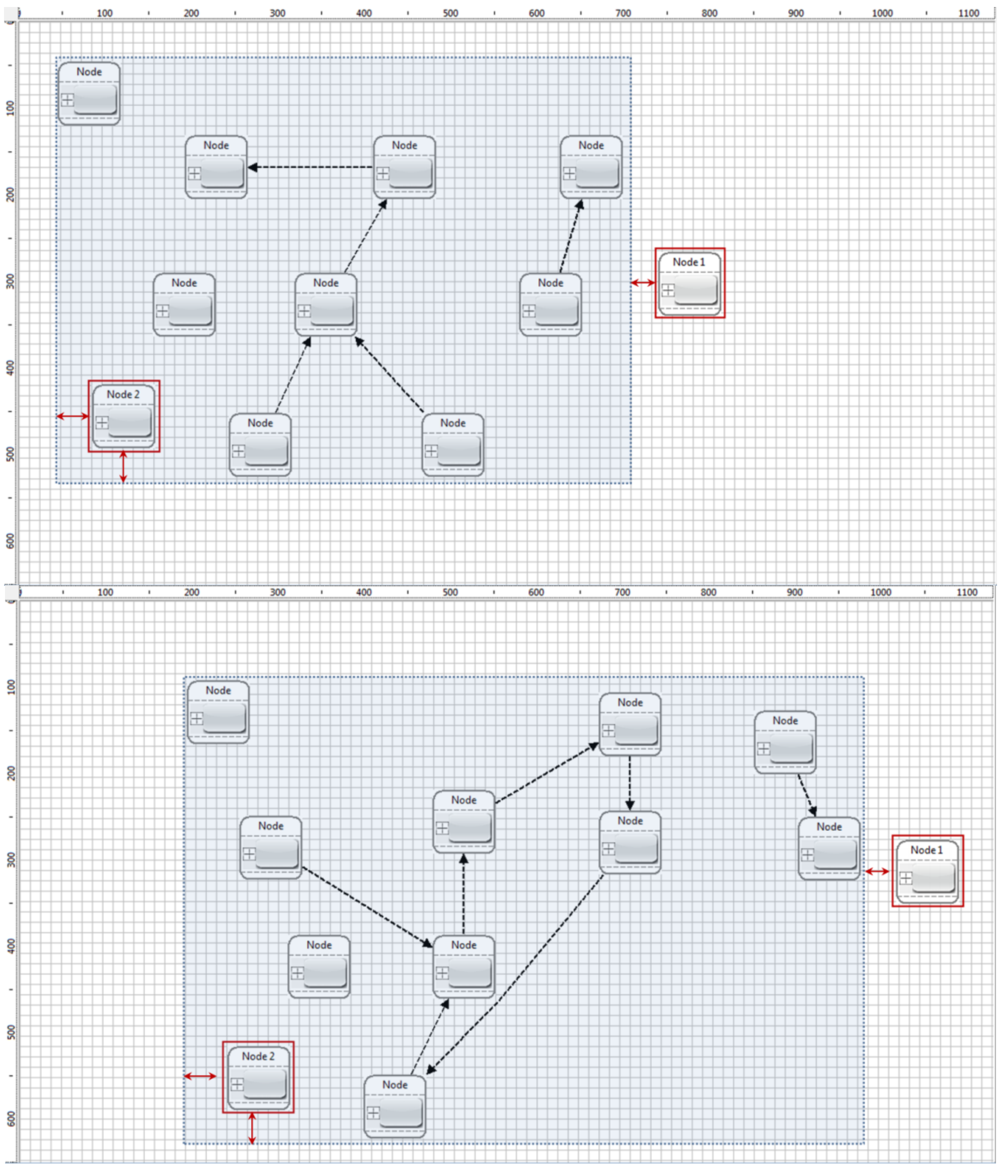


Figure 4.14 – Using coordinates relative to the boundary of the existing model in the demonstration (top) to place the element in the location relative to the existing model in every model evolution scenario (bottom)

- *Relative coordinates to model element(s)*. A more improved granularity and flexible reference is to set up the coordinates of a model element relative to other model element(s). As enumerated in List 4.10, users can configure X/Y based on the location of another model element. In the current implementation, a model element selector has been developed that enables users to choose any element from the existing model instance, and set up the

X or Y coordinate. For example, at the top of Figure 4.15, several model elements (i.e., *Node1*, *Node2*, *Node3*, *Node4*, *Node5*) are involved in a model transformation scenario. A user may configure the location of *Node3 using Set X Relative to Model Element Node2*, and *Set Y Relative to Model Element Node1*, so that *Node3* will always be in the same horizontal level as *Node2* and have the same vertical distance to *Node1* no matter where *Node2* and *Node1* are located in different model instances. On the other hand, both X and Y of *Node4* are configured relative to *Node5*, the result being that *Node4* is always on the upper-left part of *Node5* with the same distance as illustrated in the bottom of Figure 4.15.

List 4.10 – Layout configuration operations using relative coordinates to model element(s)

Operation Type	**Description**
Set *X* Relative to Model Element *E*	Set the desired *X* to be the current *X* relative to the *X* of the model element *E*
Set *Y* Relative to Model Element *E*	Set the desired *Y* to be the current *Y* relative to the *X* of the model element *E*

- *Configuring the appearance of model elements.* Apart from the location of model elements, the appearance (e.g., the color, shape, font, size used in the model element) is also essential to the layout of the model or even the semantics of the model.

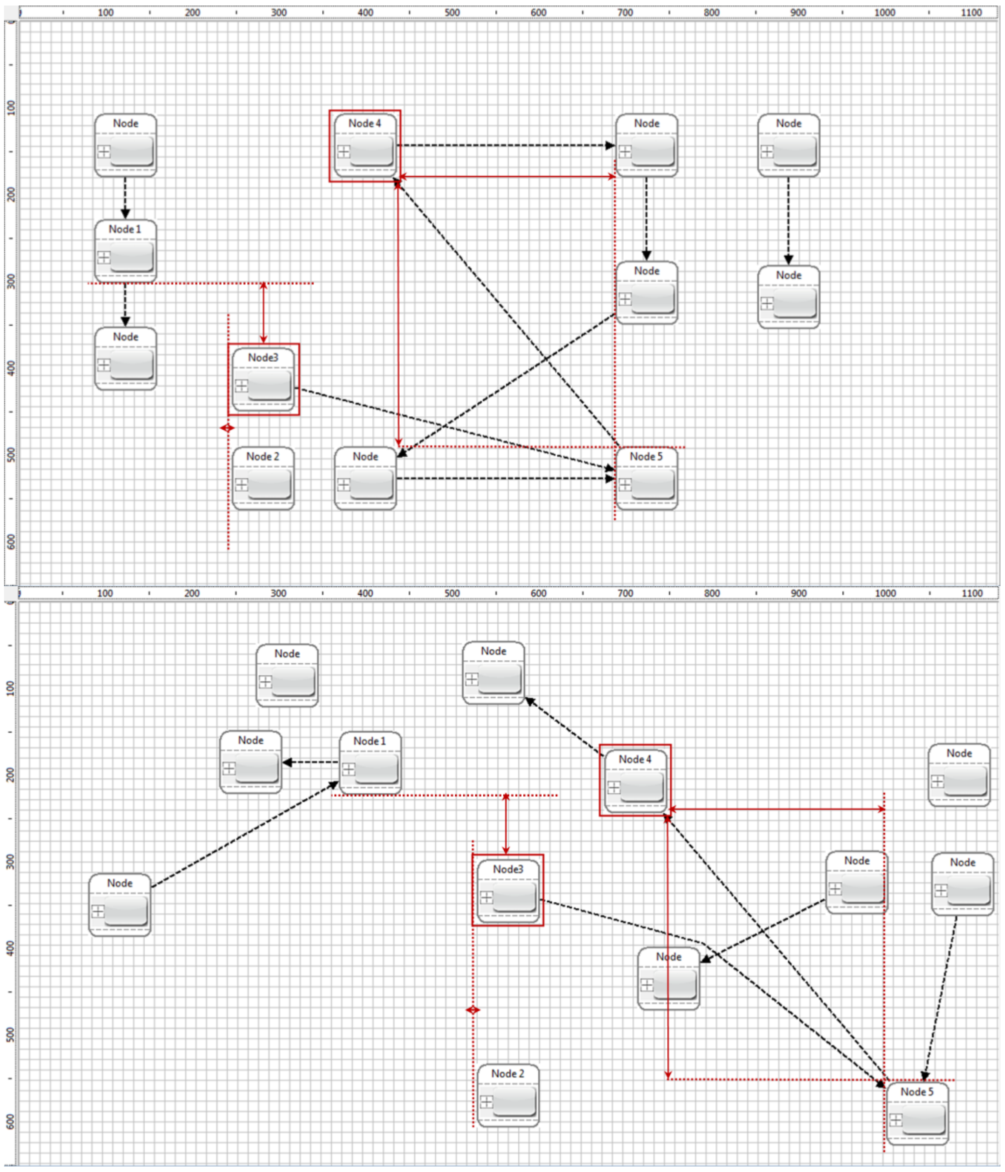
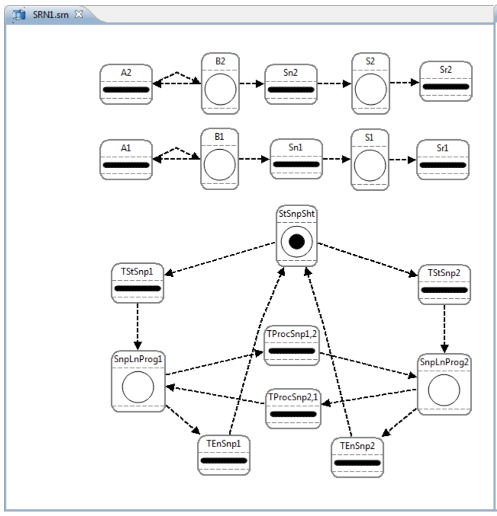


Figure 4.15 – Using coordinate relative to the other model elements in the demonstration (top) to place the element in the location relative to the same model elements in every model evolution scenario (bottom)

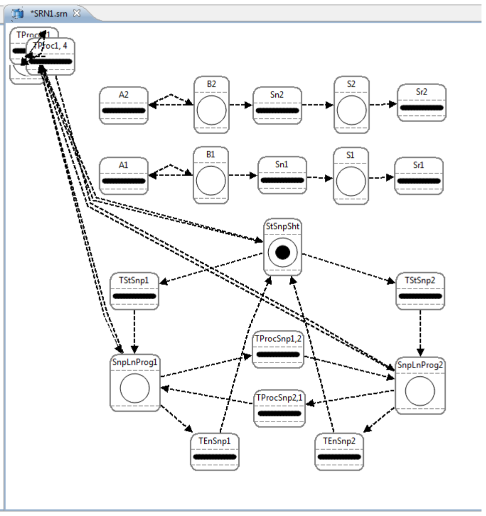
By demonstrating the layout configuration directly, users are able to customize their desired layout and preserve their mental maps (or other implicit semantic issues) in a WYSIWYG style. The approach also offers a more convenient environment to give precise positions, as well as to test and debug the resulting layout transformation. The demonstration of layout configuration occurs after the demonstration of the semantic evolution, so that the two concepts are separated without being tangled as crosscutting concerns.

4.5.1 Case Study – Background

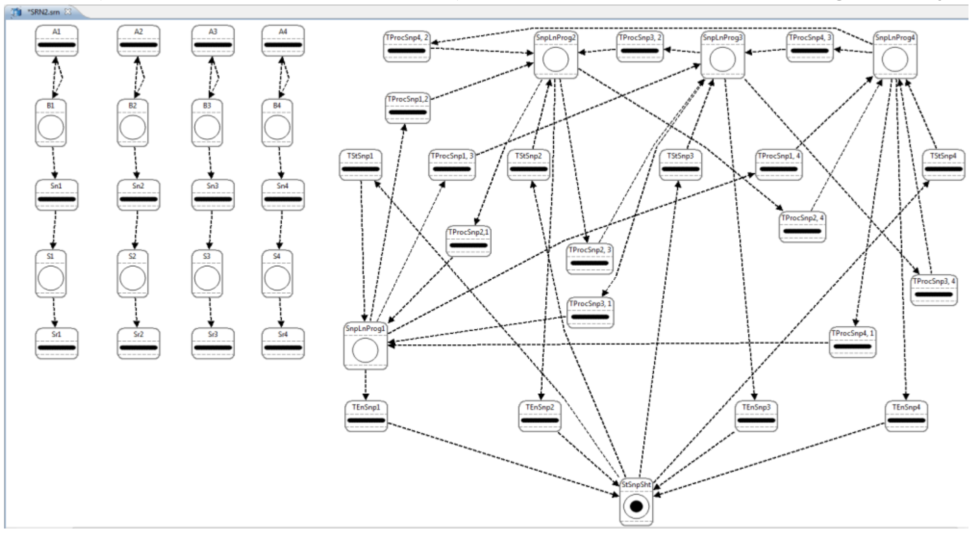
The case study is based on the same model scalability scenario described in Section 4.2.1. A number of new elements and connections are created during this model evolution scenario. The creation process can be automated by executing model transformation rules or calling APIs provided by the modeling environment. Figure 4.16b shows the SRN model after executing the transformation pattern on the model in Figure 4.16a, which scales the model from 2 event types to 4. Although the correct number of elements (i.e., 26 model elements) are created and the correct connections are made (i.e., 38 connections), all the newly created elements and connections are placed randomly in the upper-left corner of the editor and overlap with each other, which is unreadable without arranging the layout. However, manual layout arrangement is tedious and time-consuming, especially when the model is scaled to adapt a larger number of event types (e.g., over 100 new elements will be created when scaling a SRN model from 5 event types to 10, and over 150 connections are needed to connect them).



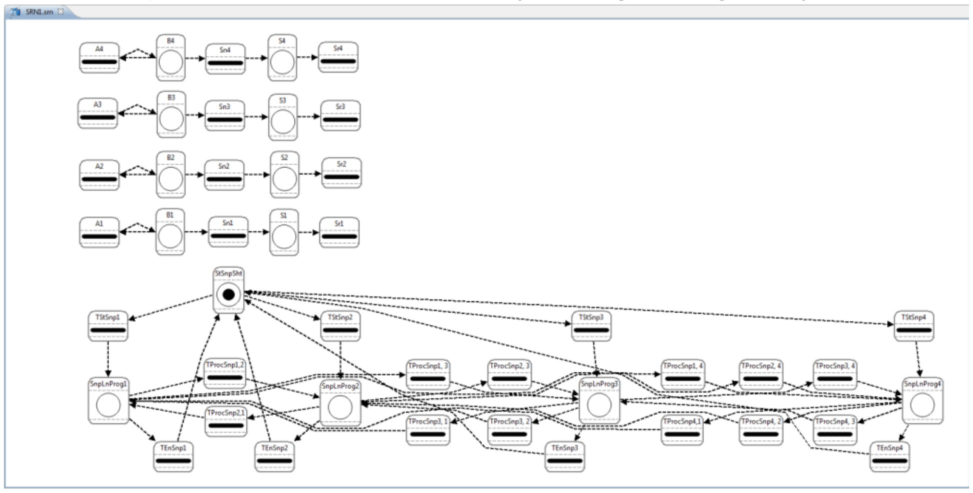
a) SRN model before evolution



b) SRN model after evolution with configuration layout



c) SRN model after evolution with layout configured using auto-layout function



d) SRN model after evolution with desired layout configuration

Figure 4.16 – Different layout configurations of SRN models

One option to avoid manual layout arrangement is to use the auto-layout functionality provided by the modeling tool. For instance, Figure 4.16c shows the scaled SRN model after applying the auto-layout function embedded in the GMF editor. Compared with Figure 4.16b, it can be seen that the overlaps of all the newly created elements are removed; the location of each element is changed so that the distances between two elements are more similar; and all the elements connected are grouped together. A clear and readable model is obtained by a single mouse-click. However, a readable model does not necessarily preserve the implicit semantics and a user's mental map. As shown in Figure 4.16c, it is challenging to determine the corresponding part in the execution snapshot for each of the existing event types, while in Figure 4.16b the execution snapshot is clearly separated by different event types. On the other hand, the layout of event definitions in Figure 4.16c is changed from the original horizontal arrangement to vertical. Although it does not significantly affect the understandability or implicit semantics of the definitions, users might have their own preferences of placing the event definition horizontally, and the auto-layout functionality obviously destroyed this particular mental map.

4.5.2 Case Study – Solution

After demonstrating the model transformation as shown in Section 4.2.1, the model evolution at the semantics level has been accomplished. At this point, users can continue to drag-and-drop each element in the editor and confirm the desired location using the provided layout configuration operations.

Figure 4.17 shows the desired layout configuration for each element in the model transformation process. According to the three steps in this model evolution scenario, the newly created model elements and connections belong to three parts. The first part is the event definition (i.e., *A3, B3, Sn3*, *S3*, *Sr3*). Assume that most users prefer to place these elements always above the previous definitions. Therefore, they use the uppermost boundary of the existing model as the reference for *Y*, and the *X* coordinate of each element in event type *1* for *X*. Users would generally perform the operations in List 4.11 in the layout demonstration.

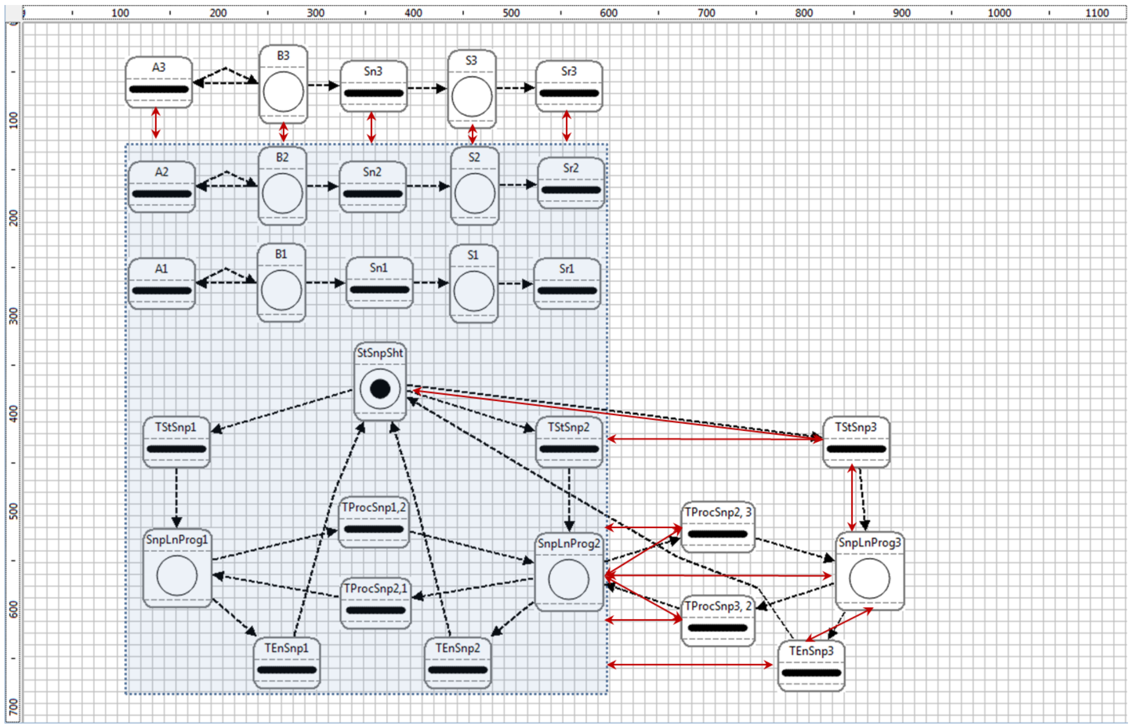


Figure 4.17 – The layout demonstration in action for the first motivating example

For the new execution snapshot part definition (i.e., *TStSnp3*, *SnpLnProg3*, *TEnSnp3*), we set all the *X* values to be relative to the rightmost boundary, and *Y* values relative to the root of the execution snapshot *StSnpSht* (*TStSnp3.Y* is set to be directly relative to *StSnpSht.Y*, *SnpLnProg3.Y* is set to be relative to *TStSnp3.Y*, and *TEnSnp3.Y* to be relative to *SnpLnProg3.Y*), see List 4.12.

List 4.11 – Operations to configure layout demonstration for part one of the motivating example
(The layout demonstration is immediately after the model transformation demonstration)

Sequence	**Operation Performed**
36	Set *SRNRoot.A3.Y* Relative to Uppermost Outside
37	Set *SRNRoot.A3.X* Relative to *A1.X*
38	Set *SRNRoot.B3.Y* Relative to Uppermost Outside
39	Set *SRNRoot.B3.X* Relative to *B1.X*
40	Set *SRNRoot.Sn3.Y* Relative to Uppermost Outside
41	Set *SRNRoot.Sn3.X* Relative to *Sn1.X*
42	Set *SRNRoot.S3.Y* Relative to Uppermost Outside
43	Set *SRNRoot.S3.X* Relative to *S1.X*
44	Set *SRNRoot.Sr3.Y* Relative to Uppermost Outside
45	Set *SRNRoot.Sr3.X* Relative to *Sr1.X*

List 4.12 – Operations to configure layout demonstration for part two of the motivating example

Sequence	**Operation Performed**
46	Set *SRNRoot.TStSnp3.X* Relative to Rightmost Outside
47	Set *SRNRoot.TStSnp3.Y* Relative to*SrnRoot.StSnpSht.Y*
48	Set *SRNRoot.SnpLnProg3.X* Relative to Rightmost Outside
49	Set *SRNRoot.SnpLnProg3.Y* Relative to *TStSnp3.Y*
50	Set *SRNRoot.TEnSnp3.X* Relative to Rightmost Outside
51	Set *SRNRoot.TEnSnp3.Y* Relative to *SnpLnProg3.Y*

Finally, for the *Execution Snapshot Transitions*, the *X* is relative to the rightmost boundary, and *Y* is relative to the *Snapshot Place* it is connected to, see List 4.13.

List 4.13 – Operations to configure layout demonstration for part three of the motivating example

Sequence	Operation Performed
52	Set *SRNRoot.TProcSnp2,3.X* Relative to Rightmost Outside
53	Set *SRNRoot.TProcSnp2,3.Y* Relative to*SrnRoot.StSnpSht.Y*
54	Set *SRNRoot.TProcSnp3,2.X* Relative to Rightmost Outside
55	Set *SRNRoot.TProcSnp3,2.Y* Relative to *TStSnp3.Y*

After the demonstration is completed, the recording engine calculates all the values and integrates them in the final generated transformation pattern. Executing the final pattern will result in the model shown in Figure 4.16d.

4.6 Experimental Validation

Experimental evaluation of this research is based on various empirical techniques and measurements. The expected benefits of the MTBD transformation framework will be indicated by its generality, separation of MTLs and metamodel definitions, productivity and practicality.

4.6.1 Generality

This characteristic ensures that the MTBD approach is applicable to different modeling languages. The current implementation of MT-Scribe is a plug-in to GEMS, and triggered in the model editor. Thus, any modeling language defined in GEMS that can be edited in the GEMS model editor is able to apply MTBD to address the model transformation and evolution problems, which means that MTBD is a general solution. In the cases studies shown in previous sections, a number of models in different DSMLs have been used to test different types of model evolution tasks. The demonstrated capability to handle different DSMLs reflects the generality of the approach. Of course, for other modeling tools, MT-Scribe would need to be adapted, but its generality across modeling languages would still hold true.

4.6.2 Separation from MTLs and Metamodel Definitions

Using MTBD, users are only involved in editing model instances to demonstrate the specific model transformation process on concrete examples and avoiding refinement after the demonstration. All of the other procedures (i.e., optimization, inference, generation, execution, execution control and correctness checking) are fully automated. In both the steps where users are involved, all of the information exposed to users is at the model instance level, rather than the metamodel level. For instance, the demonstration is done using the basic editing operations in the concrete model editor; the attribute configuration is accomplished using the attribute refactoring editor which contains all the concrete attribute values from all the available elements and connections; the containment confirmation to give constraints on a structural precondition is simply realized by a one-click operation on the desired model element or connection; and the extra precondition on attributes is given using the dialog where users can access all the elements touched in the demonstration and type the constraints directly. The generated patterns are invisible to users (Figures 4.9 and 3.17 are presented for the sake of explanation, which are not visible to users when using MTBD). Therefore, users are isolated fully from metamodel definitions and implementation details. Furthermore, no model transformation languages and tools are used in the implementation of MTBD. Thus, users are completely isolated from knowing any model transformation languages or programming language concepts.

4.6.3 Productivity

Productivity addresses performance issues regarding the degree of effort that users need to put forth to realize a model transformation task. Similar to the development of MTLs, which aimed to improve the manual transformation process, MTBD is designed to further enhance the productivity over both MTLs and manual transformation. Experiments on the improved productivity using a MTL over manual transformation have already been done [Lin, 2007]. To achieve some indication of the level of improvement offered by MTDB, we select some model transformation tasks as experimental scenarios and compare the cost to realize them using three different approaches. As a baseline, we first count the mouse and keyboard operations that a user must perform during a traditional manual transformation process. A second measure will consider the number of Source Lines Of Code (SLOC) of the transformation specification written in a specific MTL to perform the same task as the manual baseline. Finally, we will observe the amount of effort needed to describe the same transformation using MTBD. These quantitative measurements will be compared and observations made regarding the productivity concerns of each approach.

Five model transformation tasks are selected for experimental consideration. These tasks represent the typical model evolution scenarios. More importantly, these tasks have been well-addressed using MTLs, so that we can better compare the efforts by using MTBD to accomplish the same results. The final comparison is shown in Table 4.2.

Table 4.2

Comparison of accomplishing model transformation tasks using three approaches

Example	**Manual Process**	**MTL(ECL)**	**MTBD**
Model Refactoring *Extract Super Class*	9 operations for 3 subclasses 27 operations for 30 subclasses	28 SLOC	9 editing operations 3 refinement operations
Model Scalability *Scale SRN Models*	57 operations from 2 event types to 4 event types 159 operations from 4 event types to 6 event types	170 SLOC	35 editing operations 1 refinement operations
Model Scalability *Scale EQAL Models*	26 operations from 3 sites to 4 sties 175 operations from 4 sites to 8 sites	124 SLOC	16 editing operations 3 refinement operations
Aspect-Oriented Modeling *Weave aspects to QoSAML Models*	6 operations to weave 3 transition strategies 12 operations to weave 6 transition strategies	23 SLOC	3 editing operations 2 refinement operations
Aspect-Oriented Modeling *Weave aspects to ESML Models*	9 operations to weave 3 logging elements 27 operations to weave 9 logging elements	40 SLOC	4 editing operations 8 refinement operations

The manual process column illustrates the efforts needed to complete each of the tasks by manually editing the source models. Because the efforts of manual editing depend on the scale of the transformation (e.g., performing the transformation on a larger model costs more efforts than performing the same task on a smaller model), the efforts on two different scales have been listed for each task. However, the numerical counts of the operations cannot fully reflect the real efforts needed in the manual process, due to the fact that it usually costs additional effort to manually locate the model elements to perform the operations, as well as do the manual computation. The main purpose of the manual process column is to provide a basic overview of the complexity of the transformation tasks.

The MTL column shows the effort needed to write the model transformation rules in MTLs. Because all the examples have been done using ECL, we analyzed all the source codes and counted the SLOC. Compared with the MTBD column, it can be seen that only a small number of operations are needed using MTBD to accomplish the exact same tasks that were done by writing transformation rules.

In addition, to better identify the productivity advantage of using MTBD, we can take a more detailed analysis on the specific part of the MTL code and see how MTBD can achieve the same purpose in a more end-user centric manner. List 4.14 shows part of the code to implement the AOM case study presented in Section 4.3.1. One essential part of the AOM task is to identify the desired locations to weave the aspect. In the ECL transformation rules, the location to weave aspects is defined by extended OCL constraints (e.g., `forAll(), select()`) together with APIs provided in the transformation language (e.g., `models("State"), atoms()`). The process becomes more complex when the different APIs are called and used together in a single statement. By contrast, the main location specification in MTBD is automatically handled in the demonstration process. It is the recording engine that detects the location of where the operation occurs and generalizes the location context information, so that users focus on selecting a desired location without being aware of a generalized location process.

The specific constraints on the preconditions using MTBD are more intuitive and direct than writing transformation rules. By selecting and clicking on the desired model elements or connections, constraints on the structure can be specified. The location and selection of the attribute in MTBD is realized by clicking on the element in the precondition specification dialog and providing much simpler expressions based on the instance model. However, in ECL, OCL expressions and condition statements need to be applied (e.g., `if … select(m | m.kindOf() == “Action”)->size() >= 1`). When it comes to defining the precondition on attribute values, we believe that MTBD is simpler than using conditional statement with model accessing APIs. For example, the following is an expression that would be needed in a typical model transformation rule using the traditional approach:

```
findAtom("Priority").findAttributeNode("InitialValue").getInt(pri);
```

Regarding the actual aspect composition process, it has to be implemented using model manipulation APIs in ECL (e.g., `parent().addConnection("Transition", "Transition","Transition",endID,prevID),Connection.addAttribute("Guard",guard)`), while using MTBD, the composition process is demonstrated using the basic editing operations (i.e., add, delete, update attributes).

List 4.15 shows another excerpt of the ECL to implement the model scalability example – Scale EQAL Models in Table 4.2. To control the number of execution times, recursive calls are used in the ECL transformation rules. In MTBD, a user simply identifies related operations as generic, and the execution controller will handle executing the transformation pattern as many times as needed.

List 4.14 – Excerpt of the ECL code to weave aspects to QoSAML models [Gray, 2002]

```
defines AddTransition, FindConnectingState, ApplyTransitions;

strategy AddTransition(stateName, prevID, guard : string; prevPri : integer)
{
     declare pri, minVal, maxVal, avgVal : integer;
     declare endID : string;
     declare aConnection : node;
     findAtom("Priority").findAttributeNode("InitialValue").getInt(pri);
     if (pri == prevPri + 1)
     then
         getID(endID);
         findAtom("Min").findAttributeNode("InitialValue").getInt(minVal);
         findAtom("Max").findAttributeNode("InitialValue").getInt(maxVal);
         avgVal := (minVal + maxVal) / 2;
         <<CComBSTR action(stateName);
         action.Append("="+XMLParser::itos(avgVal)); >>
         aConnection :=
         parent().addConnection("Transition", "Transition", "Transition",
             endID, prevID);
         aConnection.addAttribute("Guard", guard);
         aConnection.addAttribute("Action", action);
     endif;
}

strategy FindConnectingState(stateName, guard : string)
{
     declare pri : integer;
     declare startID : string;
     findAtom("Priority").findAttributeNode("InitialValue").getInt(pri);
     getID(startID);
     if (pri< 4)
     then
         parent().models("State")->
         forAll(AddTransition(stateName, startID, guard, pri));
     endif;
}

strategy ApplyTransitions(stateName, guard : string)
{
     declare theModel : node;
     theModel := findModel(stateName);
     theModel.models("State")->forAll(FindConnectingState(stateName, guard));
}
```

We have not performed a formal user study on the comparison between the two approaches. However, with the comparative effort shown in Table 4.2, we believe that for general end-users who have no experience of using MTLs, MTBD provides a feasible alternative without a steep learning curve.

List 4.15 – An excerpt of a transformation rule written in ECL to scale EQAL models while controlling the number of execution times [Gray et al., 2005]

```
//traverse the original sites to add CORBA_Gateways
//n is the number of the original sites
//m is the total number of sites after scaling
strategy traverseSites(n, i, m, j : integer)
{
  declare id_str : string;
  if (i <= n) then
    id_str := intToString(i);
    rootFolder().findModel("NewGateway_Federation").
    findModel("Site " + id_str).addGateWay_r(m, j);
    traverseSites(n, i+1, m, j);
  endif;
}

//recursively add CORBA_Gateways to each existing site
strategy addGateWay_r(m, j: integer)
{
  if (j<=m) then
    addGateWay(j);
    addGateWay_r(m, j+1);
  endif;
}
```

4.6.4 Practicality

MTBD is designed to support model evolution tasks. We have identified five types of model evolution tasks in practice in the previous sections. By realizing several common examples from each type of model evolution task, it is demonstrated that MTBD can be used to support diverse types of model evolution tasks.

4.7 Summary

MTBD has been applied to support several common model evolution activities (i.e., model scalability, model refactoring, aspect-oriented modeling, model management, and model layout). Experimental validation is also discussed in this chapter to assess the benefits and effectiveness of MTBD in supporting model evolution. Particularly, the validation is done on the generality, the separation of MTLs and metamodel definitions from end-users, the productivity, and the practicality. It can be seen that, as a general model transformation approach that is applicable to any DMSLs in GEMS, MTBD can enable general end-users to implement their desired model evolution activities, while being fully isolated from knowing any MTLs and understanding metamodel definitions, and with less perceived effort.

With an increasing number of model transformation patterns being generated, it becomes equally important to enable users to better share these patterns and reuse them. As another contribution, Chapter 4 provides an extension to MTBD that further improves the MTBD user experience with a mechanism to help users to share, exchange and reuse their model evolution knowledge and model transformation patterns.

CHAPTER 5

LIVE MODEL TRANSFORMATION BY DEMONSTRATION: TOOL SUPPORT TO IMPROVE MODEL TRANSFORMATION REUSE

Model Transformation By Demonstration (MTBD) provides an end-user centric approach to implement various model transformation tasks. When additional users are enabled to contribute to model evolution activities using MTBD, reusing model transformation knowledge and patterns becomes an essential issue, particularly when multiple users work collaboratively in a specific domain. This chapter presents a tool kit called Live-MTBD, an extension to MTBD, which focuses on enabling users to perform demonstration more flexibly, share transformation patterns across different editors, and reuse patterns with guidance. The overview of Live-MTBD will be given first, followed by its usage and implementation details. In addition, a case study is offered to illustrate using the toolkit to assist with demonstration, pattern sharing and reuse. Related work and concluding remarks are presented in the rest of the chapter.

5.1 Live Model Transformation By Demonstration (Live-MTBD)

The Live-MTBD concept starts with the need to reuse model transformation patterns in the context of MTBD. Reuse becomes increasingly important, because when more users are enabled to implement model transformations using MTBD, a number of patterns with the same or similar purposes might be created by different users at various times or locations, which implies a potentially large reusable transformation pool. On the other hand, with the diverse knowledge level and expertise background, different users may possess numerous ideas about model evolution activities, and therefore it is in many cases required to reuse the transformation patterns from each other.

In order to support the reuse of model transformation patterns in the context of MTBD, three areas can be enhanced. First, it is necessary to further improve the user experience of MTBD and make the use of MTBD more preferable by end-users. In other words, encouraging more users to adapt MTBD and demonstrate transformations is the prerequisite to building a large model transformation pattern pool. Moreover, when transformation patterns are inferred and generated by different users, they should be immediately available to others for reuse. This requires a mechanism to share the transformation patterns among different users in their individual model editors. Finally, having access to a number of existing transformation patterns does not guarantee that users can choose the correct pattern to reuse at the proper time, particularly when they are not the initial creator of the pattern. Another key aspect to support reuse is to have an intelligent mechanism to aid and guide users to reuse the necessary patterns in appropriate situations.

Live-MTBD is an extension of MTBD that contains three features to cover the enhancement of the three aspects summarized above. *Live Demonstration* provides a more general demonstration environment that allows users to specify editing activities based on their editing history. In order to improve the sharing of model transformation patterns among different users, *Live Sharing* (a centralized model transformation pattern repository), has been designed so that transformation patterns can be reused across different editors. A live model transformation matching engine (*Live Matching*) has been developed to match the existing transformation patterns automatically at modeling time, and provides suggestions and guidance to users on reusing applicable patterns during editing time. The rest of the section will provide details on each of the three features.

5.1.1 Live Demonstration

The specification of a model transformation using MTBD is given by a demonstration. Although MTBD is designed to be applicable to end-users, being able to use MTBD to demonstrate a transformation does not guarantee that every user will actually use MTBD to do the demonstration and specify the transformation pattern. As shown in Figure 5.1, if a user has a certain model transformation task in mind and wants to implement it, he or she can then prepare the appropriate source model, and demonstrate the transformation process using MTBD to create and generate the finalized transformation pattern. However, in most cases, the user creates a model and starts to edit it without thinking about any model transformation tasks or scenarios. As the editing process ensues, it is very likely that the user realizes that there are a number of the same or similar editing activities that are based on a pattern and can be automated as a model transformation process. It is also possible that the user completes a very complex editing activity, and then realizes that this editing activity can be specified as a transformation to be reused in the future to avoid the same manual editing process. In other words, it is a common scenario in practice that users may not realize the need of a model transformation pattern until they completely finish the editing process. The problem associated with this scenario is that users may not be willing to use MTBD to demonstrate and specify the transformation pattern after the fact, because 1) they have to redo a demonstration of the finished editing process, and this process can be complex and tedious; 2) the re-demonstration should be performed on an appropriate source model, but there might not be available source models without manually modifying the existing complete model instances. As a result, a number of reusable transformation patterns may not be demonstrated and generated through MTBD, although users might have performed the necessary editing process in different model instances multiple times.

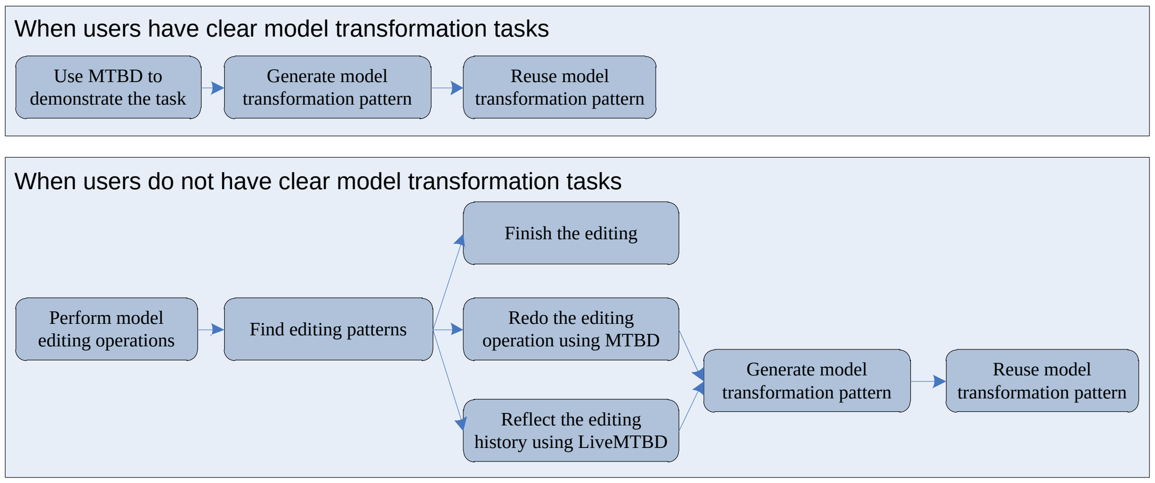

When users have clear model transformation tasks
Use MTBD to demonstrate the task
Generate model transformation pattern
Reuse model transformation pattern
When users do not have clear model transformation tasks
Perform model editing operations
Find editing patterns
Finish the editing
Redo the editing operation using MTBD
Reflect the editing history using LiveMTBD
Generate model transformation pattern
Reuse model transformation pattern

Figure 5.1 – Different user editing scenarios

Therefore, in order to encourage users to specify model transformation patterns using MTBD for future reuse, the challenges of re-demonstration need to be solved. The key of the solution is to reduce the effort of the re-demonstration, and more specifically, the effort to repeat the same editing operations users have already performed, and the effort to find the appropriate and available source model for the re-demonstration.

As a solution to make MTBD a more flexible demonstration approach, live demonstration is implemented so that users can completely avoid repeating the same set of editing operations and finding the available source model instance. Live demonstration is realized using a recording engine that works continuously to record every editing operation performed in the editor. Then, whenever a user realizes a need to specify and summarize a certain model transformation pattern for a past editing activity, they can simply go back to the recording view and check all the operations that are related with the specific editing activity, after which the original MTBD inference engine infers the transformation from the archived editing events. Thus, users specify their desired editing activity by reflecting on their editing history, rather than by an intentional demonstration.

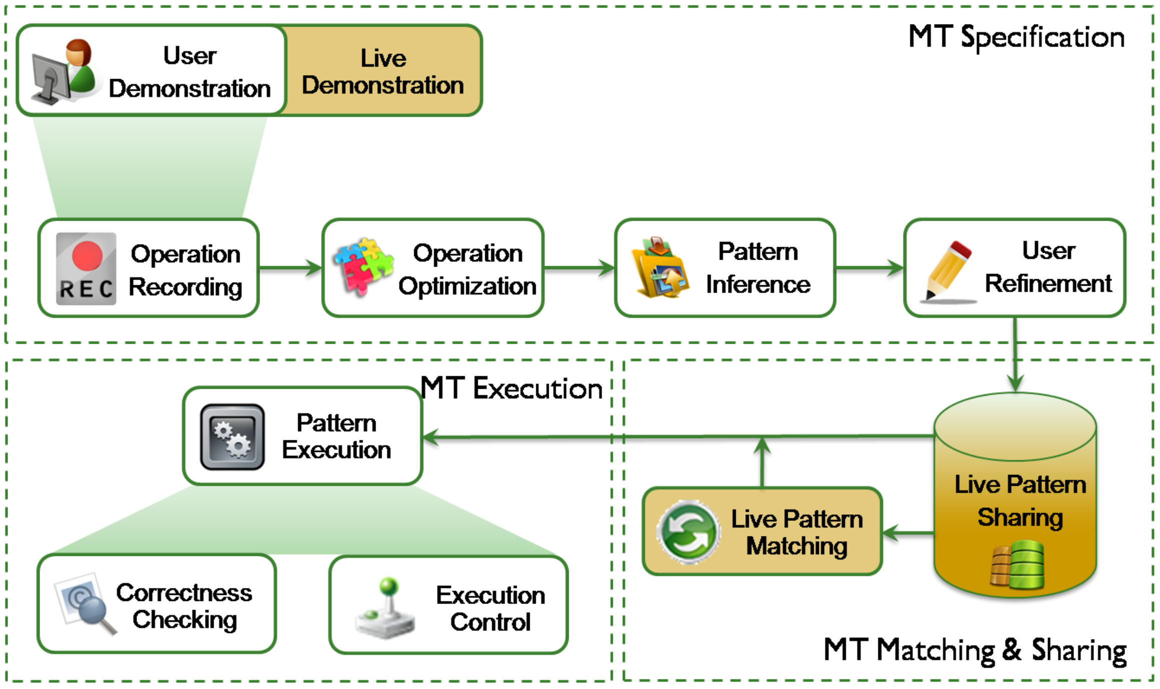


Figure 5.2 – The overview of Live-MTBD toolkit

Based on the formal specification in Section 3.2, live demonstration enables the generation of $\vec{\Delta}_m$ (i.e., the sequence of model modifications on the source model M_i) by selecting a set of editing operations S_{op} from the editing history H. $\vec{\Delta}_m$ will then be used as the same input to function $TG(M_i, \vec{\Delta}_m)$ to generalize the initial transformation pattern. As shown in Figure 5.2, Live Demonstration is based on the original demonstration framework, modifying the recording engine to keep track of all the editing operations without explicitly starting a demonstration. However, users still have the option to initialize a demonstration in the regular way.

5.1.2 *Live Sharing*

MTBD keeps a local repository to save all the generated model transformation patterns. Although it is sufficient for a single user to specify and reuse model transformation tasks, it becomes a barrier when multiple users are involved and need to exchange patterns across different modeling environments. *Live Sharing* is another part of Live-MTBD, which realizes the sharing of patterns at editing time using a centralized repository.

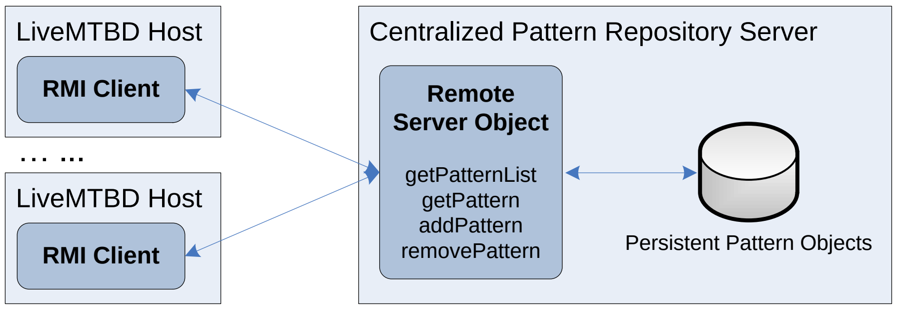


Figure 5.3 – The implementation of the centralized pattern repository

In the MTBD implementation, a class has been defined to specify a complete model transformation pattern, including the preconditions and the transformation actions. Each generated transformation pattern is represented by an instance of this class. Thus, it is possible to serialize the object instances and persist them in the local repository.

To support a centralized pattern repository, the local persistent pattern objects are moved to a remote server, enabling different Live-MTBD clients to communicate with it. Java RMI (Remote Method Invocation) is used to implement the server side. Three service API calls have been implemented in the remote server object as shown in Figure 5.3: 1) *getPatternList* returns a list of the existing transformation patterns in the repository; 2) *addPattern* can add a newly generated transformation pattern to the repository; 3) *getPatterns* can retrieve patterns from the repository with unique pattern names; 4) *removePattern* can be used to delete an existing pattern from the repository with a unique name.

In each Live-MTBD client, the remote server object can be gained through the RMI registry. After a model transformation pattern is generated and finalized, it will be passed to the server using the *addPattern* service call. When users want to apply certain transformation patterns, the whole list of existing patterns can be returned and displayed from the repository using *getPatternList*. Selecting one or multiple patterns leads to retrieving the corresponding patterns from the repository through *getPatterns*, being loaded by the MTBD execution engine. The execution controller console shown in Figure 3.7 enables the removal of patterns, which is realized using the *removePattern* service call.

Using *Live Sharing*, users are offered a transparent pattern sharing environment. Different users at different locations can contribute to the pattern repository at any time, which are immediately available to be reused by any other user at model editing time.

5.1.3 Live Matching

With *Live Demonstration* and *Live Sharing*, users are enabled to create and share transformation patterns, creating a set of patterns in the centralized pattern repository. However, the ultimate goal of creation and sharing is to support and improve the reuse of model transformation patterns. As mentioned in the beginning of this chapter, the availability of a large number of transformation patterns does not necessarily ensure a desired reuse scenario. In order to reach the desired reuse, we need to, 1) know exactly if there is already an existing pattern in the repository for reuse; 2) fully understand the existing pattern and make sure it is the correct one to reuse. Both of these are by no means easy tasks, because patterns can be added to the repository any time, so users need to refresh and check the pattern list frequently to get the latest available patterns and determine if there are potentially reusable ones, which is a tedious and time-consuming process. On the other hand, the purpose and usage of a pattern can only be found from its name and description, without a formal definition of the internal preconditions and transformation actions being visible to users. This exerts a challenge for users to understand the accurate usage of a pattern correctly. In many cases, users simply test and execute the pattern and determine if it is the appropriate one to reuse, but this is sometimes risky when executing patterns on existing valid model instances, because any failure of the undo function in the editor or an accidental save operation will lead to breaking the existing models if an incorrect pattern is executed.

To assist with the reuse of transformation patterns, automatic and intelligent mechanisms are needed. *Live Matching*, being another part of the Live-MTBD toolkit, is designed and implemented to help users find the right patterns to reuse in the appropriate context. *Live Matching* monitors the user's selection in the model editor, and triggers the automatic pattern matching process whenever the user's selection is changed. The matching process loads all the existing patterns from the repository and reads the user's selection as the input model to check if the precondition of each pattern can be satisfied. The final list of matched patterns will be displayed in an editor view, as well as showing the number of matched locations in the current model.

Formally, *Live Matching* is a modified version of the execution function $\xi(M_j, \vec{P}', \vec{T}')$. We define it as $\Psi(M_j, S_t)$, where M_j is the input model defined by the user's selection, and S_t is the set of all the existing transformation patterns, each pattern being specified by a tuple $\langle \vec{P}', \vec{T}' \rangle$. The function Ψ returns the set of transformation patterns S_t', which is a subset of S_t, where each $\vec{P}'$ in S_t' can be satisfied on the input model M_j.

An event listener is added to the model editor to capture any change on the selection in the editor. A view is also provided to display the matched patterns on the current selection state, and the number of the match locations. Selecting the patterns from the view can trigger the execution of the patterns automatically. In this way, users are notified about all the available transformation patterns that can be applied at the current location with the satisfied precondition, so that the chance is reduced for missing an opportunity to reuse a pattern.

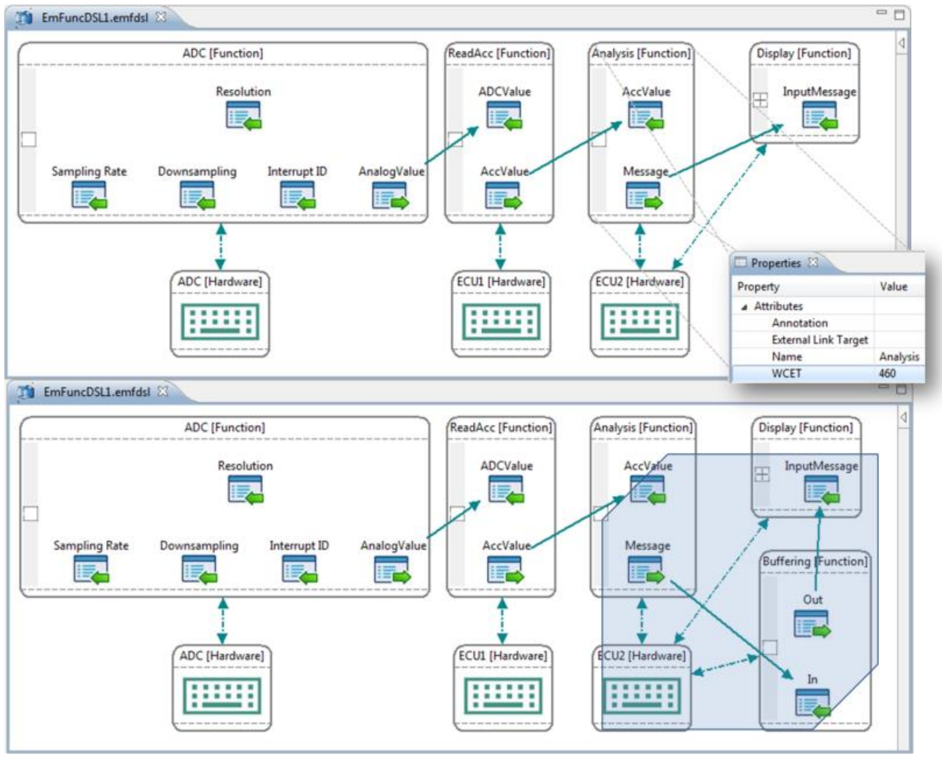
5.2 Case Study

This section presents a case study from practice, where Live-MTBD is applied to support the creation, sharing and reuse of model transformation patterns using MTBD in an embedded system controller domain.

5.2.1 Background

The example is based on the Embedded Function Modeling Language (EmFuncML), which has been used to support modeling embedded controllers in the automotive industry [Sun et al., 2011-a]. EmFuncML enables the following: 1) model the internal computation process and data flow within functions; 2) model the high-level assignment and configurations between functions and supporting hardware devices; 3) generate platform-dependent implementation code; and 4) estimate the Worst Case Execution Time (WCET) for each function.

The top of Figure 5.4 shows an excerpt of the model describing functions used in an automotive system. *ReadAcc* (i.e., Read Acceleration) reads output data from *ADC* (i.e. Analog-to-Digital Converter) and sends the processed data to the *Analysis* function, which then transmits messages to the *Display* function. The input/output ports of each function are given (e.g., *ADC* has four input ports: *Resolution*, *SamplingRate*, *Downsampling*, *InterruptID*; and one output port *AnalogValue*). The hardware devices (e.g., *ADC*, *ECU*) are presented, to which the corresponding functions are assigned. A tool has been developed to estimate the WCET of each function based on the internal computation logic. For the sake of ensuring a smooth data flow and quick processing time, the WCET of each function should be less than *300ms*; otherwise, it is defined as a WCET violation.



Property	Value
◢ Attributes	
Annotation	
External Link Target	
Name	Analysis
WCET	460

Figure 5.4 – EmFuncML models before (top) and after (bottom) applying *Buffering* function

In practice, EmFuncML is used by both hardware and software engineers in a collaborative way. One common task occurring when using EmFuncML is to specify the *ADC* function. For example, the upper left part of Figure 5.4 shows the *ADC* configuration, which is modeled through a sequence of approximately 20 editing operations to create the *ADC* function, input/output ports, set its names and types, and create the *ADC* hardware device with the assignment connection. Hardware engineers are more experienced than software engineers in this part of the configuration. Thus, the complex editing operation of creating an *ADC* can be specified as a reusable model transformation using MTBD by hardware engineers that can be used by different colleagues in their modeling process when the *ADC* needs to be modeled in other system contexts. However, using traditional MTBD, users must plan ahead and explicitly provide a demonstration that specifies the desired editing activity. A challenge is when a user does not realize the potential for reusing an editing activity until it is part-way through. For example, the hardware engineer configures *ADC* by performing a sequence of editing operations. After the editing is completed, the engineer may then think (post-editing) that because the *ADC* is a commonly used component in embedded systems, the editing activity just performed should be summarized and saved as a reusable model transformation pattern. Therefore, he or she may begin a demonstration and repeat exactly the same editing operations for the sake of inferring the transformation pattern. This repetition could be tedious and time-consuming if the editing activity to demonstrate is complex.

Another common practice in the configuration of functions in EmFuncML is that if a WCET violation occurs, a *Buffering* function can be added between the source function and the target function that receives data to ensure the correct data flow. At the bottom of Figure 5.4, *Analysis* sends a message data to *Display*. However, the WCET of *Analysis* is *460ms*, which is longer than the desired processing time. Therefore, a *Buffering* function is added between *Analysis* and *Display*, which serves as intermediate storage for the transmitted data. In this case, embedded software system engineers who are familiar with functional timing requirements may perform the *Buffering* editing activity frequently in the editor whenever the WCET violation is detected. Therefore, this model transformation process can be specified as a transformation pattern using MTBD to enable automation and reuse.

It can be seen from the examples in this section that if model transformation patterns can be shared among users with different expertise or levels of experience, the reuse captured in a transformation rule can contribute to a knowledge base, improving the collaborative construction of models in the same domain.

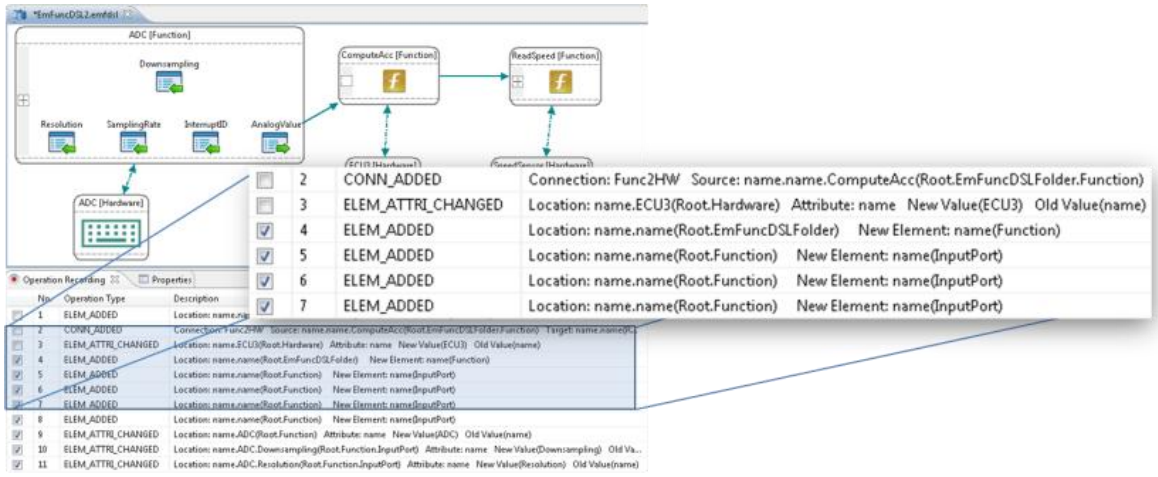
In addition, archiving model transformation rules does not guarantee the appropriate and correct reuse of the rules, due to a lack of suggestion or guidance about when and where to apply the transformation rules, particularly when the rules are specified by other users. For instance, it is likely that hardware engineers fail to reuse the *ApplyBuffer* transformation if it has been specified by software engineers, because they do not realize the issues involving WCET. Likewise, when software engineers are trying to configure the correct *ADC* for their system, the *ADC* creation transformation specified by hardware engineers may not be reused either, simply because the software engineers are not aware of the existence of a model transformation that can fulfill their needs directly.

5.2.2 LiveMTBD in Action

This section shows how to use "live" features in Live-MTBD to improve pattern specification, sharing and reuse.

In order to enable a more flexible demonstration and avoid repeating the same demonstration, live demonstration can be used so that the recording engine works continuously to record every editing operation performed in the editor. As can be seen in

Figure 5.5, a user creates the whole model by adding the *ComputeAcc* function, *ADC* function and hardware, and then *ReadSpeed*. Although explicit demonstrations were not performed using MTBD, after the complete model is specified, the user may check the related editing operations from the recording view to construct the operation list as an input to the inference engine, followed by generating the transformation pattern (e.g., the *CreateADC* transformation pattern as shown in Figure 5.6. This is an abstract representation of a transformation pattern in MTBD, which is not visible to end-users) with the normal steps. This pattern can be applied to any function, and changes the selected function into a fully configured *ADC* function by adding four input ports and one output port, as well as the corresponding *ADC* hardware. In this way, users specify their desired editing activity by reflecting on their editing history, rather than by an intentional demonstration.



	No.	Operation Type	Description
☐	1	ELEM_ADDED	Location: name.na
☐	2	CONN_ADDED	Connection: Func2HW Source: name.name.ComputeAcc(Root.EmFuncDSLFolder.Function) Target: name.name(R
☐	3	ELEM_ATTRI_CHANGED	Location: name.ECU3(Root.Hardware) Attribute: name New Value(ECU3) Old Value(name)
✓	4	ELEM_ADDED	Location: name.name(Root.EmFuncDSLFolder) New Element: name(Function)
✓	5	ELEM_ADDED	Location: name.name(Root.Function) New Element: name(InputPort)
✓	6	ELEM_ADDED	Location: name.name(Root.Function) New Element: name(InputPort)
✓	7	ELEM_ADDED	Location: name.name(Root.Function) New Element: name(InputPort)
✓	8	ELEM_ADDED	Location: name.name(Root.Function) New Element: name(InputPort)
✓	9	ELEM_ATTRI_CHANGED	Location: name.ADC(Root.Function) Attribute: name New Value(ADC) Old Value(name)
✓	10	ELEM_ATTRI_CHANGED	Location: name.ADC.Downsampling(Root.Function.InputPort) Attribute: name New Value(Downsampling) Old Va...
✓	11	ELEM_ATTRI_CHANGED	Location: name.ADC.Resolution(Root.Function.InputPort) Attribute: name New Value(Resolution) Old Value(name)

Figure 5.5 – Live demonstration enables demonstration by checking the editing history

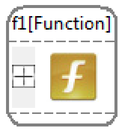
Precondition	Actions	
	1. **Set** *f1.name = "ADC"*	11. **Add** InputPort *ip4*
	2. **Add** InputPort *ip1*	12. **Set** *ip4.name = "InterruptID"*
	3. **Set** *ip1.name = "Resolution"*	13. **Set** *ip4.type = "String"*
	4. **Set** *ip1.type = "double"*	14. **Add** OutputPort *op1*
	5. **Add** InputPort *ip2*	15. **Set** *op1.name = "AnalogValue"*
	6. **Set** *ip2.name = "Downsampling"*	16. **Set** *op1.type = "double"*
	7. **Set** *ip2.type = "double"*	17. **Add** Hardware *h1*
	8. **Add** InputPort *ip3*	18. **Set** *h1.name = "ADC"*
	9. **Set** *ip3.name = "SampingRate"*	19. **Connect** *f1* to *h1*
	10. **Set** *ip3.type = "double"*	

Figure 5.6 – Final transformation pattern for *CreateADC*

The original MTBD saves finalized patterns locally. To ease the sharing of patterns and enhance the editing activities, Live-MTBD changes the repository to a centralized repository, which can be accessed by any user at any time. All the patterns generated by different users are stored automatically in the centralized repository, and they are immediately available for users to choose in the pattern execution step, which provides a live collaborative environment. As shown in Figure 5.7, the pattern execution controller displays all the patterns that exist in the current repository, with *CreateADC* being created by a hardware engineer and *ApplyBuffering* being created by a software engineer. With this feature, users can exchange and benefit from each others' knowledge during the modeling process.

Finally, in order to assist users in reusing the correct transformation patterns, live matching in Live-MTBD offers user guidance about applicable model transformation patterns during editing. Live matching is triggered during two occasions: 1) the selected input model changes, or 2) the available patterns in the repository changes. As an example shown in the top of Figure 5.8, after we finalize the two transformation patterns, *CreateADC* and *ApplyBuffer*, if the users do not select any part of the model, the whole model instance is included as the input model to the inference engine, and live matching indicates that both patterns can be applied. Because there are five functions available in the current editor, *CreateADC* is matched 5 times; while the *ApplyBuffer* can be matched to the *ReadSpeed* function whose WCET is greater than 300. Double-clicking on any of the matched patterns triggers its execution directly, but live matching requires user approval before executing the pattern.

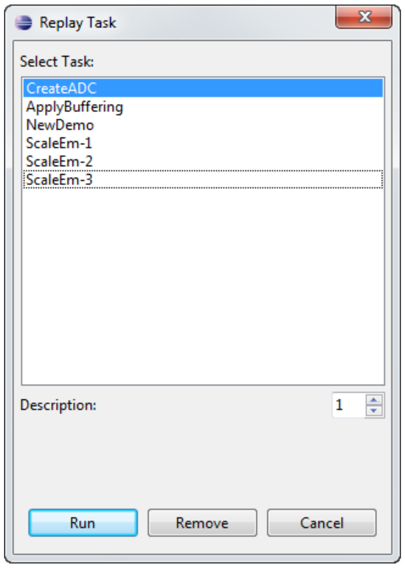
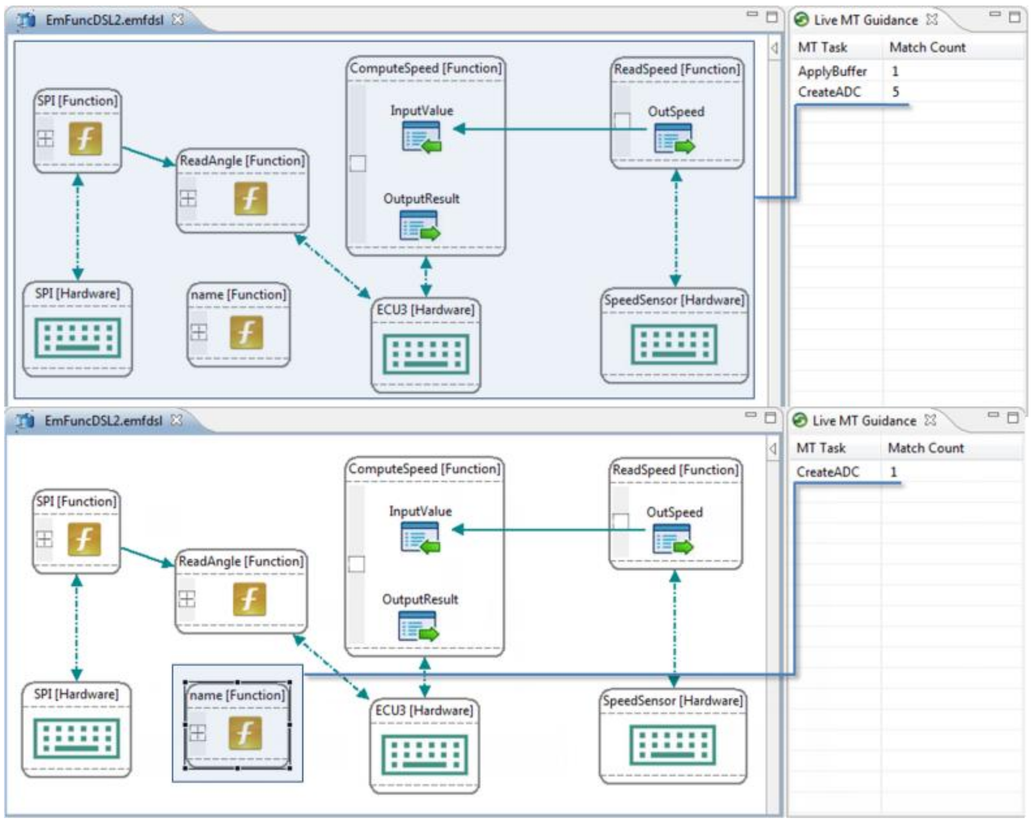


Figure 5.7 – Pattern execution controller to show all the patterns from a centralized repository

At the bottom of Figure 5.8, a user may change the selections on the model from the default to the single function newly added to the model. At this point, only *CreateADC* can be matched, and the precondition of *ApplyBuffer* cannot be satisfied due to the insufficient model elements and connections in the input model. Executing *CreateADC* can transform this function automatically to a fully configured *ADC* function.



MT Task	Match Count
ApplyBuffer	1
CreateADC	5

MT Task	Match Count
CreateADC	1

Figure 5.8 – Live matching suggests applicable transformations in the current selection

5.3 Related Work

Some work has been done to realize automatic model completion features to create and modify the existing model elements automatically from an incomplete state to a complete state. Sen et al. proposed to transform the metamodel and associated instance models to an Alloy specification, including static semantics [Sen et al., 2010-a]. Then, the partial model can be completed automatically by applying a SAT solver. This approach provides guidance and assistance to end-users in the model editing process, but the limitation is that the inferred complete models are mainly based on the formal input constraints, rather than end-user customizations. In other words, specific constraints and rules have to be defined in order to enable the desired model completion, which is the same as writing transformation rules in MTLs. Thus, it shares the similar challenges of using MTLs.

Mazanek et al. implemented an auto-completion feature for diagram editors based on graph grammars [Mazanek and Minas, 2009]. Given an incomplete graph (model) in the editor, all possible graphs that can be generated using the grammar production rules will be suggested to users. Although this is a runtime and live suggestion feature, the suggestions are totally dependent on the grammar production rules, which require users to specify a number to restrict the times of production in order to avoid infinite production loops. Also, the graph grammar may not be fully compatible to process domain-specific modeling languages, because there are usually specific node or connection types associated with each element, as well as the different attributes. This approach cannot express user-customized evolution activities (e.g., the *WCET* must be greater than *300*).

General MTLs, particularly graphical MTLs [Mens and Gorp, 2005] based on left and right side patterns, can all be extended with a live model transformation feature without much modification, although this is still not a common practice. VIATRA2 [Balogh and Varró, 2006] already supports live model transformation matching features. For instance, triggers can be defined as special rules to execute certain model transformations at modeling time. However, a suggestion or guidance before applying the transformation is not available in the environment.

Based on graphical MTLs, Rath et al. [Rath et al., 2008; Bergmann et al., 2009] performed a detailed investigation on live model transformations using incremental pattern matching techniques. They applied the Rete algorithm (an efficient pattern matching algorithm for implementing production rule systems) to preserve the full transformation context in the form of pattern matches that improved the performance of the live transformation. Their live model transformation was mainly aimed at supporting incremental model transformations and model synchronization between source and target models, although it could be applied to automate the editing activities as well. The full implementation of their approach is based on VIATRA2, which requires the usage of graph transformation rules at the metamodel level. Their matching technique could be helpful to improve our live matching feature.

Finally, there are also related works that support model transformation reuse. Rather than focusing on reusing the complete transformation, Iacob et al. summarized a number of model transformation patterns and enabled reusing and extending these patterns in QVT [Iacob et al., 2008]; Sen et al. presented a novel approach to adapt a metamodel so that an existing model transformation written for a different metamodel can be reused [Sen et al., 2010-b].

5.4 Conclusion

This chapter presents another contribution of the dissertation on improving the creation, sharing and reuse of model transformation patterns when using MTBD, through a set of “live” features: live demonstration provides a different demonstration approach in order to encourage the creation of model transformation patterns; live sharing makes all the generated patterns available to all the users to reuse, and live matching helps users to reuse the right pattern at the right time. These features have been fully implemented as the toolkit Live-MTBD integrated with the original MTBD. Users have the option to use these features or not.

Although similar functionality and features can be seen in other MTLs and tools, there was no work available to integrate all these features seamlessly together with a model transformation approach. In addition, with the same goal of MTBD to focus on end-users, Live-MTBD is realized at an automatic and transparent level, so that users are fully isolated from the low-level implementation details. Users only focus on their general editing activities, while the operation recording, sharing of patterns, and pattern matching are carried out transparently.

CHAPTER 6

MODEL TRANSFORMATION BY DEMONSTRATION DEBUGGER: AN END-USER FACILITY TO DEBUG MODEL TRANSFORMATION EXECUTION

Model Transformation By Demonstration (MTBD) has the potential to ease the specification and execution of model transformation tasks. Combined with Live-MTBD, users are exposed to a large resource of transformation patterns to use. However, not every transformation pattern is correctly demonstrated and specified. Similar to writing programs, bugs can also occur during a user demonstration and refinement process, which will bring about transforming the models into undesired states. This chapter presents the third part of the contribution in this dissertation – MTBD Debugger, which is a debugger based on the MTBD execution engine, enabling users to step through the transformation execution process and track the model's state during a transformation. MTBD Debugger also focuses on the end-user friendliness, so the low-level execution information is hidden during the debugging process. An overview of MTBD Debugger will be given first, followed by its usage and implementation details. Additionally, a case study is provided to illustrate usage of the debugger to assist tracking and locating errors in transformation patterns. Related work and concluding remarks are presented in the rest of the chapter.

6.1 Model Transformation By Demonstration Debugger

MTBD eases the specification of model transformations by a demonstration-based approach, and allows users to execute the generated transformation patterns on any model instance directly. Although the main goal of MTBD is to avoid the steep learning curve and make it end-user centric, there is not a mechanism to check or verify the correctness of the generated transformation patterns. In other words, the correctness of the final transformation pattern totally depends on the demonstration and refinement operations given by the user, and it is impossible to check automatically whether the transformation pattern accurately reflects the user's intention. In practice, similar to producing bugs when writing programs, it is also inevitable that bugs will be introduced in the transformation patterns due to the incorrect operations in the demonstration or user refinement step when using MTBD. Incorrect patterns can lead to errors and transform the model into undesired states. For instance, users may perform the demonstration of an attribute editing using the value of a wrong model element; they may give preconditions that are either too restrictive or too weak; or they may forgot to mark certain operations as generic.

Obviously, an incorrect transformation pattern can cause the model to be transformed into an incorrect and undesired state or configuration, which may be observed and caught by users. However, knowing the existence of errors and bugs cannot guarantee the correct identification and their location, because MTBD hides all the low-level and metamodel information from users. Also, the final generated pattern is invisible, which makes it challenging to map the errors in the target model to the errors in the demonstration or refinement step. This issue becomes even more apparent when reusing an existing transformation pattern generated by a different user, such that the current users who did not create the original pattern usually have no idea about how to track the cause of errors and bugs in the transformation.

In order to enable users to track and ascertain errors in transformation patterns, a transformation pattern execution debugger is needed that can work together with the pattern execution engine. In fact, a number of model transformation debuggers have already been developed for different MTLs [Allilaire et al., 2006]. However, the main problem with these debuggers is that they work by tracking the MTL rules or codes, which is at the same level of abstraction as the MTL and therefore not appropriate for end-users. Because MTBD has already raised the level of abstraction above the general level of MTLs, the associated MTBD Debugger should be built at the same level of abstraction. Thus, the goal of MTBD Debugger is to provide users with the necessary debugging functionality without exposing them to low-level execution details or metamodel information.

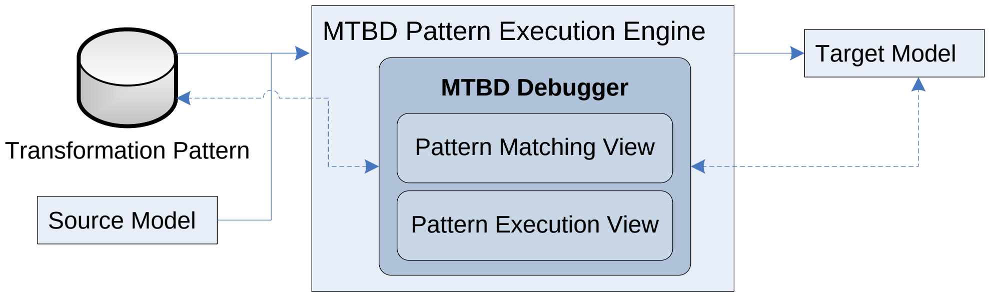


Figure 6.1 – The overview of MTBD Debugger

To realize this goal, MTBD Debugger is based on the structure of a transformation pattern. As mentioned in Chapter 3, a transformation pattern contains the precondition of a transformation (i.e., including the structural precondition and attribute precondition) and the sequence of transformation actions. During the execution of a transformation pattern, any error occurring can be traced back to the errors in either the precondition or the transformation actions. From the technical perspective as shown in Figure 6.1, the goal of MTBD Debugger is to help users to correctly map the effect of a transformation exerted on the target model instance to the precondition and actions specified in the transformation pattern, so that users can track the cause of an undesired transformation result.

The main functionality of MTBD Debugger is supported by enabling the step through execution of a transformation pattern and displaying the related information with each step in two views – Pattern Execution View and Pattern Matching View. Users can directly observe what action is about to be executed, what are the matched model elements for the operation, and more importantly how the matched elements are determined based on what types of preconditions, so that they can follow each step and check if it is the desired execution process.

6.1.1 Pattern Execution View

The Pattern Execution View lists all the actions to be executed in a transformation pattern in sequence. As shown in Figure 6.4, the view displays the type of the action, the main target element used for this action, whether the action is generic or not, and the related details based on the type of the action.

In the debugging mode, users can step through each action one-by-one. Before the execution of the action, all the matched elements that will be used for the action are highlighted in the Pattern Matching View, so that users can determine which elements are going to be used for the execution of the action. If the required target element cannot be matched, "*null*" will be displayed.

After the action is executed, the Pattern Execution View highlights the next action. At the same time, the model in the editor is updated with the execution of the previous action. Users can check the properties and structure of the latest model instance and determine if it is transformed into the desired state.

6.1.2 Pattern Matching View

The Pattern Matching View works together with the Pattern Execution View to provide relevant information about the matched model elements. From Figure 6.4, it can be seen that it shows the model element type, the precondition associated with it, and the specific model element that is matched in the current model. The list includes all the model elements needed in the transformation pattern. As mentioned in the previous section, the execution of each action will trigger the highlight of all the needed model elements in this view.

6.1.3 Common Bugs and Tracking Solution

The two views in MTBD Debugger can be used to assist tracking the following bugs commonly occurred in the usage of MTBD.

Over-Matched/Under-Matched Precondition. The refinement on the inferred transformation pattern needs user involvement. During this step, incorrect preconditions can be given by users, which will lead to failures on matching the desired parts of the model. For instance, users may provide insufficient constraints, and cause the pattern to be over-matched in a model, making the transformation process carried out in many undesired locations. On the contrary, too restrictive preconditions can also be given by users mistakenly, which will trigger an under-matched pattern execution process, preventing the desired parts of the model from being transformed. The Pattern Matching View can highlight all the matched model elements before the execution of every single transformation action. In addition, the precondition used to match each element will be shown as well to inform users how and why the current element is being matched. Using this view, users can directly track the information about all the matched elements and their matching reasons, in order to determine the errors caused by incorrect precondition specification.

Incorrect Generic Operation. Besides precondition specification, another type of user refinement is to identify the generic operations. A common bug caused in this step is that users either forget to check certain generic operations or identify more generic operations than needed. Incorrect configuration of generic operations will cause the transformation actions taken for an undesired number of execution times. To track the bugs related with generic operations, a specific column in the Pattern Execution View displays the generic configuration for each transformation action in a pattern, so that users can clearly check the correctness of the configuration.

Incorrectly Chosen Elements in Demonstration. The correctness of inferred pattern depends on the user's demonstration. If incorrect elements are chosen during a demonstration, it will trigger the inference engine to infer wrong elements types or relationship, which will finally cause either the failure of matching the desired parts of the model or the transformation actions taken on the wrong element. Such type of bugs can be tracked using the Pattern Matching view and the editor together. Before the execution of each transformation action, the matched element for the current action will be highlighted in the Pattern Matching view. A user can then locate the elements in the editor and decide if they are the desired elements to be matched.

Incorrect Attribute Expression. Attribute transformation is well supported in MTBD by allowing users to specify the desired attribute transformation expression. An incorrect expression produces the wrong attribute values. Therefore, in the Pattern Execution view, the detailed attribute expression stored in the pattern will be displayed for users in order to enable them to check its correctness.

6.2 Case Study

This section presents a case study that illustrates the use of MTBD Debugger to support tracking and debugging errors in several practical model transformation tasks in a textual game application domain.

6.2.1 Background

The case study is based on a simple modeling language called MazeGame. A model instance is shown in Figure 6.2. A *Maze* consists of *Rooms*, which can be connected to each other. Each *Room* can contain *Gold*, a *Weapon* or a *Monster* with the *strength* attribute to specify the power. This modeling language is used to generate a textual game in Java, enabling players to type textual commands to move in the maze and collect all the gold without being killed by monsters. A model instance describes a specific maze configuration. Collecting weapons during game-play increases a player's power, which can be used to kill monsters. We constructed this metamodel in GEMS.

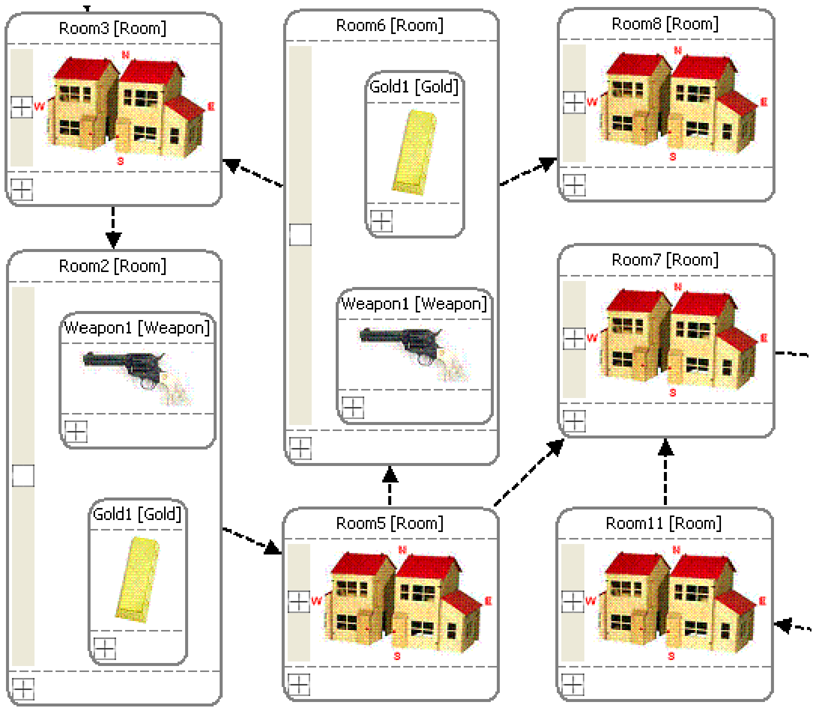


Figure 6.2 – An excerpt of a MazeGame model instance

Model evolution tasks always need to be performed for the maintenance purposes in this domain. For instance, for those rooms that contain gold and a weapon (the two unfolded rooms in Figure 6.2, *Room2* and *Room6*), the transformation removes one gold piece, replaces the weapon with a monster, and sets the strength of the new monster to be half of the strength of the weapon being replaced. This transformation is used when the maze designer discovers that the number of monsters is far less than that of weapons, making the game too easy.

6.2.2 Debugging in Action

In order to illustrate the usage of MTBD Debugger, we choose some common bugs or mistakes users make when using MTBD, and show how to use MTBD Debugger to track and locate these errors.

Debugging Example 1. This first example is based on the following transformation task: if a *Monster* is contained in a *Room*, whose *strength* is greater than *100*, replace this *Monster* with a *Weapon* having the same *strength*, and add a *Gold* in the same *Room*. Figure 6.3 shows a concrete example for this transformation task.

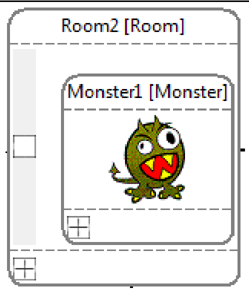
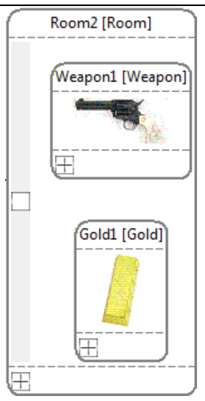
	
Monster1.stength = 120	Weapon1.strength = 120

Figure 6.3 – The excerpt of a MazeGame model before and after replacing the monster

Based on this scenario, a user starts the demonstration by first locating a *Room* with a *Monster* in it, and deleting the *Monster* followed by adding a *Weapon* plus a *Gold*. The *strength* of the new *Weapon* can be configured using the attribute refactoring editor. Finally, a precondition on *Monster* is needed to restrict the transformation (Monster1.strength > 100). As shown in List 6.1, the user performed all the correct operations except mistakenly provided the incorrect precondition (Monster1.strength > 10).

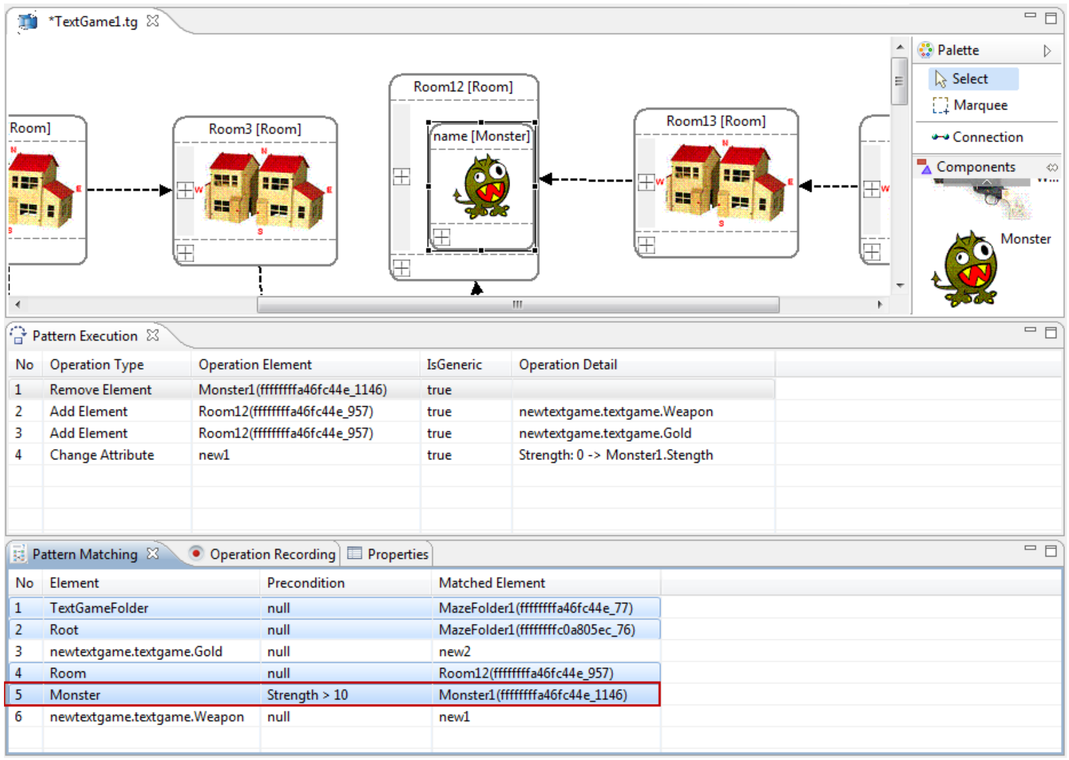
List 6.1 – Operations for demonstrating replacing a *Monster*

Sequence	**Operation Performed**
1	Remove *Monster1* in *Root.TextGameFolder.Room2*
2	Add a *Weapon* in *Root.TextGameFolder.Room2*
3	Add a *Gold* in *Root.TextGameFolder.Room2*
4	Set *Root.TextGameFolder.Room2.Weapon.strength* *= Monster1.strength = 120*
5	Set precondition on *Monster1*: *Monster1.strength > 10*

When applying this finally generated pattern to the model, it is found that the transformation takes place in every *Room* with a *Monster* in it, which is not the desired result. Obviously, because the *strength* of every *Monster* is greater than *10*, so the incorrect precondition can be satisfied with all *Monsters* in the model instance.

To debug the error, we execute the transformation pattern again using MTBD Debugger. As shown in Figure 6.4, the Pattern Execution view lists all the operations to be performed, while the Pattern Matching view provides the currently matched elements for the transformation pattern. Users can step through each of the operations, and the corresponding model elements needed for each operation will be highlighted. For instance, the very first operation in this scenario is to remove the *Monster* in the *Room*. Before executing this operation and stepping to the next one, we can clearly find out which *Monster* is currently matched as the target to be removed. In this case, the *Monster1* in *Room12* is about to be removed. If we check the *strength* attribute of *Monster1* (e.g., *30*), we can ensure that there is something wrong with the precondition we specified in the demonstration, because the *strength* of this Monster is not greater than

100. At this point, we can double check the precondition in the Pattern Matching view, which shows the actual precondition is "*Strength* > *10*", not "*Strength* > *100*" as desired. The bug is therefore identified and located.



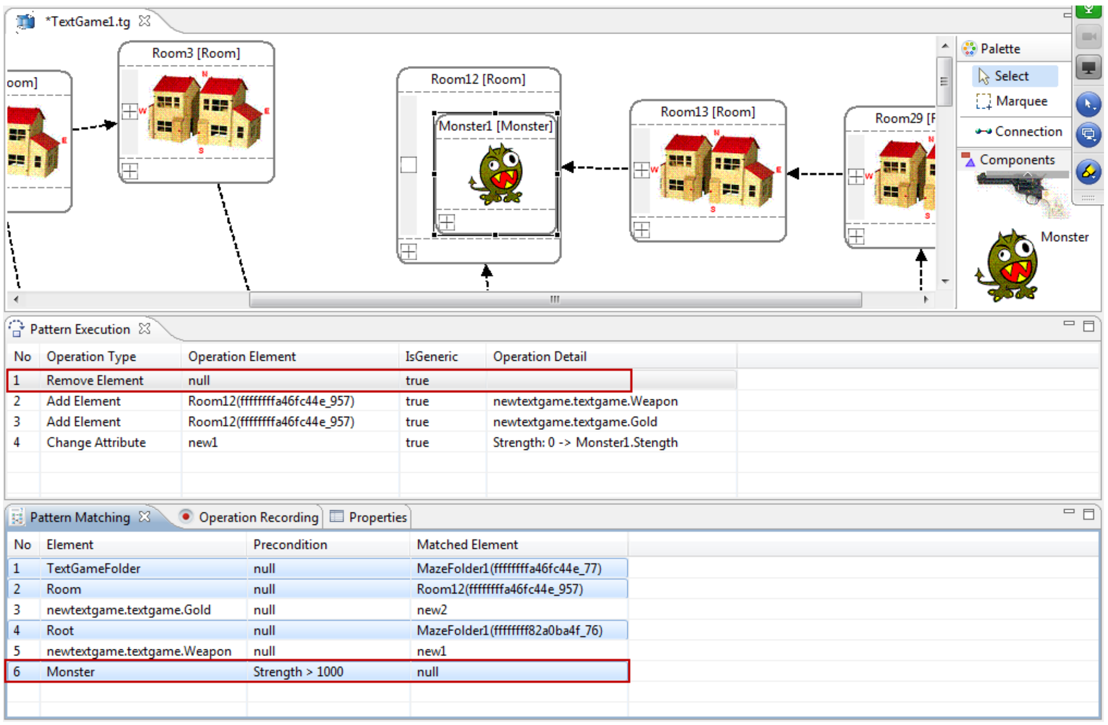
No	Operation Type	Operation Element	IsGeneric	Operation Detail
1	Remove Element	Monster1(ffffffffa46fc44e_1146)	true	
2	Add Element	Room12(ffffffffa46fc44e_957)	true	newtextgame.textgame.Weapon
3	Add Element	Room12(ffffffffa46fc44e_957)	true	newtextgame.textgame.Gold
4	Change Attribute	new1	true	Strength: 0 -> Monster1.Stength

No	Element	Precondition	Matched Element
1	TextGameFolder	null	MazeFolder1(ffffffffa46fc44e_77)
2	Root	null	MazeFolder1(ffffffffc0a805ec_76)
3	newtextgame.textgame.Gold	null	new2
4	Room	null	Room12(ffffffffa46fc44e_957)
5	Monster	Strength > 10	Monster1(ffffffffa46fc44e_1146)
6	newtextgame.textgame.Weapon	null	new1

Figure 6.4 – Debugging the transformation pattern of Example 1

The bug of the first example comes from a mistakenly specified precondition that over-matched the model elements. In the second example, we present how to debug a transformation pattern that contains preconditions that are under-matched.

Debugging Example 2. The second example is based on the same transformation scenario as the first one to replace the *Monster* with a *Weapon*. However, in this second demonstration, instead of giving the correct precondition "*Strength* > *100*", the user specified "*Strength* > *1000*" by mistake. As we can imagine, the result of executing this transformation pattern will probably not replace any of the *Monsters* in the model instance, because there are seldom *Monsters* whose *strength* is greater than *1000*.



Pattern Execution

No	Operation Type	Operation Element	IsGeneric	Operation Detail
1	Remove Element	null	true	
2	Add Element	Room12(ffffffffa46fc44e_957)	true	newtextgame.textgame.Weapon
3	Add Element	Room12(ffffffffa46fc44e_957)	true	newtextgame.textgame.Gold
4	Change Attribute	new1	true	Strength: 0 -> Monster1.Stength

Pattern Matching | Operation Recording | Properties

No	Element	Precondition	Matched Element
1	TextGameFolder	null	MazeFolder1(ffffffffa46fc44e_77)
2	Room	null	Room12(ffffffffa46fc44e_957)
3	newtextgame.textgame.Gold	null	new2
4	Root	null	MazeFolder1(ffffffff82a0ba4f_76)
5	newtextgame.textgame.Weapon	null	new1
6	Monster	Strength > 1000	null

Figure 6.5 – Debugging the transformation pattern of Example 2

Similar to the first example, when using the MTBD Debugger to step through the execution process, we can find out the currently matched model elements for each operation. As shown in Figure 6.5, the first operation to remove the *Monster* contains a *null* operation element as the target, which means that there is not a *Monster* in the current model instance that can be matched as an operand for this operation. We may think that there is again something wrong with the precondition, so we take a look at the precondition in the Pattern Matching view, and we find the bug results from the precondition being set as "*Strength* > *1000*".

Debugging Example 3. Using MTBD, one of the scenarios that likely cause bugs is the refinement on the transformation actions in order to identify generic operations. The third example is based on the scenario that we want to remove all the pieces of *Gold* in all the *Rooms*, no matter how many pieces there are in the *Room*, as shown in Figure 6.6.

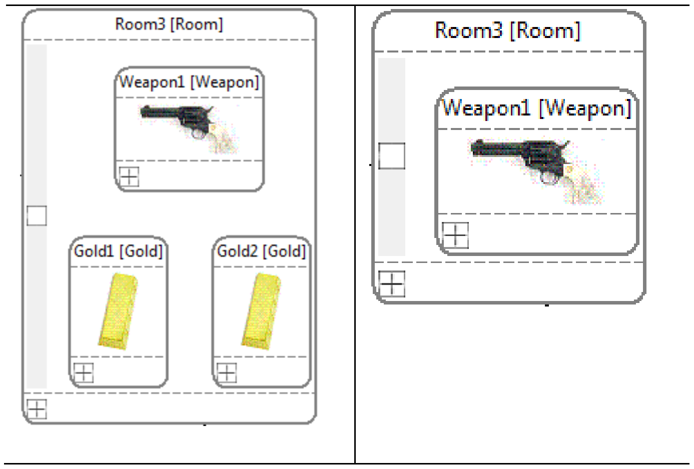


Figure 6.6 – The excerpt of a MazeGame model before and after removing all *Gold*

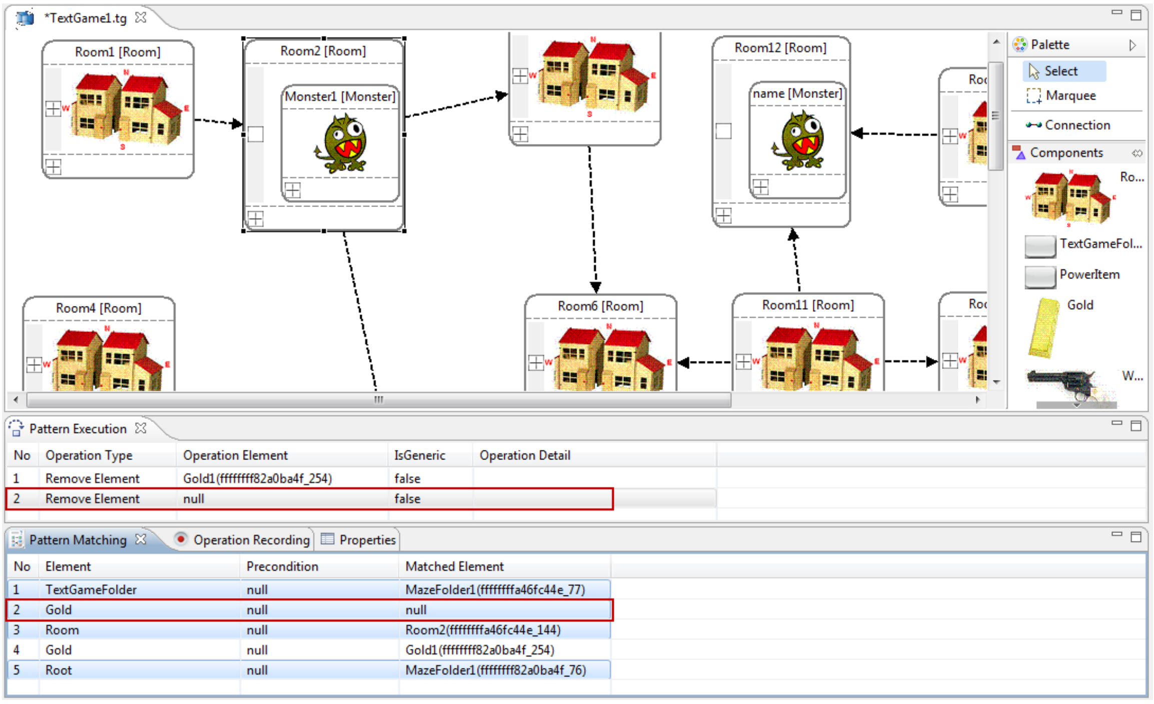
To specify the transformation pattern, a user performs a demonstration on a *Room* that contains two pieces of *Gold*. Two operations were performed as listed in List 6.2.

List 6.2 – Operations for demonstrating removing all pieces of *Gold*

Sequence	**Operation Performed**
1	Remove *Gold1* in *Root.TextGameFolder.Room3*
2	Remove *Gold2* in *Root.TextGameFolder.Room3*

Without giving further refinement on the transformation actions, the user completed the demonstration. When executing the generated transformation pattern on the model, however, it is found that the Rooms that contain only one piece of Gold were not transformed as expected.

To track the error, we re-execute the pattern using MTBD Debugger. As listed in the Pattern Execution view, we can see that there are two operations in this pattern, and each operation requires a different target element (i.e., the *Gold* to remove). When the *Room* contains only one piece of *Gold*, the second operation cannot be provided with a correct operand as shown in Figure 6.7. Thus, the problem of this bug comes from the fact that the transformation actions are not generic so that it always requires a fixed number of model elements to enable the correct transformation. As mentioned in Chapter 3, the demonstration should be concise, such that users should only demonstrate a single case followed by identifying the necessary generic operations. In this case, the correct demonstration should be done by removing only one piece of *Gold* and then marking it as generic.



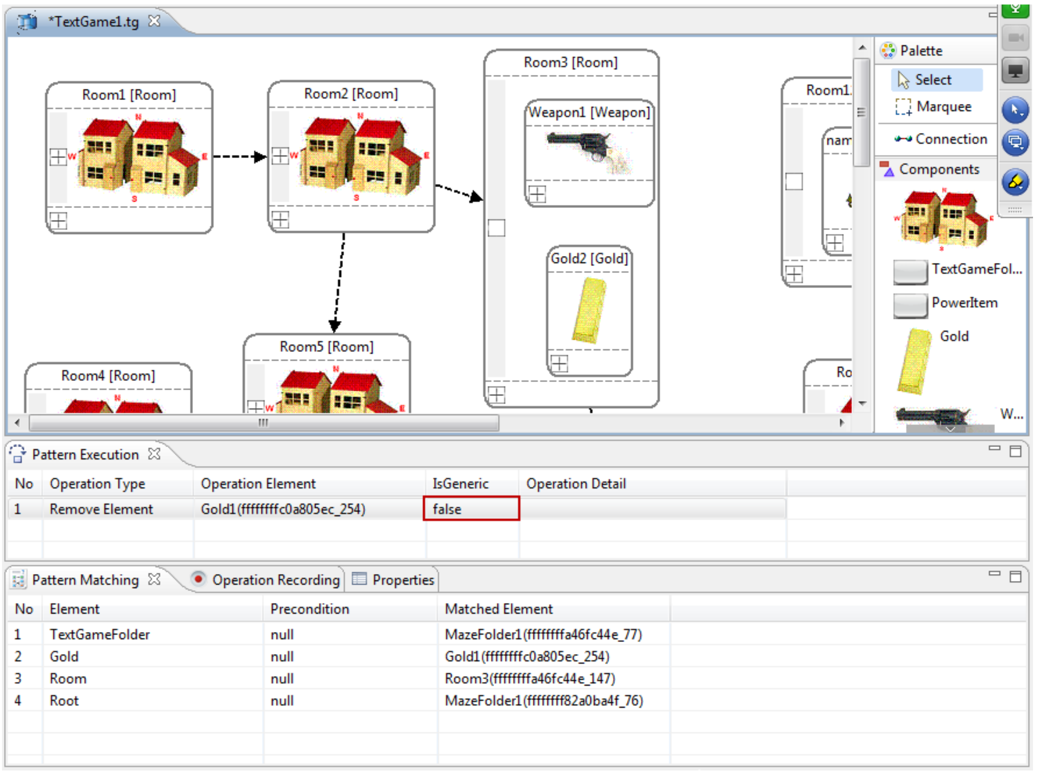
No	Operation Type	Operation Element	IsGeneric	Operation Detail
1	Remove Element	Gold1(ffffffff82a0ba4f_254)	false	
2	Remove Element	null	false	

No	Element	Precondition	Matched Element
1	TextGameFolder	null	MazeFolder1(ffffffffa46fc44e_77)
2	Gold	null	null
3	Room	null	Room2(ffffffffa46fc44e_144)
4	Gold	null	Gold1(ffffffff82a0ba4f_254)
5	Root	null	MazeFolder1(ffffffff82a0ba4f_76)

Figure 6.7 – Debugging the transformation pattern of Example 3

Debugging Example 4. Following Example 3, the user re-demonstrated removing pieces of *Gold* by only performing a single removal operation. However, the wrong transformation pattern is generated again due to the user forgetting to mark the operation as generic. This time, when the pattern is executed, only one piece of *Gold* can be removed in each *Room*.

To track the error, the MTBD Debugger can show whether each operation is generic or not. As shown in Figure 6.8, when stepping through the execution in *Room3* (which contains two pieces of *Gold*), the user can find that another *Room* will be matched after removing only one piece of *Gold*. The user may think that the problem is caused by the generic operations, so by double-checking the generic status, it can be seen from the Pattern Execution view that the removal operation is not generic.



No	Operation Type	Operation Element	IsGeneric	Operation Detail
1	Remove Element	Gold1(ffffffffc0a805ec_254)	false	

No	Element	Precondition	Matched Element
1	TextGameFolder	null	MazeFolder1(ffffffffa46fc44e_77)
2	Gold	null	Gold1(ffffffffc0a805ec_254)
3	Room	null	Room3(ffffffffa46fc44e_147)
4	Root	null	MazeFolder1(ffffffff82a0ba4f_76)

Figure 6.8 – Debugging the transformation pattern of Example 4

Debugging Example 5. Another common error that occurs when using MTBD is choosing the wrong element in the demonstration process, particularly in the attribute editing demonstration. For example, the user wants to replace all the *Monsters* with *Weapons*, as well as doubling the strength of the new *Weapons*, as shown in Figure 6.9.

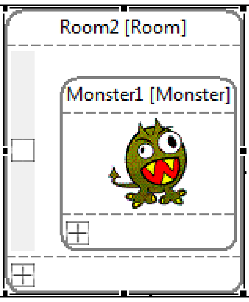
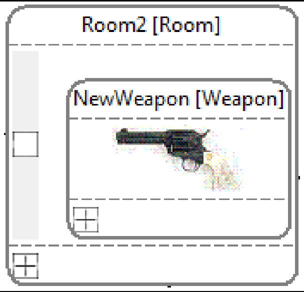
	
Monster1.Strength = 76	NewWeapon.Strength = 152

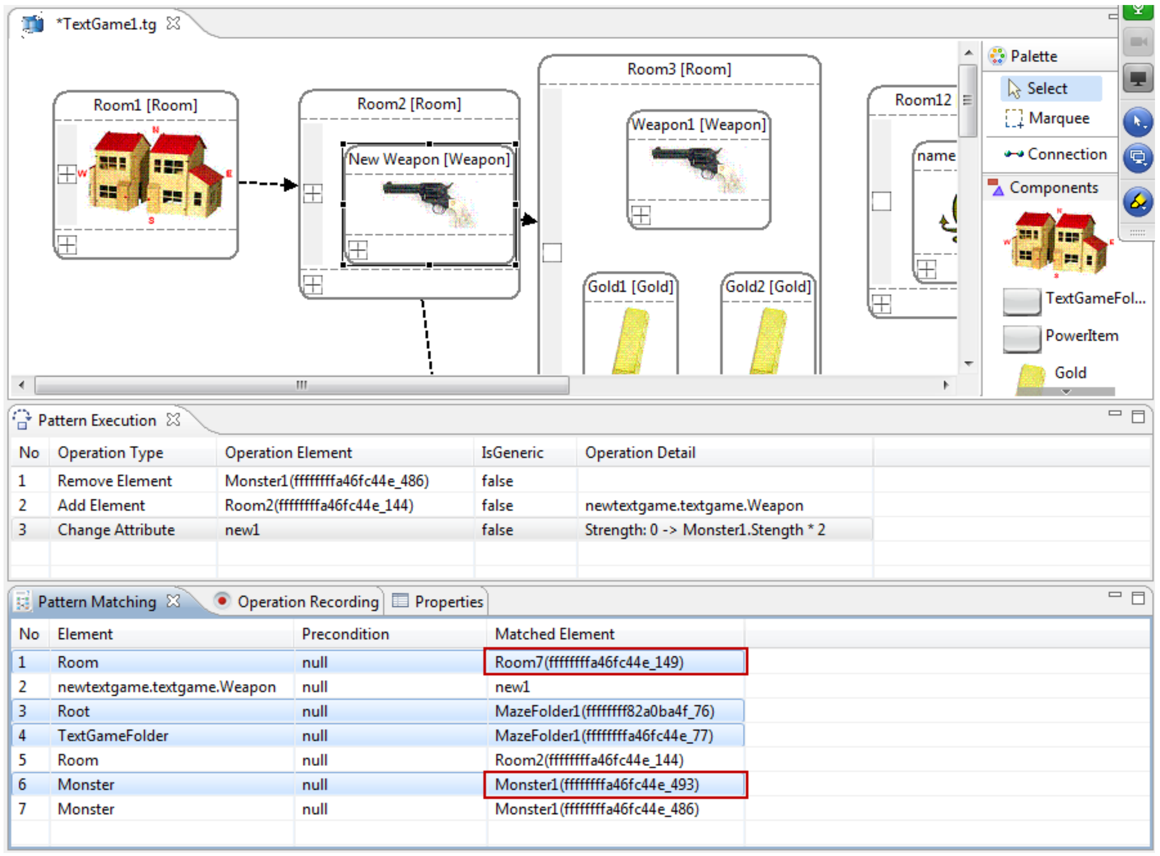
Figure 6.9 – The excerpt of a MazeGame model before and after doubling the new weapon

The following operations are performed as listed in List 6.3. An attribute transformation is demonstrated using the attribute refactoring editor. The expected computation of the strength is to use the removed *Monster* and double its strength value. However, operation 3 in the list mistakenly selects the wrong *Monster* (i.e., *Monster1* in *Room1*) which is not the *Monster* that has just been removed (i.e., *Monster1* in *Room2*). The wrong execution result triggered by this bug is that the new *Weapon* being added in the *Room* uses the strength value of the *Monster* in a different *Room*, which is not what users expect to double.

List 6.3 – Operations for demonstrating replacing a *Monster* and doubling the strength

Sequence	Operation Performed
1	Remove *Monster1* in *Root.TextGameFolder.Room2*
2	Add a *Weapon* in *Root.TextGameFolder.Room2*
3	Set *Root.TextGameFolder.Room2.Weapon.strength* = *Root.TextGameFolder.Room1.Monster1.strength* * 2 = *152*

This type of bug can be located easily using MTBD Debugger as shown in Figure 6.10. When we step through each operation, we can clearly see the used elements in the Pattern Matching view. In this case, the remove element operation is done on *Monster1* in *Room2*, while the change attribute operation uses the *Monster1* in *Room7*, which means that we probably chose the wrong element in the demonstration of the attribute changing process.



No	Operation Type	Operation Element	IsGeneric	Operation Detail
1	Remove Element	Monster1(ffffffffa46fc44e_486)	false	
2	Add Element	Room2(ffffffffa46fc44e_144)	false	newtextgame.textgame.Weapon
3	Change Attribute	new1	false	Strength: 0 -> Monster1.Stength * 2

No	Element	Precondition	Matched Element
1	Room	null	Room7(ffffffffa46fc44e_149)
2	newtextgame.textgame.Weapon	null	new1
3	Root	null	MazeFolder1(ffffffff82a0ba4f_76)
4	TextGameFolder	null	MazeFolder1(ffffffffa46fc44e_77)
5	Room	null	Room2(ffffffffa46fc44e_144)
6	Monster	null	Monster1(ffffffffa46fc44e_493)
7	Monster	null	Monster1(ffffffffa46fc44e_486)

Figure 6.10 – Debugging the transformation pattern of Example 5

6.3 Related Work

Being one of the most popular MTLs, ATL has an associated debugger [Allilaire et al., 2006] to provide the basic debugging options similar to general-purpose programming languages, such as step-by-step execution, setting up breakpoints, and watching current variables. Additionally, simple navigation in source and target models is supported. However, all these debugging options are closely related with the language constructs, so it is inappropriate for general end-users who do not have the knowledge of ATL to use. Similarly, in the Fujaba modeling environment, Triple Graphical Grammar (TGG) rules [Koenigs, 2005] can be compiled into Fujaba diagrams implemented in Java, which allows debugging the TGG rules directly [Wagner, 2011].

Schoenboeck et al. applied a model transformation debugging approach [Schoenboeck et al., 2009] using Transformation Nets (TNs), which is a type of colored Petri Net. The original source and target metamodels are used as the input to derive *places* in TNs, while model instances are represented as *tokens* with the *places*. The actual transformation logic is reflected by the *transitions*. The derived transformation TNs provides a formalism to describe the runtime semantics and enable the execution of model transformations. An interactive OCL console has been provided to enable users to debug the execution process. TNs are at a higher level of abstraction than the MTLs (e.g., QVT is used as the base MTL in this approach), so this approach helps to isolate users from knowing the low-level execution details. In addition, the formalism can be applied to implement some of the model transformation verification tasks.

However, although TNs can be considered as a DSML to assist debugging model transformations, it is a different formalism from the specific model transformation area and can be used as a general-purpose specification in many domains, which inevitably limits its end-user friendliness. Most users may find it challenging to switch their model transformation tasks to colored Petri Net transition processes. On the other hand, TNs also aim at defining the underlying operational semantics that are hidden in the model transformation rules, and this exerts an extra burden in its understandability to general end-users. Finally, applying OCL specification to perform and query the debugging information is not a desired end-user approach, because it requires the knowledge of a new language even though it is a tiny DSL.

A similar work has been done by Hibberd [Hibberd et al., 2007] which presents forensic debugging techniques to model transformation by using the trace information between source and target model instances. The trace information can be used to answer debugging questions in the form of queries that help localize the bugs. In addition, a technique using program slicing to further narrow the area of a potential bug is also shown. Compared with MTBD Debugger, which is a live debugging tool, this work focuses on a different context – forensic debugging. Similar to the ATL debugger, it aims at providing debugging support to general MTLs used in MDE.

Another related work is done on debugging a different type of model transformation – Model-to-text (M2T) [Dhoolia et al., 2010]. Dhoolia et al. present an approach for assisting with fault localization in M2T transformations. The basic idea is to create marks in the input-model elements, followed by propagating the marks to the output text during the whole transformation, so that a dynamic process to trace the flow of data from the transform input to the transform output can be realized. Using the generated mark logs and a location where a missing or incorrect string occurs in the output, the fault space that the user can examine incrementally to locate the fault can be identified.

6.4 Conclusion

This chapter presents the third part of the contribution in the dissertation on supporting the MTBD debugging process of model transformation patterns in an end-user centric matter. The MTBD Debugger works by allowing users to step through each action in the transformation pattern and check all the relevant information through two views. The MTBD Debugger has been implemented as an extension to the MTBD execution engine and integrated with the original MT-Scribe. Users have the option to debug an execution.

Although different debuggers have already been developed to work with other MTLs and tools, most of them are at the same level of abstraction as the associated MTLs, requiring the knowledge of the language itself or the metamodel definitions. In order to seamlessly integrate with MTBD at the same level of abstraction, MTBD Debugger is designed to be user-centric, so that users are isolated from the low-level implementation details and abstract metamodel information.

CHAPTER 7

FUTURE WORK

This chapter outlines research directions that will be investigated as future work. To further enhance the expressiveness and functionality of MTBD, several new features are proposed to enable users to demonstrate and specify more diverse transformation tasks using a more intelligent inference engine. Regarding the live features in Live-MTBD, the current limitations and drawbacks will be pointed out, followed by a discussion of the solutions as future work to address these problems. Although the MTBD debugger helps users track potential errors in the generated transformation pattern, a mechanism to verify whether a transformation pattern truly reflects the desired transformation scenario is still not available, which will be another key direction for the future. Finally, we will also propose how to apply MTBD to another significant model transformation scenario – exogenous model transformation.

7.1 Enhance MTBD Capacity

This section describes extensions to the capabilities of MTBD through additional demonstration options. In addition, extending the inference capability of MTBD using multiple demonstrations and logical programming are described.

7.1.1 Supporting Additonal Types of Specification in Demonstration

In MTBD, the capability of the transformation depends on the expressiveness of the demonstration. Although demonstration is very end-user friendly, it is not as expressive as MTLs. Some tasks could be specified easily by MTL expressions, but turn out to be very difficult to demonstrate. For instance, scaling an element having the maximum value of a specific attribute is currently not possible using MTBD, because there is no way to demonstrate selecting the maximum value or adding this restriction as a precondition. The same task could be implemented by function calls, selection or iteration facilities available in most MTLs. Another example is that most MTLs support conditional statements to specify the different transformation scenarios based on certain conditions. Using MTBD, preconditions are specified for the same transformation task, which means that different transformation tasks based on branch conditions are not possible.

To make MTBD more expressive and powerful, additonal features are needed to address these commonly occurring specification needs. We can either add new interfaces and options for users to do more diverse demonstration, or enrich the user refinement step to give more restrictive and specific preconditions and actions. For example, to support selecting the element with the maximum attribute value, an option can be added in the attribute precondition specification dialog to let users click on “must be maximum.” The execution engine will check if the value is the maximum among all the elements during the execution. To support the transformation tasks based on conditional branches, users can be allowed to provide a marker in certain steps of the demonstration, followed by the specific preconditions for this marked part of the actions. As a result, different preconditions can be attached to different parts of the transformation actions, and the execution engine will execute all parts of the actions only when the precondition can be matched. While improving the additional types of specification in demonstration, it is also worth building a mechanism to rewind the demonstration if users find something wrong during the demonstration. The current MT-Scribe does not support rewinding a demonstration, so users always have to redo the demonstration if incorrect operations are performed during a demonstration.

However, when designing and implementing the additional features, we need to take into consideration the tradeoffs existing between simplicity and functionality, because when new functions are extended to MTBD by designing some other user-friendly demonstration or refinement interfaces, its simplicity and user friendliness would likely be undermined. Therefore, because it is not easy to make MTBD a fully complete replacement to a well-defined model transformation language to support all possible model transformation tasks, our focus has been toward making MTBD practical for most scenarios. When encountering difficulties in using MTBD to solve common model transformation problems in practice, the most needed and essential features and functions will be selected and added into MT-Scribe by designing user-friendly and user-centric interfaces and mechanisms that are capable of implementing the desired function. On the other hand, enabling more diverse types of demonstration can make the patterns more complex, which increases the chance of creating conflicting patterns. Thus, another key issue to improve MTBD is to design new algorithms to detect conflicts among different patterns and avoid the interference. By such an incremental and selective extension process, we believe a proper balance can be achieved between simplicity, functionality, and practicality.

7.1.2 Enable Model Transformation Inference based on Multiple Demonstrations

The current inference is based on a single demonstration from users, rather than a series of demonstrations for different scenarios. Although a single demonstration requires much less effort from a user, it often contains limited information about the desired scenario, restricting the accuracy of the transformation pattern being inferred. The desired number of demonstrations given by users as the input to the inference engine is another issue that needs to be further investigated. It is also useful to make multiple demonstrations that contain negative demonstrations as well. For example, users can demonstrate a scenario that is not desired. Combined with positive demonstrations, more restrictive preconditions can be integrated into the final transformation pattern.

In addition, to further improve the inference engine, some artificial intelligence or machine learning techniques could be applied to MTBD. As mentioned in Chapter 3, related work has been done to apply logical programming to infer the transformation rules automatically from a set of given input facts. Similarly, the demonstrations can be considered as the input facts, leading to the generation of the pattern using the logical inference engine. Machine learning is another promising technique to improve the inference result for MTBD. The recorded user operation history can be a useful source of empirical data to capture or recognize the patterns automatically. For instance, when users frequently perform certain editing behavior (e.g., a user always adds an *Output Port* after adding an *ADC* function), the learning engine can summarize the repeated actions and ask users if they want to generate the pattern based on their editing history.

7.2 Improve Live-MTBD Tool Support

Live-MTBD provides a set of basic features to improve the creation, sharing and reuse of model transformation patterns. As an initial version, however, there are still limitations associated with each feature. This section points out these issues as the future work to improve Live-MTBD tool support.

7.2.1 Enhance the Correctness and User Experience of Live Demonstration

Forming the transformation pattern from the editing history using live demonstration is very flexible compared with the explicit demonstration, but it also leads to a possibility that the selected editing operations from the history may not be accurate. For instance, without a mechanism to guide the selection of operations related with certain model elements, extra unnecessary operations could be added accidentally to the pattern, which cannot be filtered by the optimization algorithm; or an incomplete pattern is inferred due to the insufficient operations chosen from the view. Therefore, a crucial aspect for the future work is how to ensure the correctness of the selections when using live demonstration. This actually raises a similar issue about how to verify a generated model transformation pattern and determine if it really reflects the user's demonstration intention, which will be discussed in Section 7.3.

In addition, the current selection of editing operations from the history is done in a list view, which shows all the information about each operation in text. This is error-prone for users to make the right selection of operations, particularly when the list is long and the needed operations are not sequentially next to each other. Thus, it would be very helpful to provide a graphical interface to show exactly where an operation occurred in the model and what model elements and connections are involved in this operation. With graphical guidance, users can reflect on their editing history easily and reduce the chance of making an incorrect selection when using live demonstration.

7.2.2 Add Management Features for Live Sharing

The current implementation of live sharing simply provides a centralized pattern repository and stores all the patterns together without classification. This could lead to matching transformation patterns that are not designed for the current modeling language. Based on the current design of the MTBD execution engine, a transformation pattern can only be matched to the model instances that conform to the same metamodel (i.e., belong to the same DSML) used in the demonstration. Thus, it is meaningless to show all the existing transformation patterns in the execution controller to the user. Instead, only the patterns created in the same DSML should be shown. The filtering of patterns can help users to better select the desired patterns from the repository, but also improve the performance of live matching, because the matching engine will only match the patterns that potentially can be applied in the current model instance.

The desired management features for live sharing also includes recording and showing more detailed information about each pattern in the repository, such as the creator of the pattern, the use case description, and the pattern creation date and time. A pattern searching function can be implemented in the execution controller to help users locate the correct pattern from the large pattern repository.

7.2.3 Improve the Performance of Live Matching

Although live matching has been applied as a useful tool to help users recognize reusable patterns at editing runtime, its usage suffers from poor performance. Because the current implementation of live matching loads all the patterns from the repository and carries out the matching process on the input selected part of the model whenever the selection changes, it could increase the workload of the matching engine when there are a large number of patterns to match or the user changes the selection frequently. Thus, new algorithms or techniques are needed to reduce the workload and improve the matching performance. As mentioned in Chapter 5, the Rete algorithm can be applied to preserve the full transformation context in the form of pattern matches that improve the performance of the live transformation. The same approach can be applied in our case. Moreover, caching is another option to improve the performance by caching the matching result based on the selection and the patterns, so that the repeated matching process can be avoided and the workload of the matching engine can be reduced.

7.3 MTBD Debugger

The MTBD debugger can be applied to the core elements specified in a model transformation pattern. However, one drawback of the current views used in the debugger is that they are textual and not visual. For instance, the Pattern Matching View shows all the needed elements for each action. However, the containment relationship among these elements cannot be seen clearly. It would be very helpful to have another view that shows all the currently involved model elements and their relationships visually. In other words, a view that can capture the specific part of the current model that is used for the next transformation action. This can enable users to catch and check the matched elements easily.

Another option that is useful in the general debugging process, but missing in the MTBD debugger, is the concept of setting a breakpoint. In some large model transformation scenarios (e.g., scaling up a base model to a large and complex state), it is not necessary to watch all the actions being executed one-by-one, so setting a breakpoint would make the debugging more useful in this case. Thus, in the Pattern Execution View, it would be helpful to enable the breakpoint setup in the action execution list.

7.4 Apply MTBD to Exogenous Model Transformation

MTBD was designed to support model transformation problems within the same domain or metamodel, because the demonstration of a transformation process occurs in the model editor, but editing models conforming to different metamodels within the same editor is currently not supported. However, we believe that the demonstration-based approach can be applied also to exogenous model transformation scenarios, by recording the operations needed to change the model from one domain to another domain and conducting the inference process. The main challenge to enable exogenous model transformation is to provide a flexible demonstration environment. This could be implemented by either designing an editor that allows users to edit models without metamodel restrictions (e.g., change the meta type of an element in the editor, change the attribute name or attribute data type, or add connections between elements although there are no connections defined in the metamodel), or implementing an interactive editing environment between two different editors so that users can make mappings, and drag and drop elements to perform the desired demonstration. After the demonstration is realized, the other steps in MTBD can be modified to adapt to exogenous model transformations.

CHAPTER 8

CONCLUSION

Model transformation is a core part of DSM and plays an indispensible role in many applications of model engineering (e.g., code generation, model mapping and synchronization, model evolution, and reverse engineering). The traditional way to implement model transformations is to use executable MTLs to specify the transformation rules and automate the transformation process. However, the use of model transformation languages may present some challenges to users due to the steep learning curve and the difficulties of understanding metamodels, particularly to those who are unfamiliar with a specific transformation language. Moreover, reusing the specific transformation rules is not well supported in most MTLs and tools, because there lacks a way to directly share the existing rules or a mechanism to provide guidance to users about which rules to use for the correct purpose. In addition, most MTLs do not have an associated debugger. Even if the debuggers are available, they usually work at the same level of abstraction as MTLs.

The overall goal of the research described in this dissertation is to provide an end-user centric approach to implement model transformation tasks in various model evolution activities. The key contributions include: 1) designing and implementing the new demonstration-based approach to address the challenges of using traditional MTLs to support implementing model transformation tasks, 2) investigating tools to improve sharing and reusing the existing transformation, 3) developing a debugger associated with the model transformation engine that is at the same level of abstraction as the new model transformation approach and is end-user centric.

8.1 The MTBD Model Transformation Approach

To simplify the model transformation implementation, we described a new approach in Chapter 3 – Model Transformation By Demonstration (MTBD). Instead of writing MTL rules manually, users are asked to demonstrate how the model transformation should be done by directly editing the model instance to simulate the model transformation process step-by-step. A recording and inference engine has been developed to capture all user operations and infer a user's intention in a model transformation task. A transformation pattern is generated from the inference, specifying the precondition of the transformation and the sequence of operations needed to realize the transformation. This pattern can be reused by automatically matching the precondition in a new model instance and replaying the necessary operations to simulate the model transformation process.

Using MTBD, users are enabled to specify model transformations without the need to use a MTL. Furthermore, an end-user can describe a desired transformation task without detailed understanding of a specific metamodel. We have applied MTBD in different model evolution activities – model refactoring, model scalability, aspect-oriented modeling, model management and model layout. Chapter 4 presents some of the typical model transformation tasks in each activity. From these examples, it can be seen that MTBD can be applied generally to different application domains in practice, be used by end-users without the knowledge of MTLs and metamodels, and can improve the productivity compared with doing the transformation either manually or by writing MTL rules.

8.2 The Live-MTBD Toolkit

The Live-MTBD toolkit presented in Chapter 5 can be applied to improve the reuse of model transformation patterns. The main obstacles of reuse come from missing the specification of many reusable transformation patterns, a lack of a sharing mechanism for transformation patterns, and the challenge of reusing the correct pattern from the repository. Thus, three new features were developed as an extension toolkit to MTBD to improve the reuse: 1) *Live Demonstration*, provides a more general demonstration environment that encourages and eases the specification of transformation patterns based on their editing history, 2) in order to improve the sharing of transformation patterns among different users, *Live Sharing* – a centralized model transformation pattern repository allows users to reuse transformation patterns across different editors, 3) a live model transformation matching engine – *Live Matching* has been developed to match the existing transformation patterns automatically at modeling time, and provides reuse suggestions and guidance to users during model editing. Based on a practical case study, we presented how to use Live-MTBD to improve the reuse of model transformation patterns.

8.3 The MTBD Debugger

Chapter 6 presents the debugger designed and implemented specifically for MTBD. It focuses on providing necessary debugging options when executing MTBD transformation patterns, which includes displaying the sequence of transformation actions and the model elements matching the preconditions. The related information is displayed in two views. Users can step through each of the transformation actions one by one, and observe the information about the model being transformed during the transformation execution time. With the same goal of MTBD, the associated MTBD debugger was built to allow end-users to perform debugging tasks, without the need to understand the abstract metamodel definition or the low-level implementation details.

To conclude, DSM has been applied to raise the level of abstraction, address the difficulties associated with developing complex systems, and enable end-users to participate in software development. However, MTLs, which are the common technology to support model evolution, are obviously not at the same abstraction level as models, which prevent a wider range of model users from contributing to system evolution and development, thus restraining the power of DSM. To address this abstraction gap with respect to model transformations, MTBD allows end-users to contribute to model evolution tasks at the same level of abstraction as modeling systems using DSM. Additionally, performing model evolution tasks usually involves other activities such as sharing and reusing the model evolution knowledge, debugging and tracking errors during a model evolution process. Live-MTBD and the MTBD Debugger were created for these purposes. The essential feature of the Live-MTBD and MTBD Debugger is that they both work at the same level of abstraction as MTBD. This dissertation brings the activities related to model evolution closer to the end-users, promoting the usage of DSM to more end-users.

LIST OF REFERENCES

[Agon, 1998] Carlos Agon, "OpenMusic: Un langage visuel pour la composition musicale assistée par ordinateur," *Ph.D. Thesis*, IRCAM University Paris, 1998.

[Agrawal, 2003] Aditya Agrawal, Gábor Karsai, and Ákos Lédeczi, "An End-to-End Domain-Driven Software Development Framework," *International Conference on Object-Oriented Programming, Systems, Languages, and Applications - Domain-driven Track*, Anaheim, CA, October 2003, pages 8-15.

[Allilaire et al., 2006] Freddy Allilaire, Jean Bézivin, Frédéric Jouault, and Ivan Kurtev, "ATL: Eclipse Support for Model Transformation," *The Eclipse Technology eXchange Workshop (eTX) of the European Conference on Object-Oriented Programming (ECOOP)*, Nantes, France, July 2006.

[Arendt et al., 2009] Thorsten Arendt, Florian Mantz, Lars Schneider, and Gabriele Taentzer, "Model Refactoring in Eclipse by LTK, EWL, and EMF Refactor: A Case Study," *Models and Evolution Joint MODELS Workshop*, Denver, CO, October 2009, pages 38-47.

[Atkinson and Kuhne, 2003] Colin Atkinson, and Thomas Kuhne, "Model-Driven Development: A Metamodeling Foundation," *IEEE Software*, vol. 20, no. 5, May 2003, pages 36-41.

[ATL Transformation Zoo, 2011] ATL Transformation Zoo, http://www.eclipse.org/m2m/atl/atlTransformations/, 2011.

[Balasubramanian et al., 2006-a] Daniel Balasubramanian, Anantha Narayanan, Chris van Buskirk, and Gabor Karsai, "The Graph Rewriting and Transformation Language: GReAT," *Electronic Communication of the European Association of Software Science and Technology*, vol. 1, 2006, 8 pages.

[Balasubramanian et al., 2006-b] Krishnakumar Balasubramanian, Aniruddha Gokhale, Yuehua Lin, Jing Zhang, and Jeff Gray, "Weaving Deployment Aspects into Domain-Specific Models," *International Journal on Software Engineering and Knowledge Engineering*, vol. 16., no. 3, June 2006, pages 403-424.

[Balogh and Varró, 2006] Zoltán Balogh and Dániel Varró, "Advanced Model Transformation Language Constructs in the VIATRA2 Framework," *Symposium on Applied Computing*, Dijon, France, April 2006, pages 1280-1287.

[Balogh and Varró, 2009] Zoltán Balogh and Dániel Varró, “Model Transformation by Example using Inductive Logic Programming,” *Software and Systems Modeling*, vol. 8, no. 3, July 2009, pages 347-364.

[Battista et al., 1994] Giuseppe Di Battista, Peter Eades, Roberto Tamassia, and Ioannis Tollis, “Algorithms for Automatic Graph Drawing: An Annotated Bibliography,” *Computational Geometry: Theory and Applications*, vol. 4, 1994, pages 235-282.

[Bergmann et al., 2009] Gábor Bergmann, István Ráth, and Dániel Varró, “Parallelization of Graph Transformation based on Incremental Pattern Matching,” *Electronic Communication of the European Association of Software Science and Technology,* vol. 18, 2009, 15 pages.

[Biermann et al., 2006] Enrico Biermann, Karsten Ehrig, Christian Köhler, Günter Kuhns, Gabriele Taentzer, and Eduard Weiss, “Graphical Definition of In-Place Transformations in the Eclipse Modeling Framework,” *International Conference on Model Driven Engineering Languages and Systems*, Genova, Italy, October 2006, pages 425-439.

[Blair et al., 2009] Gordon Blair, Nelly Bencomo, and Robert France, “Models@run.time,” *IEEE Computer,* vol. 42, no. 10, 2009, pages 22-27.

[Booch, 1997] Grady Booch, *Object-Oriented Analysis and Design with Applications*, Addison-Wesley, 1997.

[Brooks, 1987] Frederick Brooks, “No Silver Bullet - Essence and Accident in Software Engineering,” *IEEE Computer*, vol. 20, no. 4, April 1987, pages 10-19.

[Brosch et al., 2009-a] Petra Brosch, Philip Langer, Martina Seidl, Konrad Wieland, Manuel Wimmer, Gerti Kappel, Werner Retschitzegger, and Wieland Schwinger, “An Example is Worth a Thousand Words: Composite Operation Modeling By-Example,” *International Conference on Model Driven Engineering Languages and Systems*, Denver, CO, October 2009, pages 271-285.

[Brosch et al., 2009-b] Petra Brosch, Martina Seidl, Konrad Wieland, Manuel Wimmer, and Philip Langer, “The Operation Recorder: Specifying Model Refactorings By-example,” *International Conference on Object Oriented Programming Systems Languages and Applications - Tool Demonstration*, Orlando, FL, October 2009, pages 791-792.

[Budinsky et al., 2004] Frank Budinsky, David Steinberg, Ed Merks, Raymond Ellersick and Timothy J. Grose, *Eclipse Modeling Framework,* Addison-Wesley, 2004.

[Burnett et al., 2004] Margaret Burnett, Curtis Cook, and Gregg Rothermel, “End-user Software Engineering,” *Communications of the ACM*, vol. 47, no. 9, January 2004, pages 53-58.

[COM, 2011] Component Object Model (COM) Technology, http://www.microsoft.com/com/, 2011.

[CWM, 2011] Object Management Group, Common Warehouse Metamodel, http://www.omg.org/technology/documents/modeling_spec_catalog.htm#CWM, 2011

[Czarnecki and Helsen, 2006] Krzysztof Czarnecki, and Simon Helsen, "Feature-based Survey of Model Transformation Approaches," *IBM Systems Journal*, vol. 45 no. 3, 2006, pages 621-645.

[Cypher, 1993] Allen Cypher, *Watch What I Do: Programming by Demonstration*, Cambridge, MA, MIT Press, 1993.

[Deridder et al., 2008] Dirk Deridder, Jeff Gray, Alfonso Pierantonio, and Pierre-Yves Schobbens, "Report on the International Workshop on Model Co-evolution and Consistency Management," *Workshop on Model Co-Evolution and Consistency Management (MCCM)*, Toulouse, France, September 2008, pages 120-123.

[Dhoolia et al., 2010] Pankaj Dhoolia, Senthil Mani, Vibha Singhal Sinha, and Saurabh Sinha, "Debugging Model-Transformation Failures Using Dynamic Tainting," *European Conference on Object-Oriented Programming*, Maribor, Slovenia, June 2010, pages 26-51.

[Eberspächer, 2011] Eberspächer Flexray Card. http://www.eberspacher.com/, 2011.

[Eclipse, 2011] Eclipse, http://www.eclipse.org/, 2011.

[Eclipse EMFT, 2011] Eclipse Modeling Framework Technology (EMFT), http://www.eclipse.org/modeling/emft/, 2011.

[Eclipse VE, 2011] Eclipse Visual Editor, http://www.eclipse.org/vep, 2011.

[Edwards, 2004] George Edwards, Gan Deng, Douglas Schmidt, Aniruddha Gokhale, and Bala Natarajan, "Model-Driven Configuration and Deployment of Component Middleware Publish/Subscribe Services," *International Conference on Generative Programming and Component Engineering*, Vancouver, Canada, October 2004, pp. 337-360.

[Elrad et al., 2002] Tzilla Elrad, Omar Aldawud, and Atef Bader, "Aspect-Oriented Modeling: Bridging the Gap between Implementation and Design," *International Conference on Generative Programming and Component Engineering*, Pittsburgh, PA, October 2002, pages 189-201.

[EMF Refactor, 2011] EMF Refactor, http://www.mathematik.uni-marburg.de/~swt/modref/, 2011.

[EMF Tiger, 2011] EMF Tiger, http://tfs.cs.tu-berlin.de/emftrans/, 2011.

[EMP, 2011] Eclipse Modeling Project, http://www.eclipse.org/modeling/, 2011.

[Fowler, 1999] Martin Fowler, *Refactoring: Improving the Design of Existing Code*, Addison-Wesley, 1999.

[France et al., 2003] Robert France, Sudipto Ghosh, Eunjee Song, and Dae-Kyoo Kim, "A Metamodeling Approach to Pattern-Based Model Refactoring, " *IEEE Software*, vol. 20, no. 5, September 2003, pages 52-58.

[Freescale, 2011] Freescale S12 Microcontroller. http://www.freescale.com/, 2011.

[Fuggetta, 1993] Alfonso Fuggetta, "A Classification of CASE Technology," *Computer*, vol. 26, no. 12, December 1993, pages 25-38.

[Gamma et al., 1995] Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides, *Design Patterns: Elements of Reusable Object-oriented Software*, Addison Wesley, 1995.

[GEF, 2011] Graphical Editing Framework, http://www.eclipse.org/gef/, 2011.

[GEMS, 2011] Generic Eclipse Modeling System (GEMS), http://www.eclipse.org/gmt/gems/, 2011.

[GMF, 2011] Graphical Modeling Framework, http://www.eclipse.org/modeling/gmf/, 2011.

[Google App Inventor, 2011] Google App Inventor, http:// appinventor.googlelabs.com/, 2011

[Gray, 2002] Jeff Gray, "Aspect-Oriented Domain-Specific Modeling: A Generative Approach Using a Metaweaver Framework," *Ph.D. Thesis,* Vanderbilt University, Nashville, TN, 2002.

[Gray et al., 2001] Jeff Gray, Ted Bapty, Sandeep Neema, and James Tuck, "Handling Crosscutting Constraints in Domain-Specific Modeling," *Communications of the ACM*, vol. 44, no. 10, October 2001, pages 87-93.

[Gray et al., 2005] Jeff Gray, Yuehua Lin, Jing Zhang, Steve Nordstrom, Aniruddha Gokhale, Sandeep Neema, and Swapna Gokhale, "Replicators: Transformations to Address Model Scalability," *International Conference on Model Driven Engineering Languages and Systems*, Montego Bay, Jamaica, October 2005, pages 295-308.

[Gray et al., 2006] Jeff Gray, Yuehua Lin, and Jing Zhang, "Automating Change Evolution in Model-Driven Engineering," *IEEE Computer*, Special Issue on Model-Driven Engineering (Doug Schmidt, ed.), vol. 39, no. 2, February 2006, pages 51-58.

[Gray et al., 2007] Jeff Gray, Juha-Pekka Tolvanen, Steven Kelly, Aniruddha Gokhale, Sandeep Neema, and Jonathan Sprinkle, "Domain-Specific Modeling," *Handbook of Dynamic System Modeling*, CRC Press, 2007, Chapter 7, pages 7-1 through 7-20.

[Gray et al., 2009] Jeff Gray, Sandeep Neema, Jing Zhang, Yuehua Lin, Ted Bapty, Aniruddha Gokhale, and Douglas Schmidt, "Concern Separation for Adaptive QoS Modeling in Distributed Real-Time Embedded Systems," *Behavioral Modeling for Embedded Systems and Technologies: Applications for Design and Implementation*, (Luis Gomes and Joao Fernandes, eds.), Idea Group, 2009, Chapter 4, pages 85-113.

[Greenfield and Short, 2004] Jack Greenfield and Keith Short, *Software Factories: Assembling Applications with Patterns, Models, Frameworks, and Tools*, John Wiley and Sons, 2004.

[Grimes, 2002] Richard Grimes, *Developing applications with Visual Studio .NET*, Addison Wesley, 2002.

[Harrison, 2004] Warren Harrison, "The Dangers of End-User Programming," *IEEE Software*, vol. 21, no. 4, July 2004, pages 5-7.

[Hayes, 2008] Brian Hayes, "Cloud Computing," *Communications of the ACM*, vol. 51, no. 7, July 2008, pages 9-11.

[Hibberd et al., 2007] Mark Hibberd, Michael Lawley, and Kerry Raymond, "Forensic Debugging of Model Transformations," *International Conference on Model Driven Engineering Languages and Systems*, Nashville, TN, October 2007, pages 589-604.

[Hirel et al., 2000] Christophe Hirel, Bruno Tuffin, and Kishor S. Trivedi, "SPNP: Stochastic Petri Nets. Version 6.0," *Computer Performance Evaluation Modeling Techniques and Tools*, Schaumburg, IL, March 2000, pages 354-357.

[Iacob et al., 2008] Maria-Eugenia Iacob, Maarten W. A. Steen, and Lex Heerink, "Reusable Model Transformation Patterns," *Enterprise Distributed Object Computing Conference Workshops*, Munich, Germany, September 2008, pages 1-10.

[Jouault et al., 2008] Frédéric Jouault, Freddy Allilaire, Jean Bézivin, and Ivan Kurtev, "ATL: A Model Transformation Tool," *Science of Computer Programming*, vol. 72, no. 1-2, June 2008, pages 31-39.

[Jouault and Bézivin, 2006] Frédéric Jouault and Jean Bézivin, "KM3: A DSL for Metamodel Specification," *International Conference on Formal Methods for Open Object-based Distributed Systems*, Bologna, Italy, June 2006, pages. 171–185.

[Jouault and Kurtev, 2005] Frédéric Jouault and Ivan Kurtev, "Transforming Models with ATL," *Satellite Events at the MoDELS Conference*, Montego Bay, Jamaica, October 2005, pages 128-138.

[Kang et al., 1990] Kyo Kang, Sholom Cohen, James Hess, William Novak, and Spencer Peterson, "Feature-Oriented Domain Analysis (FODA) Feasibility Study," *Technical Report CMU/SEI-90-TR-021*, SEI, Carnegie Mellon University, November 1990.

[Kappel, 2006] Gerti Kappel, Elisabeth Kapsammer, Horst Kargl, Gerhard Kramler, Thomas Reiter, Werner Retschitzegger, Wieland Schwinger, and Manuel Wimmer, "Lifting Metamodels to Ontologies - a Step to the Semantic Integration of Modeling Languages," *International Conference on Model Driven Engineering Languages and Systems*, Genova, Italy, October 2006, pages 528-542.

[Karr et al., 2001] David Karr, Craig Rodrigues, Joseph Loyall, Richard Schantz, Yamuna Krishnamurthy, Irfan Pyarali, and Douglas Schmidt, "Application of the QuO Quality-of-Service Framework to a Distributed Video Application," *International Symposium on Distributed Objects and Applications*, Rome, Italy, 2001, pages 67-89.

[Karsai et al., 2004] Gábor Karsai, Miklós Maróti, Ákos Lédeczi, Jeff Gray, and Janos Sztipanovits, "Composition and Cloning in Modeling and Meta-Modeling Languages," *IEEE Transactions on Control System Technology*, Special issue on Computer Automated Multi-Paradigm Modeling (Pieter Mosterman and Sebastian Engell, eds.), vol. 12, no. 2, March 2004, pages 263-278.

[Kehn, 2010] Dan Kehn, "Extend Eclipse Java Development Tools," http://www.ibm.com/developerworks/opensource/library/os-ecjdt/, 2010.

[Kelly and Tolvanen, 2008] Steven Kelly and Juha-Pekka Tolvanen, *Domain-Specific Modeling: Enabling Full Code Generation*, Wiley-IEEE Computer Society Press, 2008.

[Kiczales et al., 1997] Gregor Kiczales, John Lamping, Anurag Mendhekar, Chris Maeda, Cristina Lopes, Jean-Marc Loingtier, and John Irwin "Aspect-Oriented Programming," *European Conference on Object-Oriented Programming*, Jyväskylä, Finland, June 1997, pages 220-242.

[Koenigs, 2005] Alexander Königs, "Model Transformation with TGGs," *Model Transformations in Practice Workshop of MoDELS 2005*, Montego Bay, Jamaica, September 2005.

[Kogekar et al., 2006] Arundhati Kogekar, Dimple Kaul, Aniruddha Gokhale, Paul Vandal, Upsorn Praphamontripong, Swapna Gokhale, Jing Zhang, Yuehua Lin, and Jeff Gray, "Model-driven Generative Techniques for Scalable Performabality Analysis of Distributed Systems," *IPDPS Workshop on Next Generation Systems*, Rhodes, Greece, April 2006, 8 pages.

[KTechlab, 2011] KTechlab, http://sourceforge.net/projects/ktechlab/, 2011.

[Kurtev et al., 2006] Ivan Kurtev, Jean Bezivin, Frédéric Jouault, and Patrick Valduriez, "Model-based DSL Frameworks," *Object-Oriented Programming Systems, Languages, and Applications*, Portland, OR, October 2006, pages 602-616.

[LaTeX, 2011] LATeX – A document preparation system, http://www.latex-project.org/, 2011

[Lechner and Schrefl, 2003] Stephan Lechner and Michael Schrefl, "Defining Web Schema Transformers by Example," *Database and Expert Systems Applications*, Prague, Czech Republic, September 2003, pages 46-56.

[Lédeczi et al., 2001] Ákos Lédeczi, Árpád Bakay, Miklós Maróti, Péter Völgyesi, Greg Nordstrom, Jonathan Sprinkle, and Gábor Karsai, "Composing Domain-Specific Design Environments," *IEEE Computer*, vol. 34, no. 11, November 2001, pages 44-51.

[Lehman, 1978] Meir Lehman, "Laws of Program Evolution – Rules and Tools for Programming Management," *Infotech State of the Art Conference, Why Software Projects Fail*, April 1978, pages 11/1–11/25.

[Lenz and Wienands, 2006] Gunther Lenz and Christoph Wienands, *Practical Software Factories in .NET*, Apress, 2006.

[Lieberman et al., 2006] Henry Lieberman, Fabio Paternò, Markus Klann, and Volker Wulf, "End-User Development: An Emerging Paradigm," *End User Development – Human-Computer Interaction Series*, vol. 9, January 2006, pages 1-8.

[Lin et al., 2004] Yuehua Lin, Jing Zhang, and Jeff Gray, “Model Comparison: A Key Challenge for Transformation Testing and Version Control in Model Driven Software Development,” *Workshop on Best Practices for Model-Driven Software Development*, held at OOPSLA 2004, Vancouver, BC, October 2004.

[Lin, 2007] Yuehua Lin, “A Model Transformation Approach to Automated Model Evolution,” *Ph.D. Thesis*, University of Alabama at Birmingham, Birmingham, AL, 2007.

[Lin et al., 2005] Yuehua Lin, Jing Zhang, and Jeff Gray, “A Testing Framework for Model Transformations,” *Model-driven Software Development*, Springer, 2005, Chapter 10, pages 219-236.

[Lin et al., 2007] Yuehua Lin, Jeff Gray, and Frédéric Jouault, “DSMDiff: A Differentiation Tool for Domain-Specific Models,” *European Journal of Information Systems*, vol. 16, no. 4, August 2007, pages 349-361.

[Lin et al., 2008] Yuehua Lin, Jeff Gray, Jing Zhang, Steve Nordstrom, Aniruddha Gokhale, Sandeep Neema, and Swapna Gokhale, “Model Replication: Transformations to Address Model Scalability,” *Software: Practice and Experience*, vol. 38, no. 14, November 2008, pages 1475-1497.

[Martin, 1967] James Martin. *Design of Real-Time Computer Systems*. Prentice-Hall, Inc., Upper Saddle River, NJ, 1967.

[Mazanek and Minas, 2009] Steffen Mazanek and Mark Minas, “Business Process Models as a Showcase for Syntax-Based Assistance in Diagram Editors,” *International Conference on Model Driven Engineering Languages and Systems*, Denver, CO, October, 2009, pages 322-336.

[M2M, 2011] Model To Model (M2M) Project, http://www.eclipse.org/m2m/, 2011.

[M2T, 2011] Model To Text (M2T) Project, http://www.eclipse.org/m2t/, 2011.

[MDA, 2011] Model-Driven Architecture (MDA) Specification, http://www.omg.org/cgi-bin/doc?omg/03-06-01.

[Mens and Gorp, 2005] Tom Mens and Pieter Van Gorp, “A Taxonomy of Model Transformation and its Application to Graph Transformation,” *Workshop on Graph and Model Transformation*, Tallinn, Estonia, September 2005, 15 pages.

[Mens and Tourwé, 2004] Tom Mens and Tom Tourwé, “A Survey of Software Refactoring,” *IEEE Transactions on Software Engineering*, vol. 30, no. 2, February 2004, pages 126-139.

[Mernik et al., 2005] Marjan Mernik, Jan Heering, and Anthony M. Sloane. “When and How to Develop Domain-Specific Languages,” *ACM Computing Surveys*, vol. 37, no. 4 December 2005, pages 316-344.

[MetaCase+, 2011] MetaCase+, http://www.metacase.com/, 2011.

[Misue et al., 1995] Kazuo Misue, Peter Eades, Wei Lai, and Kozo Sugiyama, “Layout Adjustment and the Mental Map,” *Journal of Visual Languages and Computing*, vol. 6, no. 2, June 1995, pages 183-210.

[MOF, 2011] Object Management Group, Meta Object Facility specification, http://www.omg.org/technology/documents/modeling_spec_catalog.htm#MOF

[Moore et al., 2004] Bill Moore, David Dean, Anna Gerber, and Gunnar Wagenknecht, Philippe Vanderheyden, “Eclipse Development using the Graphical Editing Framework and the Eclipse Modeling Framework,” *IBM Redbooks,* International Business Machines, January 2004.

[MS VPL, 2011] Microsoft Visual Programming Language, http://msdn.microsoft.com/en-us/library/bb483088.aspx, 2011.

[Myers, 1986] Brad Myers, “Visual Programming, Programming by Example, and Program Visualization: A Taxonomy,” *SIGCHI Conference on Human factors in Computing Systems*, Boston, MA, April 1986 , pages 59-66.

[Muppala et al., 1994] Jogesh K. Muppala, Gianfranco Ciardo, and Kishor S. Trivedi, “Stochastic Reward Nets for Reliability Prediction,” *Communications in Reliability, Maintainability and Serviceability*, vol. 1, no. 2, July 1994, pages 9-20.

[Narayanan et al., 2009] Anantha Narayanan, Tihamer Levendovszky, Daniel Balasubramanian, and Gabor Karsai “Automatic Domain Model Migration to Manage Metamodel Evolution,” *International Conference on Model Driven Engineering Languages and Systems*, Denver, CO, October 2009, pages 706-711.

[Narayanan et al., 2010] Krishna Kumar Narayanan, Luis Felipe Posada, Frank Hoffmann and Torsten Bertram, “Robot Programming by Demonstration,” *Simulation, Modeling, and Programming for Autonomous Robots*, Darmstadt, Germany, November 2010, pages 288-299.

[NetBeans, 2011] NetBeans, http://www.netbeans.org/, 2011

[Nordstrom et al., 1999] Greg Nordstrom, Janos Sztipanovits, Gábor Karsai, and Ákos Lédeczi, “Metamodeling - Rapid Design and Evolution of Domain-Specific Modeling Environments,” *International Conference on Engineering of Computer-Based Systems*, Nashville, TN, April 1999, pages 68-74.

[OCL, 2011] Object Management Group, Object Constraint Language Specification, http://www.omg.org/technology/documents/modeling_spec_catalog.htm#OCL, 2011.

[QVT, 2011] MOF Query/Views/Transformations Specification, http://www.omg.org/cgi-bin/doc?ptc/2005-11-01, 2011.

[Rath et al., 2008] Istvan Rath, Gabor Bergmann, Andras Okros, and Dániel Varró, “Live Model Transformations Driven by Incremental Pattern Matching,” *International Conference on Model Transformation*, Zurich, Switzerland, June 2008, pages 107–121.

[Redmiles et al., 2004] David Redmiles, Li-Te Cheng, David Millen, and John Patterson "How a Good Software Practice Thwarts Collaboration: the Multiple Roles of APIs in Software Development," *International Symposium on Foundations of Software Engineering*, Newport Beach, CA, November 2004, pages. 221-230.

[Robbes and Lanza, 2008] Romain Robbes, and Michele Lanza, "Example-Based Program Transformation," *International Conference on Model Driven Engineering Languages and Systems*, Toulouse, France, October 2008, pages 174-188.

[Rothermel et al., 2001] Gregg Rothermel, Margaret Burnett, Lixin Li, Christopher Dupuis, and Andrei Sheretov, "A Methodology for Testing Spreadsheets," *ACM Transactions on Software Engineering and Methodology*, vol. 10, no. 1, January 2001, pages 110-147.

[Rugaber and Stirewalt, 2004] Spencer Rugaber and Kurt Stirewalt, "Model-Driven Reverse Engineering," *IEEE Software,* vol. 21, no. 4, July 2004, pages 45-53.

[Scaffidi et al., 2005] Christopher Scaffidi, Mary Shaw, and Brad Myers, "Estimating the Numbers of End Users and End User Programmers," *IEEE Symposium on Visual Languages and Human-Centric Computing*, Dallas, TX, September 2005, pages 207-214.

[Schmidt, 2006] Douglas Schmidt, "Model-Driven Engineering," *IEEE Computer*, vol. 39, no. 2, 2006, pages 25-32.

[Schmidt et al., 2000] Douglas Schmidt, Michael Stal, Hans Rohnert, and Frank Buschman, *Pattern-Oriented Software Architecture – Volume 2: Patterns for Concurrent and Networked Objects,* John Wiley and Sons, 2000.

[Schoenboeck et al., 2009] Johannes Schoenboeck, Gerti Kappel, Angelika Kusel, Werner Retschitzegger, Wieland Schwinger, and Manuel Wimmer, "Catch Me If You Can – Debugging Support for Model Transformations," *Models in Software Engineering: Workshops and Symposia at MoDELS 2009*, Denver, CO, October 2009, pages 5-20.

[Sen et al., 2010-a] Sagar Sen, Benoit Baudry, and Hans Vangheluwe, "Towards Domain-specific Model Editors with Automatic Model Completion," *SIMULATION*, vol. 86, no. 2, September 2010, pages 109-126.

[Sen et al., 2010-b] Sagar Sen, Naouel Moha, Vincent Mahé, Olivier Barais, Benoit Baudry, and Jean-Marc Jézéquel, "Reusable Model Transformations," *Software and System Modeling,* to appear, DOI: 10.1007/s10270-010-0181-9.

[Sendall and Kozaczynski, 2003] Shane Sendall and Wojtek Kozaczynski, "Model Transformation - The Heart and Soul of Model-Driven Software Development," *IEEE Software*, vol. 20, no. 5, September 2003, pages 42-45.

[Shah and Slaughter, 2003] Devang Shah and Sandra Slaughter, "Transforming UML Class Diagrams into Relational Data Models," *UML and the Unified Process*, IGI Publishing, Hershey, PA, 2003, pages 217-236.

[Sprinkle, 2003] Jonathan Sprinkle, "Metamodel Driven Model Migration," *Ph.D. Thesis*, Vanderbilt University, Nashville, TN, 2003.

[Strommer and Wimmer, 2008] Michael Strommer and Manuel Wimmer, “A Framework for Model Transformation by-example: Concepts and Tool Support,” *International Conference on Technology of Object-Oriented Languages and Systems*, Zurich, Switzerland, July 2008, pages 372-391.

[Strommer et al., 2007] Michael Strommer, Marion Murzek, and Manuel Wimmer, “Applying Model Transformation By-example on Business Process Modeling Languages,” *International Workshop on Foundations and Practices of UML,* Auckland, New Zealand, November 2007, pages 116-125.

[Sun et al., 2008] Yu Sun, Zekai Demirezen, Marjan Mernik, Jeff Gray, and Barrett Bryant, “Is My DSL a Modeling or Programming Language,” *Workshop on Domain-Specific Program Development*, Nashville, TN, October 2008, 5 pages.

[Sun et al., 2009-a] Yu Sun, Jules White, and Jeff Gray, “Model Transformation By Demonstration,” *International Conference on Model Driven Engineering Languages and Systems*, Denver, CO, October 2009, pages 712-726.

[Sun et al., 2009-b] Yu Sun, Jules White, Jeff Gray, and Aniruddha Gokhale, “Model-Driven Automated Error Recovery in Cloud Computing,” *Model-driven Analysis and Software Development: Architectures and Functions*, IGI Global, Hershey, PA, 2009, pages. 136-155.

[Sun et al., 2011-a] Yu Sun, Jeff Gray, Christoph Weinands, Michael Golm, and Jules White, “A Demonstration-based Approach to Support Live Transformations in a Model Editor,” *International Conference on Model Transformation*, Zurich, Switzerland, June 2011, pages 213-227.

[Sun et al., 2011-b] Yu Sun, Jeff Gray, Philip Langer, Gerti Kappel, Manuel Wimmer, and Jules White, “A WYSIWYG Approach to Support Layout Configuration in Model Evolution,” *Emerging Technologies for the Evolution and Maintenance of Software Models*, (Joerg Rech and Christian Bunse, eds.), Idea Group, 2011, Chapter 4, pages 92-120.

[Sun et al., 2011-c] Yu Sun, Christoph Wienands, and Meik Felser, “Apply Model-Driven Design and Development to Distributed Time-Triggered Systems,” *International Conference on Engineering and Meta-Engineering*, Orlando, FL, March 2011.

[Sunyé et al., 2001] Gerson Sunyé, Damien Pollet, Yves Le Traon, and Jean-Marc Jézéquel, “Refactoring UML Models,” *International Conference on the Unified Modeling Language*, Toronto, Canada, October 2001, pages 134–148.

[UML, 2011] Object Management Group, Unified Modeling Language Specification, http://www.omg.org/technology/documents/modeling_spec_catalog.htm#UML.

[Varró, 2006] Daniel Varró, “Model Transformation by Example,” *International Conference on Model Driven Engineering Languages and Systems*, Genova, Italy, October 2006, pages 410-424.

[Varró and Balogh, 2007] Dániel Varró and Zoltán Balogh, "Automating Model Transformation by Example using Inductive Logic Programming," *Symposium on Applied Computing*, Seoul, Korea, March 2007, pages 978-984.

[Varró et al., 2005] Gergely Varró, Katalin Friedla, and Dániel Varró, "Adaptive Graph Pattern Matching for Model Transformations using Model-sensitive Search Plans," *International Workshop on Graph and Model Transformation*, Brighton, United Kingdom, September 2006, pages 191-205.

[Wagner, 2011] Robert Wagner, "Developing Model Transformations with Fujaba," *International Fujaba Days*, Bayreuth, Germany, September 2006, pages 79–82.

[White et al., 2007-a] Jules White, Douglas C. Schmidt, and Sean Mulligan, "The Generic Eclipse Modeling System," *Model-Driven Development Tool Implementer's Forum at the 45th International Conference on Objects, Models, Components and Patterns*, Zurich Switzerland, June 2007.

[White et al., 2007-b] Jules White, Krzysztof Czarnecki, Douglas Schmidt, Gunther Lenz, Christoph Wienands, Egon Wuchner, and Lugder Fiege, "Automated Model-based Configuration of Enterprise Java Applications," *Enterprise Distributed Object Computing (EDOC)*, Annapolis, MD, October 2007, pages 301-312.

[Wimmer et al., 2007] Manuel Wimmer, Michael Strommer, Horst Kargl, and Gerhard Kramler, "Towards Model Transformation Generation By-Example," *Annual Hawaii International Conference on System Sciences*, Big Island, HI, January 2007, pages 285.

[Wright and Freeman-Benson, 2004] Darin Wright and Bjorn Freeman-Benson, *How to Write an Eclipse Debugger*, 2004, http://www.eclipse.org/articles/Article-Debugger/how-to.html.

[XMI, 2011] Object Management Group, XMI specification, http://www.omg.org/technology/documents/modeling_spec_catalog.htm#XMI.

[XSLT, 2011] W3C, XSLT Transformation version 1.0, 2011, http://www.w3.org/TR/xslt.

[Zhang, 2009] Jing Zhang, "Model-Driven Aspect Adaptation to Support Modular Software Evolution," *Ph.D. Thesis*, University of Alabama at Birmingham, Birmingham, AL, 2009.

[Zhang et al., 2004] Jing Zhang, Jeff Gray, and Yuehua Lin, "A Generative Approach to Model Interpreter Evolution," *International Workshop on Domain Specific Modeling*, Vancouver, Canada, October 2004, pages 121-129.

[Zhang et al., 2005] Jing Zhang, Yuehua Lin, and Jeff Gray, "Generic and Domain-Specific Model Refactoring using a Model Transformation Engine," *Model-driven Software Development*, Springer, 2005, Chapter 9, pages 199-218.

[Zhang et al., 2007] Jing Zhang, Thomas Cottenier, Aswin van den Berg, and Jeff Gray, "Aspect Composition in the Motorola Aspect-Oriented Modeling Weaver," *Journal of Object Technology*, Special Issue on Aspect-Oriented Modeling, vol. 6, no. 7, August 2007, pages 89–108.

[Zloof, 1975] Moshé M. Zloof, “Query-By-Example: The Invocation and Definition of Tables and Terms,” *International Conference on Very Large Data Bases,* Framingham, MA, September 1975, pages 1-24.