Bergen University College

Master Thesis

Model to Model Transformation Tool for the DPF Workbench

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Abstract

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Model to Model Transformation Tool for the DPF Workbench

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Model transformations provides a vital part of Model Driven Development. This thesis presents an editor that is an extension of the DPF Workbench that includes support for exogenous model to model transformations for DPF specifications. The purpose of the thesis is to integrate an existing model transformation environment with DPF Workbench that supports translations between different modeling languages. Available model transformation environments are designed differently according to diverse approaches to model transformations. Some popular approaches to model transformations are explored in a comparison of three model transformation environments: 1) Henshin representing traditional graph transformation on Ecore models, 2) Attributed Graph Grammar (AGG) representing traditional graph transformation, and 3) Atlas Transformation Language (ATL) representing model transformation on Ecore models. The case study presented in the thesis involves a specific exogenous model transformation that translates an UML activity diagram to a Petri Net model. The main focus with this comparison is to find a transformation language that together with the DPF Transformation Editor provides a compatible solution to model to model transformations for DPF specifications.

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor…

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Abbreviations

EMF	**E**clipse **M**odelling **F**ramework
EMP	**E**clipse **M**odelling **P**roject
GEF	**G**raphical **E**diting **F**ramework
SPO	**S**ingle **P**ushout **A**pproach
DPO	**D**ouble **P**ushout **A**pproach
NAC	**N**egative **A**pplication **C**ondition
PAC	**P**ositive **A**pplication **C**ondition
LHS	**L**eft **H**and **S**ide
RHS	**R**ight **H**and **S**ide
DPF	**D**iagram **P**redicate **F**ramework
MDE	**M**odel **D**riven **E**ngineering
UML	**U**nified **M**odeling **L**anguage
RUP	**R**ational **U**nified **P**rocess
DSML	**D**omain **S**pecific **M**odeling **L**anguage
CIM	**C**omputation-**I**ndependent **M**odel
PIM	**P**latform-**I**ndependent **M**odel
PSM	**P**latform-**S**pecific **M**odel
OMG	**O**bject **M**anagement **G**roup
MOF	**M**eta **O**bject **F**acility
OCL	**O**bject **C**onstraint **L**anguage
CPU	**C**entral **P**rocessing **U**nit
ATL	**A**TLAS **T**ransformation **L**anguage
MDA	**M**odel **D**riven **A**rchitecture
AGG	**A**ttributed **G**raph **G**rammer
QVT	**Q**uery **V**iew **T**ransformation

MDSE	**M**odel **D**riven **S**oftware **E**ngineering
MMT	**M**odel-to-**M**odel **T**ransformation

For/Dedicated to/To my…

Chapter 1

Introduction

1.1 Motivation

The first tools that supported the practices of Model Driven Engineering (MDE) were the Computer-Aided Software Engineering[1] (CASE) that was initially developed in the 1980s. MDE is a known concept to computer science and practicing the use of miniatures to provide a visual representation of a system to ease an explanation of a problem has always been around. To be able to draw an abstraction of a complex system or a problem on a piece of paper to make the explanation easier to understand. The explanation does not necessary have to be difficult to understand, but a miniature or a model will make the explanation more abstract.

When i started to work on my master program we started to visit more concepts around MDE and how we can use models and model transformations to automate a software application process. The first tools that supported this vision of MDE were the Computer-Aided Software Engineering (CASE) and was developed in the 1980s. Tools like CASE thrived to achieve this vision of MDE to be a fully usable approach to software development. This meant to use models as the major artifact in a software application. Where in the initially phases of a software development models would provide an abstraction of the problem and evolve with more details through the development process. These models would evolve to more specific technology based abstractions with the help of model transformations and in the end a fully executable software implementation of the application.

As the years went by MDE has become a strong foundation to create domain specific modeling languages. With the possibility to define meta-models with constraints proved to be a viable solution to create the structure of a modeling language or a specific modeling language. Based on this the Object Management Group (OMG) created the Unified Modeling Language[2] (UML) that became a standard for creating modeling languages. Many modeling tools adapts UML in the process of creating a domain specific modeling environment.

Lately a diagrammatic approach to utilize the visions of MDE has become more popular amongst MDE researchers. Where the focus is more on graphs and graph theory. The

Diagram Predicate Framework (DPF) is such a framework that take advantage of category theory and graph transformations to provide a formal approach to meta-modeling, model transformation and model management. For this thesis we have the following research question, *Can we extend the DPF Workbench with an editor that support model to model transformations between different Domain Specific Modeling Languages.*

1.2 The structure of the Thesis

Model to Model Transformation Tool for the DPF Workbench is structured in the following sections.

Chapter 2. This chapter is meant to explain background material to this thesis. Where we discuss the visions of model driven engineering. We also consider a specific design approach to these visions. Then we discuss modeling languages and their role in language workbenches. At the end of the chapter we go into detail on the DPF environment.

Chapter 3. This chapter introduces model transformation in general. We discuss the basic concepts of model transformations and how they are used in MDE. Later in the chapter we try to classify model to model transformations and explain design choices behind the graph based approach to achieve this.

Chapter 4. In chapter 4 we describe the problem at hand and how we want to approach this. We consider three different model transformation tools and find the tool that is best suited to be integrated with DPF.

Chapter 5. This chapter describes how we created a model to model transformation environment for the framework. We describe the model transformation environment we integrated with DPF and how this works with the transformation editor.

Chapter 6. Here we want evaluate our solution and also discuss functionality that should be included in future versions of the tool. Then we want to compare our solution with existing transformation tools and provide a conclusion at the end.

Chapter 7. In this chapter we provide a conclusion for this master thesis. We also mention some future work for the transformation tool.

Chapter 2

Background

2.1 Model Driven Engineering

When a new software is created it has always been a goal to produce high quality code at the lowest possible cost. To plan a software development project from its initial start to delivering a finished product can seem like an impossible thing to do. Because a software development cycle rarely goes as initially planned. Changes do occur, both in delivering high quality code and keeping the costs down. Traditionally when model driven engineering (MDE) is used, people think about models, for example activity diagrams and class diagrams from the popular modeling language, UML. Where models are used to raise the level of abstraction for a problem specification and describes how the software application should be implemented. For these software development processes models are indirectly used in the creation of software. This means that models are primarily used as a reference when implementing an application.

A model is an abstraction of a system, and has its origin from Latin, *modulus* that means measure or standard. A model can either be used to represent a system before it is created or to describe some major aspects of a system or a concept. When we hear the term model, many will think that it is a miniature that consists of a set of nodes and arrows. But it is important to consider that a model can also be represented by text.

Considering traditional software development processes, models are primarily used in application requirements and use-case diagrams to specify what the costumer wants. Developers can then specify models to detect important functionality of the application. A software developer may for example create flow charts, sequence diagrams, activity diagrams, class diagrams, etc, to describe how the system should behave and be implemented. A model for system architecture can also be initialized for developers to handle design choices. Rational Unified Process[3] (RUP) is an example of a software development process that is build around extensive use of models in their initial planning phase. RUP was initially created by Rational Software Corporation[4] in 2006 and was later acquired by International Business Machines Corporation[5]. This is an iterative software development process and the purpose of RUP is to be an adaptable process framework where the software project teams decide the elements that are required for a development cycle. Figure 2.1 explains the four different phases, Inception, Elaboration, Construction and Transition, with different iterations for each phase that RUP provides.

The Inception phase and the Elaboration phase is the two phases where some of the example models above are created, both under business modeling and requirements. For the Inception phase the idea is to create the software application without writing any source code. This phase is concerned with writing text and creating models that gives the developers a detailed specification on how the program should be implemented. In the Elaboration phase a prototype might be implemented to show the customer a possible implementation, but this phase also consist of creating and modifying an extensive amount text and models that specifies analysis and design choices. The goal for these two phases is to define a solid foundation of the application before starting to write code and tests. In the Construction phase the developers should know exactly how the application should be implemented by referring to documents and models created in earlier phases. RUP is only one example of how a software development process could be applied to a project. Agile development processes has become popular the last couple of years, where processes like Scrum[6] and Extreme Programming[7] (XP) has been integrated in software development teams all over the world. Both Scrum and XP thrives to focus more on the implementation and on delivering high quality code than on creating documents and models. However, models will always be a tool for developers, also in agile development processes, when some aspects of a system needs to be explained. Because to explain parts of an implementation with a model will help to make the explanation less complex and more abstract.

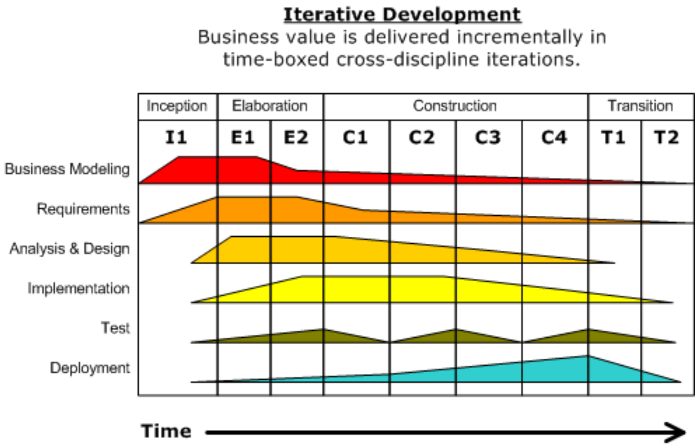


FIGURE 2.1: Iterative development cycle of Rational Unified Process.

Now we have acknowledged some development processes that are commonly used in the industry for creating software applications. Model Driven Engineering is a software development methodology that focus on creating and exploiting models. And by using these models, MDE aims at improving productivity and quality in a software developments[8]. This is achieved by not only to use models as documentation, but instead use models as the major artifact in a software development cycle. The idea is to use models at different levels of abstraction and apply model transformations to automate the implementation of these models. This will raise the level of abstraction in program and problem specification. We can divide these models into two main model classes, namely development models and runtime models. Development models are used as an abstraction above code level. These models can represent software requirements, work flow, architecture and software implementation. These development models are most commonly used in software development processes as a supplement in developing an application. Runtime models represents executable systems of a software application.

Example of such executable systems are database operations or computations of data. There has been an increase in MDE researchers that explore how runtime models can be used to support dynamic adaptation of systems for a software application[8]. The idea for MDE is to be able to specify these development models as runtime models and evolve software applications with the use of runtime models and development models as major artifacts of a development process.

A typical Model Driven Software Engineering (MDSE) scenario is to obtain an executable software application through model transformations that produce a more and more detailed version of the application until an executable version is created. We reach this level of automation by applying model transformations to models at higher levels of abstraction and producing models that contains a more detailed description of the software. This highlights one main advantage of a model driven approach, and that is to bridge the communication gap between requirements/analysis and implementation[9]. For a traditional development process today there is a gap in communication between software developers and customers[8]. Because a customer is usually not an expert in designing and implementing a software application. A customer can provide a set of requirements for a software application and take part in analysing these requirements to make sure that the development team shares the customers thought of the program. The requirements and analysis can be specified down to every detail, however a software application might experience different design choices that leads to a different implementation of the application compared to what the costumer initially specified. If the visions of MDE is adopted to a software development process then this could help to narrow the gap in communication between developers and stakeholders. Because now we can apply model transformation that changes input models to target models that represents both the design and the executable implementation of a software application. We will describe model transformations and their purpose in model driven engineering in more depths in chapter 3. Models that are provided at different level of abstractions is less complex than several thousand lines of implementation code. This represents another benefit of adopting MDSE into the development process. Because models captures and organize the understanding of a system that results in a more clear discussions among team members and new team members. One approach that introduces modeling at different level of abstraction for including MDSE in a software development process is the Model Driven Architecture.

2.1.1 Model Driven Architecture

Model Driven Architecture (MDA) is an industry architecture developed by the Object Management Group (OMG) that address the possibility to provide automation according to models in an application development cycle. MDA is a proposal for applying the practices of MDE to a system development. This architecture is a good example to use when we are discussing concepts of MDE, because of its similarity to a traditional software development process. Since it has support for standard phases in a software development process such as analysis, design and implementation. Many organizations have adopted MDA as a reference framework to include the concepts of MDE. One reason for this is the importance of OMG for the software industry. MDA is build around many concepts that OMG has released, such as the OMG specifications the Unified Modeling Language (UML) and the Meta Object Facility(MOF).

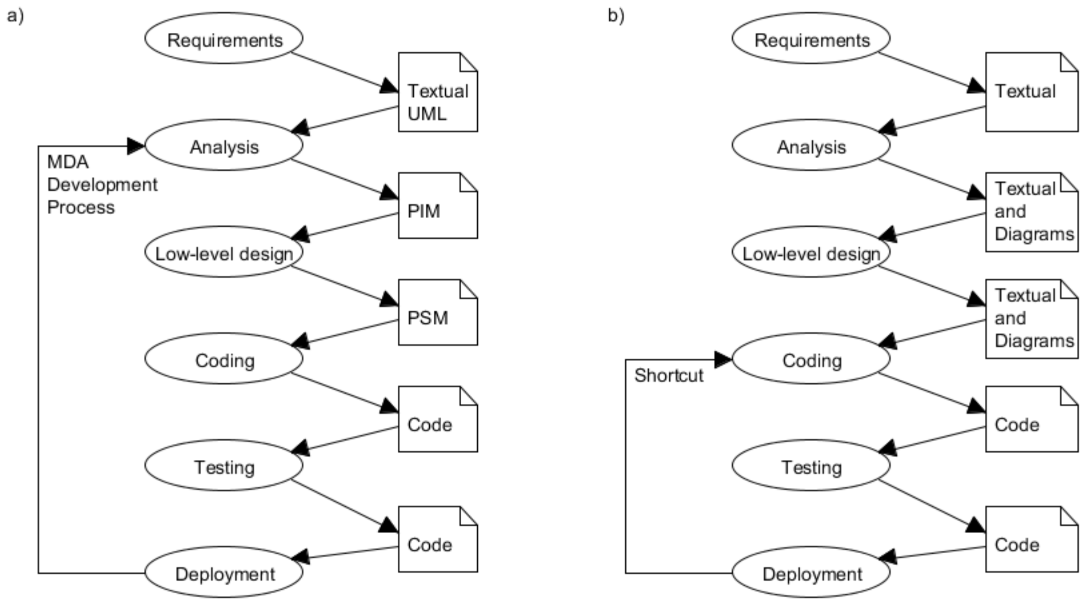


Figure 2.2: a) Model-Driven-Architecture and b) Traditional development process

Figure 2.2 gives a representation of the development process that the Model Driven Architecture provides and a traditional development process on the right side. Both of the approaches have similar starting phases, where a customer presents a list of requirements for a software application. The process to create implementation code from the requirements is where a MDE approach to software development is different. Because for MDA the idea is to use models instead of text and diagrams for the analysis and design phase. For a traditional development process these phases usually consist of creating diagrams that describes different system of the application. In MDA these diagrams or models are the main artifact for the corresponding phases, instead of just a reference for developers to use when implementing an application. The architecture then propose that implementation code is generated based on these models. A traditional software development process would have iterations for the implementation and testing to make sure that the application meets the demands of the customer. This process is continued for every iteration, where developers continually use the text and diagrams that was created earlier in the process. The idea for an MDA development process is to provide automation between models created at each development phase. Instead of going back to the code and do corrections and modifications on the application a model driven software development process goes back to analysing the problem and modify the models accordingly. With the power of automatically changing models from one phase to another and generate implementation code from the models at the last level of abstraction.

Figure 2.3 provides a representation of the models at the different layer of abstractions that is part of the Model Driven Architecture.

Computation-Independent Model (CIM) is the most abstract level of modeling and is often referred to as a business model or domain model. The model does not contain any computational implications to how the software application should behave, but express exactly what the final application should do. This model remains independent to how a system will be or currently is implemented and represents the requirements and purpose of the system. A Computation-Independent Model is often described by using a natural language to define the requirements for a software application.

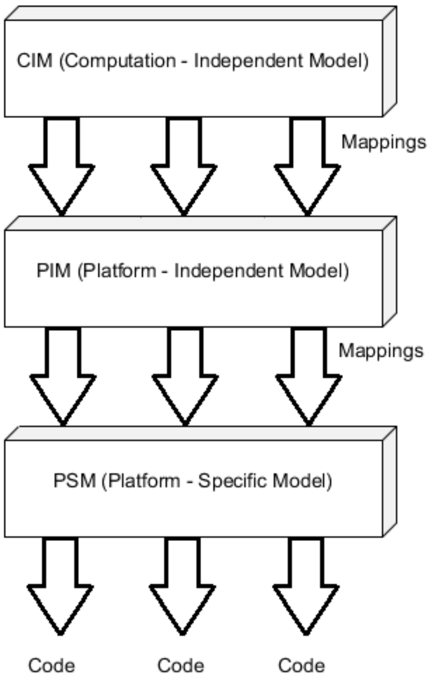


Figure 2.3: The three levels of modeling abstraction that MDA provides.

Platform-Independent Model (PIM) is the level of abstraction that describes the behavior and structure of a software application. This model is platform independent, which means that the technological platform used to implement the software application is not defined. A Platform-Independent Model will only address tasks that a software application can perform. These tasks are part of the context of the business model at the top level of abstraction.

Platform-Specific Model (PSM) is the level of abstraction that contains all required information for the behavior and structure of a software application that is linked to a specific technological platform. These specific platform technologies can be a specific programming language like a general purpose programming language, a specific operation system or a specific database technology. The Platform-Specific Model contains all the information that is required for an actual implementation of the application.

In MDA, the core activity is the starting phase, which is to analyse the problem at hand. Requirements are firstly defined and modeled as a CIM or a PIM. The CIM and PIM provides the solution for the requirements at a very high level of abstraction. The computation independent level of abstraction we provide the requirements of a solution without thinking about the actual implementation of an application. A CIM specifies the workflow of an application and how end users utilizes the application. For example the model could define the requirements for a web application that provides a collection of goods that the end users can purchase. These requirements could specify how an employee performs tasks when a new order arrives. For the implementation of an application not all of these requirements are necessary. The purpose of MDA is that models created at CIM level provides the highest level of abstraction and therefore should be readable by everyone. In figure 2.3 MDA suggest that new models are created accordingly based on a set of mappings. Models that is provided at the platform independent abstraction is not concerned with technologies that should be used for the actual implementation. PSM is more concerned with describing what tasks an application should perform. But tasks that an employee should perform, like for example making a shipment ready for transportation is not defined in a PIM. A platform specific model specifies what implementation platform and a set of precise descriptions of the technical details of the corresponding implementation platform. Mapping a model to another model is essential for applying MDA to a development process. A mapping defines correspondences between elements of two different models and can be defined between all different models.

2.2 Modeling Languages

A Modeling language is defined through three core concepts. Regardless if its either a Domain Specific Modeling Language (DSML) or a General Purpose Modeling Language (GPML). Figure 2.4 represents the three main concepts for a modeling language.

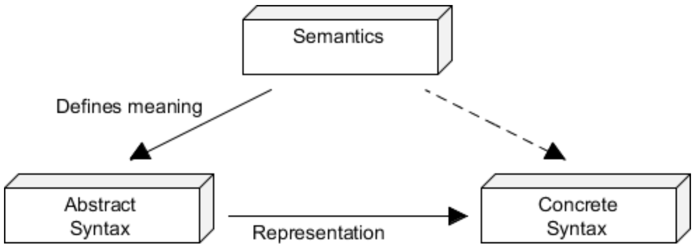


Figure 2.4: The three main ingredients of a modeling language.

A modeling language has an abstract and a concrete syntax. The abstract syntax describes the structure of the modeling language and how modeling elements can be combined together. The concrete syntax on the other hand describes a specific representation of the abstract syntax, and can either be a graphical or textual representation. The semantics of a modeling language describes the meaning of these modeling elements and the different ways to combine them for the abstract syntax and indirectly the concrete syntax. We mentioned DSML and GPML, where these two modeling languages represents one of the main classification of modeling languages. A modeling language can either be classified as a domain specific or a general purpose language. DSMLs are modeling languages that are designed for a specific domain or a concept. While GPMLs are modeling languages that is applicable for several different domains. A general purpose language lacks features that are special for a particular domain. This is one of the strengths for DSLs that is created especially for a certain domain, and therefore provide more details to a specific domain compared to a general purpose language. The Unified Modeling Language[2] (UML) is an example of a general-purpose modeling language that was accepted in 2000 by the International Organization for Standardization (ISO) as an industry standard for modeling software systems. UML was initially developed by Grady Booch, Ivar Jacobsen and James Rumbaugh at Rational Software in the 1990s. It was later adopted by the Object Management Group in 1997 and has since this day been continuously developed by the organisation. UML is often called a general purpose language because it is often referred to as a suite of languages, since it provides developers and designers with the possibility to specify applications through several different modeling languages, or diagram types that UML often is associated with. However, in the book, “Model-Driven Software Engineering in Practice” published by Marco Brambilla, Jordi Cabot and Manuel Wimmer in 2012, they state the following. *If we think to the general modeling problem, we can see UML as a DSL tailored to the specification of (mainly object-oriented) software systems[10].* This means that to decide whether UML is a DSL or a GPL is not a binary choice. But we mostly see UML as a general purpose modeling language, since it offers a wide variety of modeling languages that designers and developers can use to specify system abstractions. Whether a modeling language is classified as a general purpose or a domain specific modeling language it requires that it is described by an abstract syntax. Both the abstract syntax and the concrete syntax of a modeling language is represented as models. Therefore the specification of the abstract syntax is often referred to as a meta-model.

2.2.1 Meta-modeling

Models are a major artifact in the concept of model driven engineering (MDE). It is essential to look at every model as instances of some more abstract model. And therefore we can define a meta-model as yet another abstraction that highlights the properties of an instance model. Meta-modeling represents a vital part of MDE and constitutes the definition of a modeling language. A meta-model defines the abstract syntax and provides a description of a modeling language. Another popular definition for describing a meta-modeling is that it is a “model of models”. This definition is both unhelpful and incorrect according to Steve Cook and Stuart Kent in their paper[11] published in 2008. They think that a better definition for a meta-model is that “it is a model of the concepts expressed by a modeling language.” The exact definition of a meta-model is highly debated amongst MDE researchers[12].

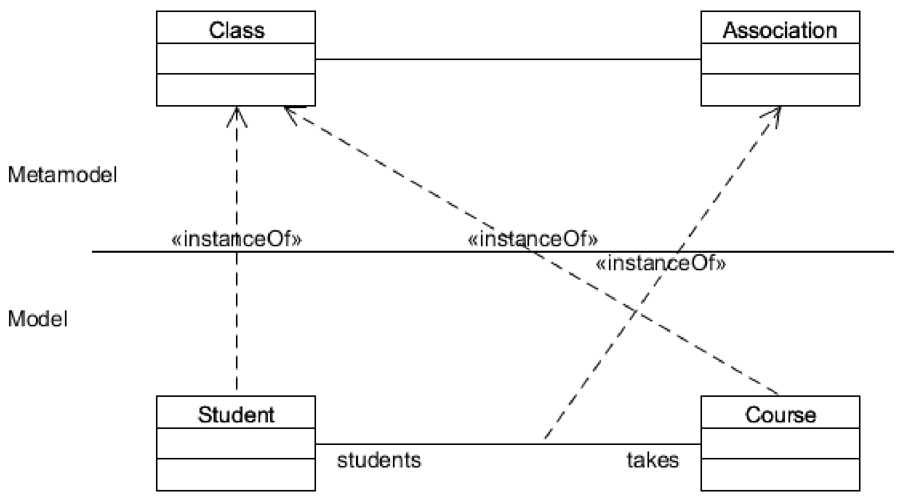


FIGURE 2.5: A simple example of a model and its meta-model.

Figure 2.5 shows a simple example of an instance model and its corresponding meta-model. This model has two classes, Student and Course, and a bidirectional association, take course and has students, that relate these two classes. The model is specified by a meta-model that consists of two meta-classes Class and Association and an association between them. Both Student and Course are an instance of the meta-class Class, while the association between Student and Course are instance of the meta-class Association. The modeling language that describes this model corresponds to the Unified Modelling Language.

Meta-Object Facility

The Meta-Object Facility[13] (MOF) is an Object Management Group standard for defining meta-models in MDE. The Object Management Group was in need of a architecture to define the UML. Through this process of finding a common platform for UML, OMG designed a four layered architecture that provides a semi-formal approach to creating meta-models. MOF later became a language for defining abstract syntax for modeling languages.

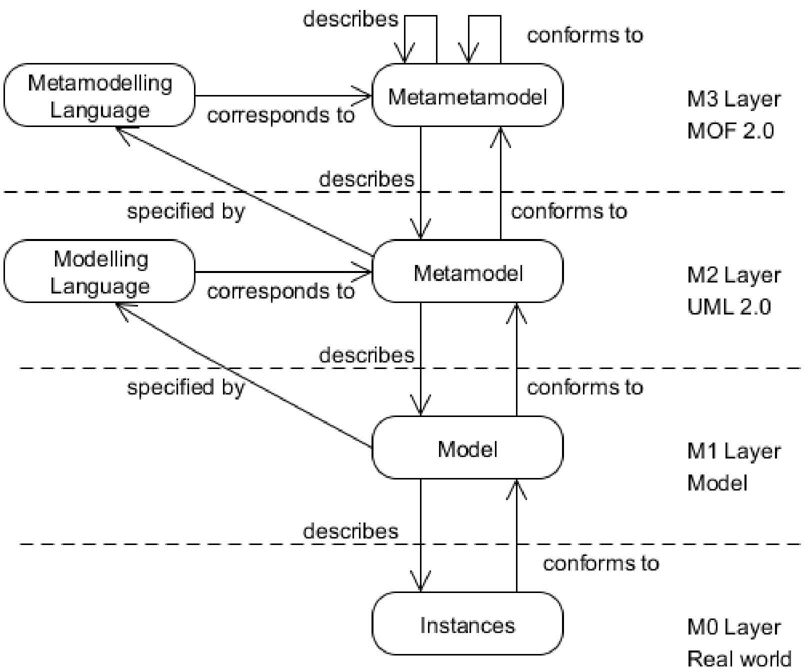


FIGURE 2.6: Example of Meta Object Facility and its four layers.

Figure 2.6 gives a impression of the four layers that are available in the Meta-Object Facility. At the top level, M_3, there is a meta-meta-model called MOF. This meta-meta-model is meant to both describe it self and conform to itself. MOF is then used to describe meta-models at the M_2 level. The UML meta-model is an example of such a meta-model. The idea is that these meta-models are specified by some meta-modeling language that corresponds to MOF. Models at the M_2 layer represents the abstract syntax for models created in the M_1 layer. This layer represents models that are created by some modeling language, like for example UML. Finally at the M_0 we have an instance model of a real world object. If we refer to our simple example concerning a model and its corresponding meta-model in figure 2.5. From this example we can create a real world object of that model, "Petter Barvik" takes a course in Model Transformations. MOF provides meta-modeling architecture where every modeling element on every layer corresponds to some modeling element one layer higher. One could say that MOF itself a Domain Specific Language (DSL) to create meta-models.

2.2.2 Constraints

Constraints impose conditions that modeling elements must satisfy and helps to define the semantics of a domain specific language. A constraints can be compared to a Boolean condition. Boolean conditions are either true or false, while constraints are either satisfied or not satisfied. Including constraints to modeling elements in the abstract syntax specifies how modeling elements are presented in an instance model. Modeling elements that are included in the abstract syntax can have constraints defined on objects, classes, attributes, links, associations, etc. A constraint is a restriction for how these elements should behave. Constraints on elements such as those above can be expressed with a natural language or by a formal language, such as the Object Constraint Language[14] (OCL). The Object Constraint Language (OCL) is a declarative programming language for describing constraints that applies to UML models. Before UML became an adopted standard of the Object Management Group (OMG), OCL was an extension language to UML. Now OCL can be used with any Meta-Object Facility (MOF) meta-model, including UML. A software developer can in combination with UML and OCL define the semantics for a modeling language[15].

The difference between object and classes needs to be specified. A class is often a meta element for an object. This means that a class could be part of a model that describes an object element, and therefore an object element is typed by the class element[16]. Figure 2.5 describes the two object elements Student and Course that are an instance of the meta-element Class.

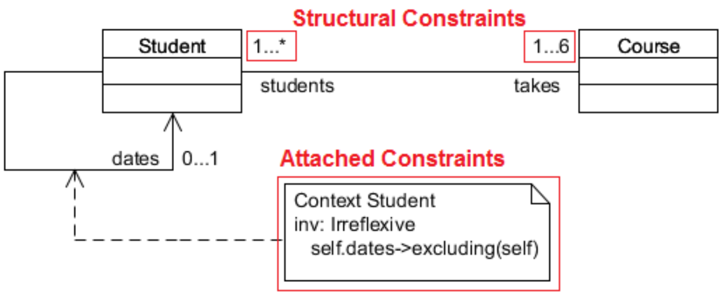


FIGURE 2.7: Example of a simple model with attached and structural constraints.

These restrictions on modeling elements can either be a structural constraint or an attached constraint. These structural constraints are defined in the structure of the models. In figure 2.7 we have extended the model we introduced in figure 2.5 with some modeling elements. We have created an association that specifies that a student can date other students. In this model we can see that the model has three multiplicity constraints that are part of the models structure. A multiplicity constraint for an association restricts the number of objects that are related to a given object. From the association constraint on this model we can see that a student requires to take at least one course and up to a maximum of six courses. The models restricts a student to not participate in any courses. The second structural constraint requires a course to have at least one student for this course to be part of a semester, and the course can have an arbitrary maximum number of students participating the course. The association dates, between two students for this model has an attached constraint that is specified in the declarative language OCL. The general form of an attached constraint has a context, in this case a Student, that specifies what object the constraint includes. The attached constraint has a name *"Irreflexive"* followed by a Boolean OCL expression that explicitly refers to itself. This constraint specifies that a student is unable to date her or him self. Constraints has a vital part in model driven engineering to measure the quality and precision of a model. A model without constraints does not work in practice. In *The Object Constraint Language: Getting Your Models Ready for MDA*[15], Jos Warmer and Anneke Kleppe states that a model without constraints would be severely underspecified. Constraints expressions written in OCL are unambiguous and results in a more precise and detailed model. If we where to remove both the structural and attached constraints from figure 2.7 then the model is less informative. There is no understanding on how the objects are related to one another.

2.3 Language Workbenches

Language workbenches are tools that lets user specify their own Domain Specific Language (DSL) and include editing tools for the newly created language. A workbench should consist of Integrated Development Environment (IDE) that lets users create their own DSMLs. Figure 2.8 is provided in the paper, *"DPF Workbench: a multi-level language workbench for MDE"*, that was published by Yngve Lamo, Xiaoliang Wang, Florian Mantz, Øyvind Bech, Anders Sandven and Adrian Rutle in 2013. The figure presents the intended use of language workbenches and consist of two phases. The first handles the definition of a new DSML and the creation of tool support such as code generation, editors, model transformations, etc. A language workbench is created by a domain expert in collaboration with an experienced developer. The latter describes the actual usage of this newly created workbench, where developers can utilize the DSML environment to create models, generate implementation code, etc. Language workbenches are a very young field in computer science, and there are many existing solutions that is open for the public to use. These concepts have the potential to change the face of programming as we know it[17], but the concepts of workbenches are still fresh to computer science.

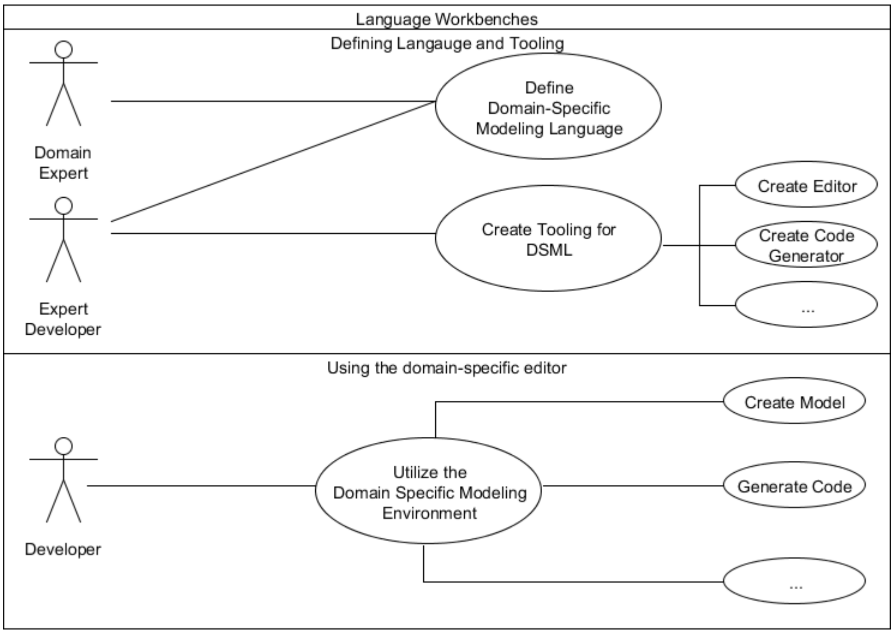


FIGURE 2.8: Intended use of language workbenches.

The concepts behind a language workbench is that the tool does not just provide the users with an IDE to create DSLs, but also generates a new IDE where this newly created DSL can be edited. In addition to an IDE that provides creation and editing of a newly created language a workbench should define support for code generation, model transformation, model versioning, etc[18]. Figure 2.9 describes components for a language workbench. Martin Fowler describes three main parts to defining a new language workbench in his paper[19]:

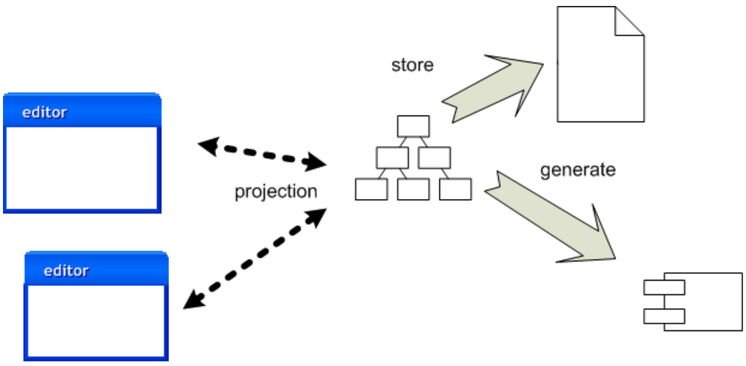


FIGURE 2.9: Components of language workbenches.

- The abstract representation for the language.
- One or more editing environments for the language.
- Defining the semantics behavior of the language.

2.3.1 EMF

Eclipse Modeling Framework is originally based on Meta Object Facility (MOF) provided by the Object Management Group (OMG). In 2003 EMF designers contributed to designing the MOF 2.0 version of the standard that was later named Essential MOF (EMOF). EMF provides the meta-model Ecore that is aligned to EMOF and is a general purpose modeling language to create modeling languages. Ecore is essentially a simplified version of class modeling in UML.

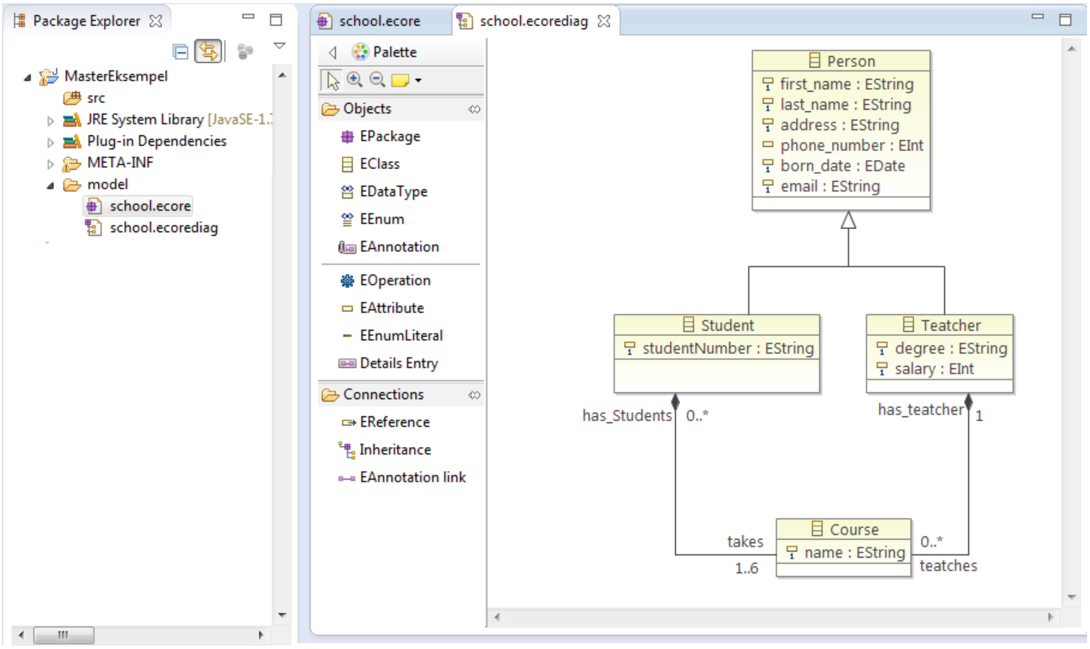


FIGURE 2.10: A graphical representation of an Ecore model.

Figure 2.10 represents an Ecore model that is created from a graphical editor. This Ecore model conforms to the Ecore meta-model and is the core language for EMF. The framework provides a two layered approach to meta-modeling where the user can create a DSL based on the Ecore meta-model. Based on the DSL the framework provides code generation facilities. Amongst generating java implementation for the model the framework also provides code generation for an editor that is based on the DSL. This editor can be used to create instances of the defined DSL.

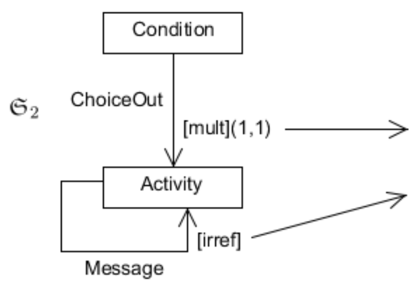
2.4 Diagram Predicate Framework

Diagram Predicate Framework[12, 18, 20] (DPF) is an ongoing research project that was first initiated by Bergen University Collage and the University of Bergen in Norway 2006. With features likes meta-modeling, model transformation and model management, DPF aims at formalising concepts of model-driven engineering. DPF is based on category theory and graph transformations and is an extension of the Generalised Sketches[21] formalism that was initially developed by Zinovy Diskin.

In October 2002 Dominique Duval published a paper where he specified that a specification can be considered as a directed graph with additional structure in the same way that a theory can be considered as a category with additional structures[22]. Generalised Sketches by Zinovy Diskin utilize the concept of sketches. A sketch, first introduced by Ehresman in 1966, is a directed graph that provides additional properties, such as colimit, limit and constraints. DPF utilize these concepts through an diagrammatic approach to meta-modeling and to facilitate the concepts of MDE. The framework provides the possibility to define an unlimited layers of meta-modeling. In DPF models are represented as specifications.

- A *specification* $\mathfrak{S} = (\mathrm{S}, \mathrm{C}^{\mathfrak{S}}:\Sigma)$ consist of an underlying graph S and a set of atomic constraints $\mathrm{C}^{\mathfrak{S}}$.
- Atomic constraints are specified by predicates from a predefined signature Σ.
- A signature $\Sigma = (\Pi\ ,\ \alpha)$ consist of a collection of predicates.

A *specification* $\mathfrak{S}$ has an underlying graph S that contains modeling elements that defines the model structure of the specification. These modeling elements are always represented as a node or an arrow. However these nodes and arrows could be specified through several layers of meta-models or specifications. The *specification* $\mathfrak{S}$ also consist of a set of constraints, these constraints will restrict the model structure of a new instance model of this specification. Figure 2.11 presents a specification $\mathfrak{S}_2$, that is defined by an underlying specification $\mathfrak{S}_3$ and describes a modeling language for some $\mathfrak{S}_1$ specification. This specification includes two nodes Condition and Activity, two arrows ChoiceOut and Message and two sets of atomic constraints. The first constraint defines that a Condition element has to be connected to exactly one Activity element for this structure. The second constraints specifies for this graph structure that an Activity element cannot be associated with it self. These constraints examples are specified as a collection of predicates from a predefined signature Σ. The table in figure 2.11 represent some of the predicates from this collection. A predicate is represented by an unique symbol Π, a shape graph α, a proposed visualisation and a semantic interpretation



Π^{Σ}	α^{Σ}	Proposed vis.	Semantic interpretation
`[mult(`m,n`)]`	$1 \xrightarrow{a} 2$	$\boxed{X} \xrightarrow[\text{[m..n]}]{f} \boxed{Y}$	$\forall x \in X : m \leq \lvert f(x) \rvert \leq n$, with $0 \leq m \leq n$ and $n \geq 1$
`[irreflexive]`	1, a	[irr], $\boxed{X}$, f	$\forall x \in X : x \notin f(x)$

FIGURE 2.11: A specification $\mathfrak{S}_2$ with some attached predicates.

An instance specification $\mathfrak{S}_{\mathrm{n}}$ that is initialised from a specification $\mathfrak{S}_{\mathrm{n+1}}$ defines a graph homomorphism between two underlying graphs. There is a graph homomorphism, $\mathrm{S_n} \longrightarrow \mathrm{S_{n+1}}$, between the underlying graph $\mathrm{S_n}$ of a specification $\mathfrak{S}_{\mathrm{n}}$ and the underlying graph $\mathrm{S_{n+1}}$ of a specification $\mathfrak{S}_{\mathrm{n+1}}$[18]. The graph homomorphism $\mathrm{S_n} \longrightarrow \mathrm{S_{n+1}}$ must satisfy a set of atomic constraints, $\mathrm{C}^{\mathfrak{S}}$ from a specification $\mathfrak{S}_{\mathrm{n+1}}$. Figure 2.12 from Adrian Rutle's dissertation, *Diagram Predicate Framework A Formal Approach to MDE*[12] that was published in 2010 represents an example of a specification that is defined by a modeling formalism.

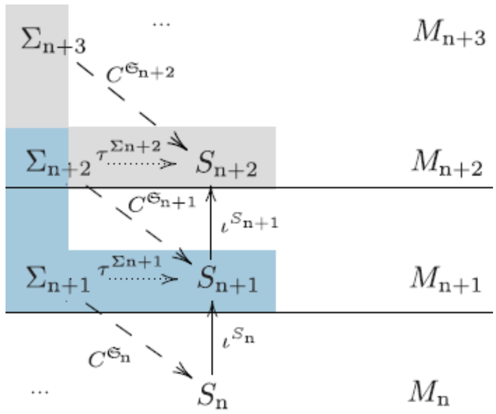


FIGURE 2.12: Meta-modeling represented as modeling formalism's in DPF.

Because in DPF a modeling language at a specific abstraction layer is represented as a modeling formalism. A modeling formalism in DPF is defined by a set of atomic constraints from a modeling formalism one abstraction layer higher and a specification that has an underlying graph and a set of atomic constraints. For example figure 2.12 represents three levels of abstractions for defining a DSML. The specification $\mathfrak{S}_n$ that is defined at M_n layer conforms to the modeling formalism one layer higher. The modeling formalism consist of a specification $\mathfrak{S}_{n+1}$ that has an underlying graph S_{n+1} and a set of predicates Z_{n+2}. Together with specification $\mathfrak{S}_{n+1}$ a set of predicates Z_{n+1} can be defined to specify a new modeling formalism for lower layer of abstractions. modeling formalism[12]. This defined modeling language, or modeling formalism provides the abstract syntax that can be used to create a specification or modeling formalism one abstraction layer lower. What is special with DPF is that a modeling formalism represents both the abstract syntax for a specification one abstraction layer lower and the concrete syntax for a specification one abstraction layer higher. The set of atomic constraints Z_{n+1} provides the semantics and the specification $\mathfrak{S}_{n+1}$ provides the abstract syntax for defining modeling elements in a new specification $\mathfrak{S}_n$. Figure 2.13 explains the difference between OMG's MOF and DPF's multi-layered meta-modeling hierarchy.

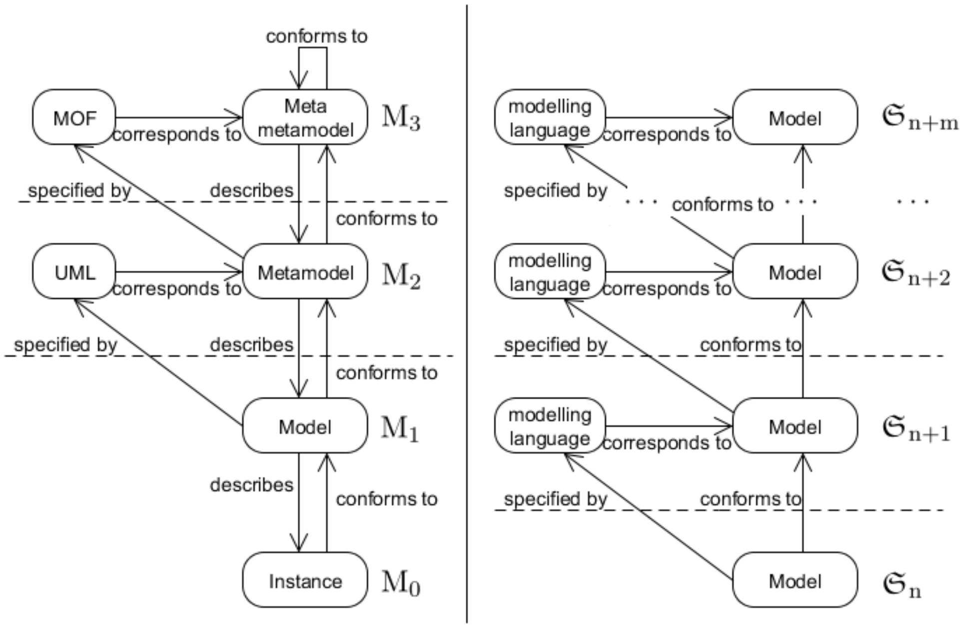


FIGURE 2.13: OMG's layers of meta-modeling and an arbitrary layer of meta-modeling.

These two sides highlights the differences between DPF and modeling environments that expand MOF to create modeling languages. While MOF based modeling environments provides two abstraction layers, DPF on the other hand provides an unlimited abstraction layers users can interact with. The reason that MOF based modeling environments provides two layers to interact with is because the layers M_2 and M_3 are usually part of the environments internal infrastructure. For example in EMF users can create models that conforms to the Ecore meta-model. The only meta-model that users of DPF are unable to interact with is located at the highest abstraction layer. A specification $\mathfrak{S}_{n+1}$ is specified by a modeling language that corresponds to a specification $\mathfrak{S}_{n+2}$. But the same specification $\mathfrak{S}_{n+1}$ also represents the abstract syntax for a specification $\mathfrak{S}_{n}$. These DPF models automatically generates a new graphical editor environment provided by the DPF Workbench.

2.5 DPF Workbench

The DPF Workbench provides a modeling environment for DPF and consist of three main components. These are the "DPF Model Editor", the "DPF Signature Editor" and the "DPF Code Generator". The first two editors provides the modeling functionality for the DPF Workbench. "DPF Model Editor" is used to create and modify DPF specifications. The "DPF Signature Editor" is used as a supplement to the "DPF Model Editor". It provides an editor to construct user defined predicate signatures. These signatures can then be used to define the semantics of a DPF specification in the "DPF Model Editor" if the predefined predicates that DPF provides does not suffice. Figure 2.14 that is provided in the article[18], explains how the "DPF Signature Editor", the "DPF Model Editor" and a DPF Model is related to each other in the DPF Workbench over different abstraction layers. The "DPF Code Generator" provides the users with a code generation environment for DPF specifications.

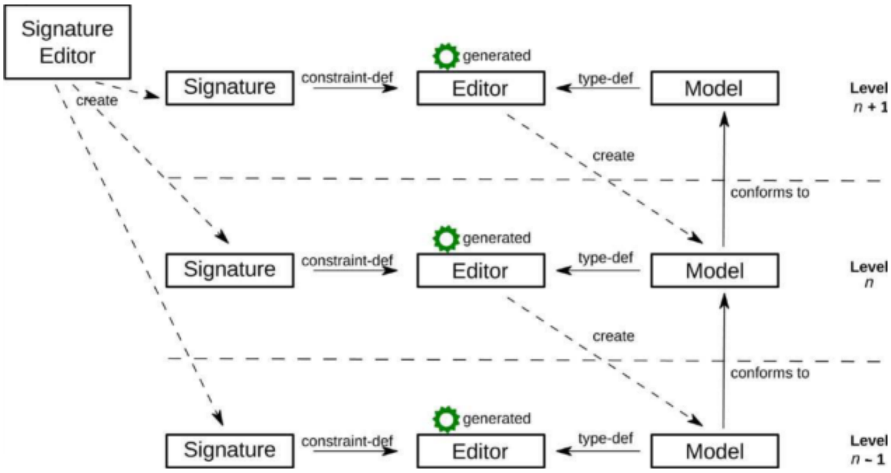


FIGURE 2.14: Generated DPF Editors in a multi-layer meta-modeling hierarchy.

DPF Model Editor

The DPF Model Editor is an extension of the Diagram Predicate Framework that provides an intuitive approach to creating modeling languages and have been created using several different technologies. In 2011 Øyvind Bech published his master thesis[23] where he designed the implementation of the DPF Model Editor that is based on the Eclipse Modeling Framework technology. This first version of the DPF Model Editor has seen several iterations and provides support for creating domain specific modeling languages. Figure 2.14 explains that a new instance of the DPF Model Editor is generated for each new model that is created. This means that every DPF specification has a corresponding editor that provides graphical editing properties to change the models. For each generated editor we can create a new DSL one abstraction layer lower that generates a new editor that correspond to this DSL.

Chapter 3

Model Transformation

Transformations are a fundamental aspect in computer science and software engineering. Whenever a computer starts up, transformation of computer systems and computer programs happens frequently. Take a compiler for instance, it plays a vital part of a computers internal infrastructure. A compiler is a computer program that translates source code written in a high-level programming language into a lower level language, such as an assembly language or machine code. This means that a computer program written in a general-purpose programming language, such as Java or C++ would be useless without a compiler, since the computer's central processing unit (CPU) depends on machine code to be able to execute a set of instructions. But also computation of primitive data values and performing operations on data structures such as lists and arrays can also be viewed as data transformations. When a programming language provides a way to type these data values or data structures, then a compiler or interpreter can apply operations to the data accordingly to the type. But when we mention data representing software artifacts such as a data schema, programs or models, then the subject of transformation approaches are meta-data. Model transformation approaches are implemented as meta-programs that reads and manipulates meta-data such as those mentioned above. An important factor when creating meta-programs that facilitate the transformation of such meta-data is that the meta-programs operates accordingly to the rich semantics of the meta-data. The software artifacts above contains meta-data that conforms to some programming language, meta-models, etc. The structure and semantics of such meta-data requires to be handled accordingly when executing a model transformation.

3.1 Basic concepts of model transformation

The very basic concept of a model transformation on the highest level of abstraction is to translate one model to another model. This model translation can either be achieved through an endogenous or an exogenous model transformation. For an endogenous model transformation we take a source model expressed in a modeling language and produce a target model expressed in the same modeling language. While an exogenous model transformation translates a source model expressed in one modeling language into a target model expressed in another modeling language. It is essential that these models remain consistent, and therefore both the source and target model have to conform to their corresponding meta-models.

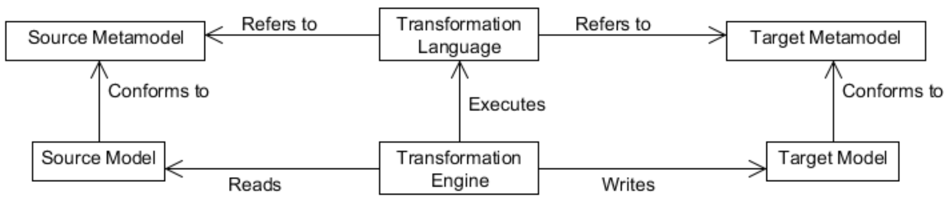


FIGURE 3.1: The basic concepts behind a model transformation.

Figure 3.1 represents the basic concepts of a model transformation. The two concepts, transformation language and transformation engine are provided by some model transformation environment. The main idea behind changing two models are to read a source model and write a target model. The transformation engine executes a set of guidelines provided by a transformation language that express how the target model is constructed. These guidelines is created from meta-data that are defined in the source and target meta-model to create an executable environment for the transformation engine. Where the transformation language refers to both the source and target meta-model when specifying these guidelines. The transformation language specifies how a translation between two models should be applied through the abstract syntax that the meta-models provides. Note that the concrete syntax for a domain specific modeling language could be represented either graphically or textually. Traditionally when we use the concept model, we consider a graphical syntax, with nodes and vertexes that are connected with arrows and edges. However a model can also have a textual representation and therefore we often say that a model transformation can produce two different kind of target models. At the highest level of abstraction these two different target models can either be produced by a Model to Text (M2T) transformation or a Model to Model (M2M) transformation. A Model to Text transformation takes a source model and produce sequences of strings as a target model. The other approach, Model to Model transformation takes a source model as an input model and produce a target model. The main distinction between the two categories is that a M2M transformation produce an instance model that conforms to some meta-model while an M2T produces implementation code as its target model. We can expand the knowledge we have so far with model transformations that these endogenous and exogenous can produce a target model over different layers of abstractions.

3.1.1 Layer of Abstractions

In the beginning of 2006 Tom Mens and Pieter Van Gorp published a paper[24] that explains different aspects of model transformations. One aspect of model transformation they address is the direction through abstraction layers for endogenous and exogenous model transformations. In their paper they state that the *"dimensions horizontal versus vertical and endogenous versus exogenous are truly orthogonal"*[24]. Horizontal and vertical model transformation are two categorizes that describes transformations over different layers of abstraction. In MDE a layer of abstraction represents models that are specified by models from a higher layer of abstraction. For example a class diagram that is specified by the UML model. Modeling elements that are defined for the class diagram is represented on one level of abstraction while modeling elements that are defined by the UML model is represented one abstraction level higher. This looks familiar concerning meta-modeling. An instance model of a meta-model is located on an abstraction layer lower than the abstract syntax. Consider table 3.1 that was published in paper[24]. The table describes some examples of different model transformations over layers of abstractions.

	Horizontal Transformation	Vertical Transformation
Endogenous Transformation	Refactoring	Formal refinement
Exogenous Transformation	Language migration	Code generation

TABLE 3.1: Example model transformations.

Previously in this section we discussed that changing a model to another model can either be applied by an exogenous or an endogenous model transformation. But when we consider these two types of model transformation we can also express that model transformations are vertically or horizontally translated amongst abstraction layers. For a vertical model transformation a target model is translated according to models that are specified on a higher abstraction level, while a horizontal model transformation produces a target model that correspond to a different abstraction layer hierarchy. The table above express that that we can have for example endogenous model transformations that provides refactoring or formal refinement of models. These two examples of model transformations are applied differently concerning abstraction layers. Refactoring is an example of a horizontal model transformation that applies changes to a model expressed in some modeling language, and since this is an endogenous model transformation we can safely assume that the abstraction level is the same before and after the transformation is applied. A specific model refactoring example is the Pull Up Attribute[25] that moves a common attribute from a subclass of a given class to this class. Language migration is another example of a horizontal model transformation, and is an exogenous model transformation that produces a model expressed in a different modeling language compared to the source model. A classical example of a language migration is to translate a class diagram to a relation database model. This example has become more or less a benchmark for model transformation tools and describes a model transformation for a modeling language that is specified through a abstraction layer hierarchy to a modeling language that is specified through another abstraction layer hierarchy. The reason for mentioning that an abstraction layer is part of a hierarchy is because there exist solutions for creating a domain specific modeling languages over an arbitrary layers of abstractions, such as the Diagram Predicate Framework[18] (DPF), metaDepth[26] or Visual Modeling and Transformation System[27] (VMTS). Comparing these with the Eclipse Modeling Framework (EMF), that provides a two layered approach to specifying a DSML, we can say that exogenous model transformations that utilizes EMOF are applied to a two layered abstraction hierarchy. EMF creates a DSML based on the Meta Object Facility and therefore provides the user the possibility to define a DSML as a meta-model and create an instance model of this DSML meta-model. While the three other tools mentioned above provides an n-layered meta-modeling environment to specifying DSMLs. This means that a source DSL might only be described in one meta-model while a target DSML might have been specified through several layers of meta-modeling. Regardless of how many abstraction layers a DMSL is defined over for a source and a target model, the model transformation is provided horizontally. Code generation is an example of a model transformation that vertically translates through layers of abstraction and is usually the final model that is produced in a model driven development cycle. Code generation is a Model to Text transformation that translates a source model that is described by a DSL and produce a target model that usually is described by a general purpose programming language, such as Java or C++. Figure 3.2 represents both a vertical model transformation and a horizontal model transformation. We can see that the vertical model transformation example represents a small portion of the MDA approach to software development, where implementation code is generated from a collection of platform specific models. The horizontal model transformation example provides a different example to model transformations, which is mering models into another model and is convenient for synchronizing models.

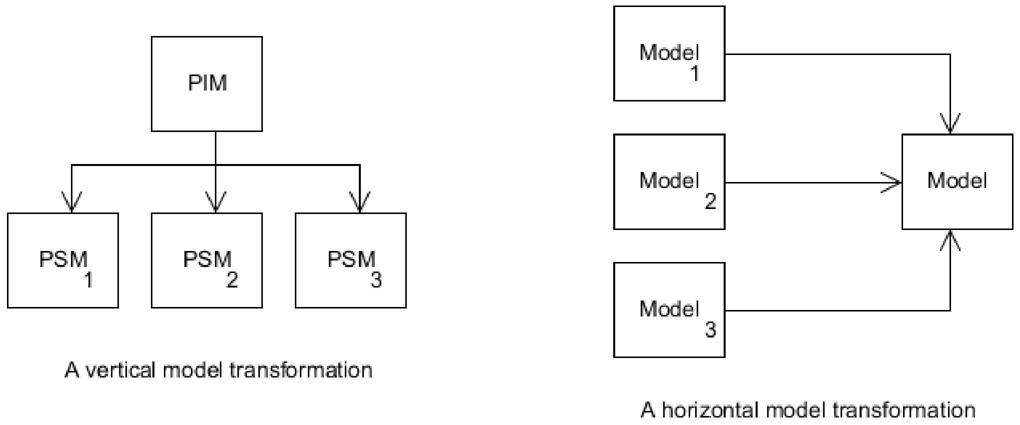


FIGURE 3.2: Vertical and horizontal model transformations.

The other provided example is a vertical model transformation that presents the last example of an endogenous model transformation, and that is refinement of a model. The three model types that MDA provides can be viewed as a endogenous model transformation that provides a model that is gradually refined into executable implementation code, by going through refinement steps that add more details to the model. For example when mapping a platform-independent model to a platform-specific model, like we discussed in section 2.1.1.

3.2 Model Transformations in MDE

Model transformations are in the center of Model Driven Engineering. The vision for MDE is to increase automation of models between level of abstractions. This vision is achieved through the use of model transformations. Either if it is to use a model to text approach to generate source code, or by transforming a model to another model where both models concrete syntax are specified by some abstract syntax from a meta-model. A model driven approach to software development thrives to keep a high level of abstraction for as long as possible through translating these models. And therefore model transformations are essential to be able to deploy model driven engineering in a software development process. The principles behind OMG's Model Driven Architecture utilize the concepts behind model transformation to a full extend. Figure 3.3 gives a representation of how MDA wishes to facilitate the use of models and model transformations in a software development. The figure was published in Kim Letkeman article, “Comparing and merging UML models in IBM Rational Software Architect”[28] in October 2010.

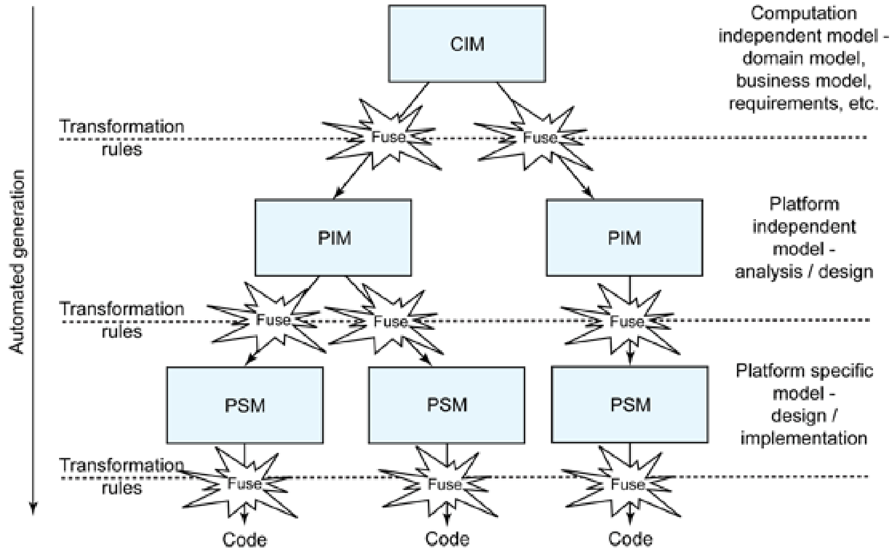


FIGURE 3.3: Model Transformations in Model Driven Architecture.

The figure presents different level of abstractions that the architecture provides and how a set of transformation rules change models between abstractions. Remember what we discussed in section 2.1.1 that the architecture represents a software design approach for developing software applications. Where it expands the requirements of a software application into models and at the last level of abstraction the architecture propose that implementation code is produced accordingly to a set of transformation rules. The code that is generated most likely requires some additional work by developers, but a major part of the implementation code is generated through the use of models. Figure 3.3 explains that a set of transformations are required for a model to fuse into another model, or said differently, for a model to be integrated into another model. The transformation rules, that specifies how a model from a high level of abstraction is translated to a model on a lower level of abstraction, provides a development process that produce implementation code through automatically generating models on different levels of abstraction. Models and model transformations are equally important for MDE to be applied in a software development process. Without model transformations models would simply represent an abstraction of a system. This means by utilizing model transformations in a software development cycle, models can evolve into executable implementation code by translating through different level of abstractions.

3.3 Existing Environments

There are a wide variety of existing model transformation environments and tools available. Some have experienced extensive testing through several iterations and some are relatively fresh to the MDE community. This section describes some of these model transformation environments and how these environments approach model transformations. Because there are several different approaches to model transformations and for the purpose of this thesis we will only address approaches that indicates model to model transformations.

OMG provides a standard that includes three such model to model transformation approaches. In 2002 OMG issued a request for proposal regarding Query/View/Transformation (QVT)[29] where they sought a standard that was compatible with other OMG specifications such as MOF, UML, OCL, etc. This later lead to the release of *Meta Object Facility (MOF) 2.0 Query/View/Transformation Specification* in April 2008. The standard specifies the three model transformation languages or approaches to model transformation,

- QVT Operational is an imperative language that support implementation of unidirectional transformations.
- QVT Relations is a declarative language that supports implementation for both unidirectional and bidirectional model transformations.
- QVT Core is also a declarative language that is meant to act as the target of transformations from QVT Relations. This is however not the case since QVT Core since there does not exist a full implementation of this language.

A unidirectional model transformation has only one mode of execution: that is, it always takes the same type of input and produces the same type of output. For a bidirectional model transformation, the same type of model can sometimes be input and other times be output[30]. A model transformation in any of these three languages can itself be regarded as a model that conforms to a corresponding meta-model that is specified in the QVT standard. Note that a model transformation implementation based on any of these three languages requires source and target models that is created according to a MOD 2.0 meta-model. Since the release of the standard there has been several implementations of these three languages. The Eclipse Foundation has contributed with implementations of the QVT standard in a subproject for the Eclipse Modeling Project[31], namely the Model to Model Transformation (MMT) project that hosts Model to Model Transformation languages. These model transformations are executed by transformation engines that are written into the Eclipse Modeling infrastructure. ATLAS Transformation Language (ATL)[32] is developed on top of the Eclipse platform and is one of three model transformation environments provided by the MMT project[33]. ATL is often referred to as a QVT Like implementation of the QVT standard. Since the language offers an approach to model transformations that is based on the three QVT languages. Because of this ATL is often referred to as a hybrid approach to model transformations. Another model transformation environment provided by the MMT is QVTo[34] that is based on the QVT Operational model transformation language.

Model transformation environments like Visual Automated Model Transformations[35] (VIATRA), Henshin[25], Graph Rewriting and Transformation Language[36] (GReAT), The Attributed Graph Grammar System[37] (AGG) and A Tool for Multi-formalism and Meta-Modelling[38] (AToM^3) are approaches that is based on category theory's theoretical work on graph transformations. Model transformations that is based on the concepts of graph transformations have a LHS and a RHS graph pattern. The LHS provides a graph structure that is used to locate matching graph structures in a source model while the pattern included in the RHS is meant to replace a matching graph structure. We will explore the concepts of graph transformations in more depths in section 3.5, but first we will explore different design features of model transformation environments.

3.4 Classification of Model Transformations

In March 2006 Krzysztof Czarnecki and Simon Helsen published a domain analysis that covered existing model transformation approaches[39]. A domain analysis represents information on software system that share a common set of features for a given domain[40, 41], and in this case the domain is model transformations. In their paper they presents the result by using feature diagrams, that provides a terminology and representation of the design choices for existing model transformation approaches. These feature diagram does not only represent model to model transformation approaches, but also consider the design choices for model to text transformation approaches. There are several different approaches to model transformations, such as operational, relational, graph based, hybrid, etc. These approaches have some similar and common features, but are designed differently. For the purpose of this thesis we will only address the model to model approaches in Czarnecki and Helsen's survey on model transformations. However it is important to address that at top level, we can divide model transformations into to categories, namely model to text and model to model transformations like we discussed in earlier sections. In this section we consider the ideas and results from Czarnecki and Helsen's report and *A Taxonomy of Model Transformation*[24] that was published by Tom Mens and Pieter Van Gorp in 2006. The diagrams in figure, figure 3.4, 3.5 and 3.6 are provided from the domain analysis paper[39].

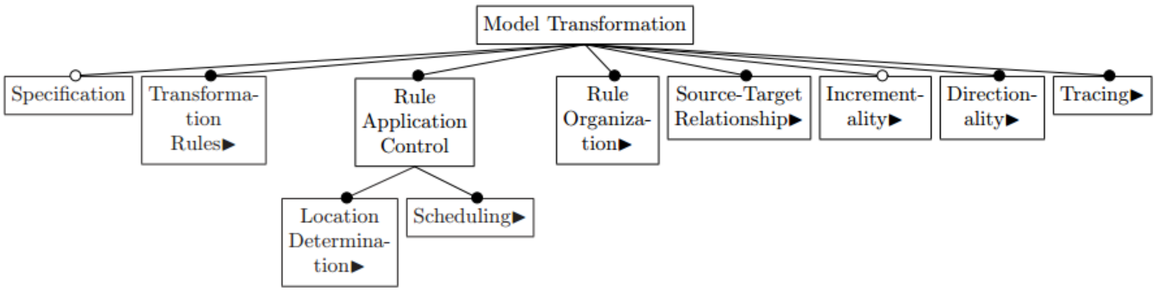


FIGURE 3.4: A domain analysis of model transformations[39].

Figure 3.4 shows the feature diagram at top level of a model transformation, where a subnode represents different design choices. These design choices can give a better understanding on different aspects of model transformations. A model transformation environment needs to tackle these design choices that figure 3.4 refer to in some manner. However, not all of these design choices are mandatory. Above each subnode in these three feature diagrams there is a black filled circle and an empty circle. The empty circle explains that these design choices are optional, like for example Specification and Incrementality, while the others are mandatory features for an implementation of model transformation approaches. The rest of this section will cover the design choices that figure 3.4 describes. Figure 3.6 represents two different curved lines between subnodes. The black filled curve line represents that the subnodes are part of an *or*-group while the other curve describes that the subnodes are part of a *xor*-group.

3.4.1 Specification

Some approaches to model transformations has a dedicated specification mechanism, such as *pre* and *post*-conditions in OCL. A specification mechanism provides special functionality during a model transformation. For example in OCL a *pre*-condition is required to be true before an operation is executed while a *post*-condition describes what will be true for the result once the operation is executed. An approach to model transformation could include a transformation specification that represents a function between source and target models that could include some operation before and after applying a transformation rule.

3.4.2 Transformation Rules

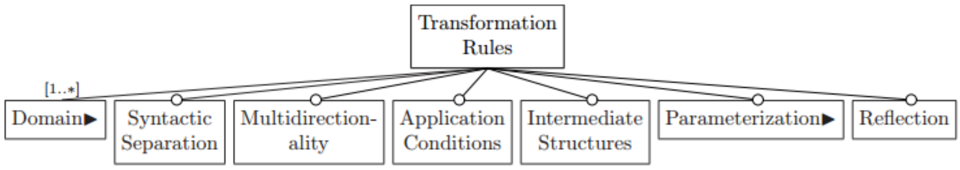


Figure 3.5: Features for transformation rules.

For a model transformation to be able to translate a model to another model it needs a set of guidelines on how to achieve this. Therefore a model transformation has a set of transformation rules that specifies how a target model is produced. A transformation rule usually defines two special patterns. One pattern represents a searching pattern while the other pattern represents the part that is produced. An obvious example of such rules are the rewrite rules, that provides a left hand side (LHS) and a right hand side(RHS) graph where both sides represents patterns that are considered when a transformation rule is applied. A function that implements some transformation steps can also be seen as a transformation rule. Regardless if the concrete syntax of a model is either textual or graphical, the users have to specify a pattern that is used to locate matches and a pattern that is used to replace these matches with a result. Defining the transformation rules are essential for model transformation approaches. There will always be a pattern that determines the searching part and a pattern that determines the translated part for a model transformation. These patterns are defined over different domains.

Domain

A transformation rule is specified by certain domains. These domains are responsible for accessing either the source or target model for each corresponding rule. A domain represents both the part that is used to find matching patterns in a source model and the part that produces a target model. For example for a classic rewriting rule we would have one domain for the LHS and one domain for the RHS of the rule.

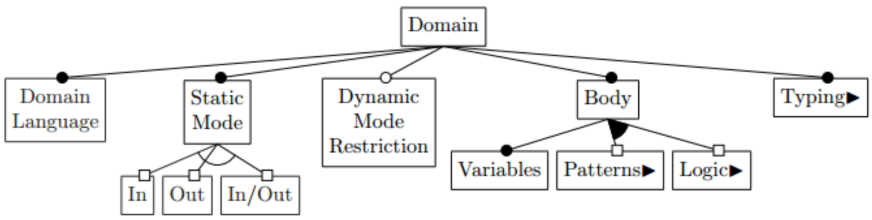


FIGURE 3.6: Features for a domain.

Figure 3.6 gives a representation of the contents of a domain. The **domain language** represents how we can structure the domains. In the context of model transformation tools that translates models that utilize the Model Driven Architecture this domain language would have the form of a meta-model expressed in the Meta Object Facility. The domain language express what language we use to define the abstract syntax for both the source and target model. **Static mode** determines if a domain represents the searching part, the produced target part, or both. Classic rewrite rules has a source domain that represents the LHS and a target domain that represents the RHS. Bidirectional transformation rules on the other hand can be applied in both directions and therefore the domains are regarded as both the source and the target domain. **Dynamic mode restriction** concerns model transformation tools that provides rules in multiple directions, that means that the source and target model can act as both a input or output model depending on what direction a transformation occurs. For these rules a domain can be restricted to act as a source domain, and not as a target domain. The **body** feature of the domain group has three subcategories and figure 3.6 describes that **Variables** are a mandatory feature for all model transformation approaches. A variable enables sharing of data types between domains, for example between a source and target domain. The next curved black line describes that the two features **Patterns** and **Logic** can both be included in a model transformation approach. The pattern feature defines the structure and syntax of transformation rules. The syntax can be represented by either using the abstract or concrete syntax of a modeling language and can either have an textual or graphical representation. The transformation rules can have a structure that represents strings, terms or graphs. The abstract syntax describes what modeling elements a certain pattern can contain while the concrete syntax determines if the modeling elements are textual or graphical. The Logic feature of a domain specifies computations and constrains on modeling elements. Logic can be expressed by different language paradigms like object-oriented or functional and can be executable or non-executable. Executable logic can take a declarative or an imperative form or both such as the implementation of a hybrid model transformation approach that ATL provides. **Typing** determines the typing of the contents of the body feature. Patterns can either be untyped, syntactically typed or semantically typed. For syntactically typing modeling elements that are part of a pattern is associated with a meta-model element.

Syntactic Separation

Other then having different domains some approaches to model transformation includes syntactic separation of accessing models. These model transformation approaches clearly separates on what models a transformation rules operates. For example rewrite rules the LHS operates on the source model while the RHS operates on the target model. Some model transformation approaches might not have any distinctive separation, like for example an model transformation implemented as a Java program.

Multi-directionality

Multi-directionality determines if a transformation rule can be applied in different directions. This is convenient for synchronizing models by using model transformations. Model transformation approaches that supports applying rules in both directions are usually defined over a domain that is both a source and a target.

Application Conditions

Transformation rules for some approaches supports application conditions. An application condition provides an extra property that specifies a filter for search patterns. Application conditions are handled differently amongst the model transformation approaches. Model transformation approaches that implements the QVT standard often use control flow statements like the *when-clause* or the *if-then-statement* that must be true in order for a transformation rule to be applied. Model transformation approaches that is based on category theory and graph transformations on the other hand specifies application conditions as separate graph structures that either requires or forbids this specific graph structure in a located matching graph structure.

Intermediate Structures

Some model transformation approaches requires intermediate structures when executing a set of transformation rules. These structures are usually only used as a supplement when applying a set of transformation rules. One example of an intermediate structure is a traceable link. These traceable links usually has a corresponding meta-model that is required to be included in a model transformation environment. Some approaches to model transformation rely on this intermediate structure to be able to translate a model. For example in AGG a traceable link is created after a rule is applied to prevent this rule for locating the exact same match next time the rule is applied.

Parameterization

Parameterization allow for passing values to a transformation rule. These values may represents data types such as primitive data types or modeling elements types. For example we can pass data types, for example modeling elements to a transformation rule. Some approaches to model transformation offers the values of a parameterization to represents *higher-order rules*. *Higher-order rules* may take other rules as parameters. A model transformation environment may perform changes to a transformation rule with these provided parameters and at the same time use these data types in other transformation rules.

Reflection & Aspect

Some model transformation environments allows for a reflective look up of target modeling elements for matching source modeling elements at runtime when target modeling elements are already transformed. For example a lazy rule in ATL allows for the possibility to explicit iterate over already transformed modeling elements and apply some reflective operation on the target modeling elements. Transformation rules that utilize an aspect-oriented extension are rules that can affect other rules when applied. Both of these categories can be used to express cross-cut concern on other transformation rules. This means transformation rules that can directly affect other transformation rules.

3.4.3 Rule Application Control

This section can be divided into two sub categories, namely locating matches for a transformation rules and how these rules are be applied. Locating a matching pattern in a source model is rarely controlled by the users. The different model transformation languages utilizes optimized searching algorithms to locate these matches, where a rule has to be applied to a specific location in a source model. Usually there are more then one exact match for each rule, and therefore a transformation engine has to consider that there are several matches for a specific search pattern in a source model. There are multiple different search algorithms for locating these matches, but these search algorithms often share a common strategy to determine matching pattern locations. Locate matches strategies could be applied deterministically or non-deterministically. It is important to differentiate between a strategy and a search algorithm. A strategy implies how an algorithm for locating matches is executed. An algorithm that is applied by a deterministic strategy, given a particular source model, will always produce the same output, with an algorithm that always pass through the same sequences during different runs. For example for directed graphs a deterministic strategy could exploit some graph traversal algorithms, such as Breadth-first search[42] (BFS) or Depth-first[42] search (DFS). An algorithm that are executed with a non-deterministic strategy on the other hand can experience different behaviors on different runs. An example of a non-deterministic strategy is *one-point* application[39] and *concurrent* application. A *one-point* application applies a rule to a non-deterministically location in a source model. This means that a rule will search for matches at random locations within a given source scope. While a *concurrent* application applies a rule to all matching locations at the same time.

Before a matching pattern can be located in a source model a model transformation environment has to have a mechanism that schedules these transformation rules. Some model transformation tools provides the user with the possibility to explicitly decide the transformation cycle for applying rules. The scheduling of transformation rules can be divided into implicit or explicit rule scheduling. An implicit rule scheduling mechanism prevents the users with any control over how transformation rules are applied, since this is already designed in the environments infrastructure. Explicitly controlling the rule schedule can either be achieved internal or external. Internal rule scheduling allows a transformation rule to invoke other transformation rules, for example lazy rules in ATL. External rule scheduling provides a mechanism that can specify the scheduling logic for transformation rules, for example executing a collection of transformation rules in sequential order. We can also select specific rules and execute these accordingly. This is achieved by providing a scheduling mechanism with an explicit condition that specifies how the transformation rules are applied. This condition could for example specify that we should apply rules according to a certain rule priority. A scheduling mechanism is then provided with rules that is applied in priority over other rules. Now we have seen that a scheduling mechanism can be defined explicitly or implicitly by the users and can have conditions that determines if the rules should be applied in a certain order. Model transformation tools also have scheduling mechanisms that provides the possibility to iterate through a set of rules. What we mean by iterating through a set of rules is that a model transformation tools applies a transformation rule until there are no more matches. Iteration scheduling mechanisms include recursion, looping and fixed number iteration through different transformation rules.

The available model transformation tools provides different solutions to both locating matches and defining rule scheduling mechanisms. Usually the users are given more freedom to defining the rule scheduling mechanism compared to determining match locations.

3.4.4 Rule Organization

This feature represents how the rules are organized and if they are easy to reuse. The rules are usually represented as a collection of rules, where these rules could either be represented in some source code or by some tree based editor. Some model transformation environments such as the QVT languages or ATL offers a modular approach to rule organizing. This means that the rules are contained in a module and are therefore easy to reuse. This gives the users the possibility to import these modules and use them in other modules. Modules may include transformation rules as lazy rules. Lazy rules are required to be included in other rules and are applied at runtime during a model transformation. Rules such as lazy rules are highly reusable and can be used in any other module or rule. In graph based model transformations rules are in most cases organized into a set of rules, where each rule is not available for other rules to use. The reason for this is because such rules are often represented graphically and therefore makes it hard to include in other rules.

3.4.5 Source - Target Relationship

The source and target model can in some cases be one and the same model. Model transformations that are applied to one and the same model are often referred to as in-place model transformations while approaches that produce a target model independently of the source model is often referred to as out-place model transformations. In AGG the source and target model are always on and the same model, and therefore AGG only supports in-place update of models. The older versions of Atlas Transformation Language (ATL) requires that a new target model, that is separated from a source model is created when applying a model transformation. Creating a new model as a target model for a model transformation specifies that this is an out-place change to a model. However since January 2013 ATL support in-place transformations through a refining mode. Other approaches offers support for both in-place or out-place updates and lets the users specify how the models should be updated. These out-place model transformations could either be changes made to an existing model or by creating a new model. QVT Relations and Henshin offers the possibility to create a new model or update an existing one. Henshin does implicitly deliver an in-place model transformation environment, that allows for in-place update of models. However, Henshin provides out-place model transformations explicitly when using the Henshin API.

3.4.6 Directionality

This section describes that a model transformation environment can translate a model in multiple direction. We can distinguish the direction of model transformations to either be unidirectional or multi-directional. An unidirectional model transformation has one source model that either translates to a target model or updates a target model. What we then can do is change the source model and source meta-model with the target model and target meta-model. But this model transformation is not multidirectional, since we have to apply two model transformation to achieve this. A multidirectional model transformation can translate in different direction, regardless of source and target metamodel. This is especially convenient for model synchronising, where we can translate in both directions.

3.4.7 Tracing

Some model transformation environment supports tracing of modeling elements during a model transformation. Tracing works like a fingerprint in a model transformation and has an unique link between elements. A traceable link provides a mapping between source and target modeling elements during a model transformation and provides information how a source modeling element relate to a corresponding target modeling element. The traceable link is stored in memory for the duration it takes to execute a set of transformation rules. Some approaches to model transformations requires that a traceable link is specified in the structure of transformation rules between source modeling elements and target modeling elements. Other approaches implicitly specify traceable links automatically during runtime of a model transformations. When there is a match in a transformation rule, a new traceable link is created between a matched source modeling element and all corresponding target modeling elements. These traceable links is very convenient when analysing and debugging a model transformation since there is tracing between source and target modeling elements for each matched transformation rule.

How traceable links are used across transformation tools varies. In ATL and QVT these traceable links are part of the internal infrastructure of the environment and are therefore handled automatically during runtime of a model transformation. For Henshin the user can use the Henshin Trace model to define traceable links between Henshin modeling elements in the graph structure of the specific rules. The trace model consists of a single class Trace with a source and target reference. The user can then create this trace element together with the transformation rules to relate source and target modeling elements. ATL has an implicit tracing mechanism that specifies relationships between the source modeling element and its corresponding target modeling element by using a native type called ASMTransientLink[43]. For every time a transformation rule locates a match, one ASMTransientLink is defined that specifies the name of the transformation rule together with the source modeling elements and the target elements. These links are added to a collection of transient links and stored internally for ATL. This means that the users of ATL cannot access these links after a model transformation has finished executing. However, as shown by Andrés Yie and Dennis Wagelaar[43], that gaining access to these ATL traces can be done explicitly by creating transformation rules that generates a tracing model based on the internal tracing information provided by ATL.

3.5 Graph based Approach to Model Transformations

One common approach to model transformations is by graph transformations, also referred to as graph rewriting. Graph rewriting can be implemented with an algebraic approach, which is based on Category Theory. Before we go into detail about graph transformation, we should quickly describe the concepts of Category Theory[44, 45]. Category theory can be used to formalize mathematical or software theory's at a high level of abstraction. In 2006 Steve Awodey published a second edition of the book, Category Theory, where he stated, *"Just as group theory is the abstraction of the idea of a system of permutations of a set or symmetries of a geometric object, category theory arises from the idea of a system of functions among some objects[46]."*

$$\begin{tikzcd} A \arrow[r, "f"] \arrow[dr, "f \circ g"'] & B \arrow[d, "g"] \\ & C \end{tikzcd}$$

FIGURE 3.7: Collection of objects A,B and C.

Category Theory can be used as a supplement to explain the theoretical aspects behind a problem or solution. A category consists of a collections of objects and functions. In figure 3.7 we have a collection of objects A, B, C and arrows f, g, g $\circ$ f. The figure describe that there is a connection between the two objects A and B. This connection indicates that there are some association between two objects. For this case this means that function f is defined in A and the values of this function are in B. When the objects represents graphs, then these connections between objects are often referred to as morphisms between graphs or graph morphisms. Morphisms are pair of maps which commute with source and target[9]. Figure 3.7 has three sets of graph morphisms, f : A $\longrightarrow$ B, g : B $\longrightarrow$ C and g $\circ$ f : A $\longrightarrow$ C. The last set of graph morphisms, g $\circ$ f indicates that there is a composite function between A and C. This basically means that if C is a function g of B and B is a function f of A, then C is the result of a function between C and A.

For the purpose of this thesis the collection of objects represents graphs and the arrows represents morphisms. A graph contains a collection of nodes and edges and is undirected when there is no distinction between two nodes associated with an edge or directed graph if an edge has a direction between two nodes. This means that each node is represented as a source and a target node for an edge. A directed graph L can be defined by L = $\{\ \mathrm{N_L}, \mathrm{E_L}, \mathrm{source_L}, \mathrm{target_L}\ \}$. $\mathrm{N_L}$ represents the collection of nodes and $\mathrm{E_L}$ represents the collection of edges that are included for the directed graph. The third and forth elements, $\mathrm{source_L}$ and $\mathrm{target_L}$, are functions that retrieves the source and target node for an edge. This collection of nodes and edges in a graph L can have a mapping to nodes and edges in another graph G. If graph structure L can be mapped with a nodes and edges in another graph G then there exist a graph homomorphism of graph L in graph G.

Graph Homomorphism

$$\begin{tikzcd} L \arrow[d, "\mathrm{m_L}"] & R \arrow[d, "\mathrm{m_R}"] \\ G & H \end{tikzcd}$$

FIGURE 3.8: Two sets of graph homomorphism of graph L in G and R in H

Figure 3.8 has two graph homomorphisms $\mathrm{L} \xrightarrow{m_{\mathrm{L}}} \mathrm{G}$ and $\mathrm{R} \xrightarrow{m_{\mathrm{R}}} \mathrm{H}$. Now if we consider the first example, if there exist a valid graph homomorphism between graph L and G, then the collection of nodes and edges in L has to be mapped to nodes and edges in G. If both graphs L and G are directed graphs then we can safely assume that the definition of graph $\mathrm{G} =\{ \mathrm{N_G}, \mathrm{E_G}, \mathrm{source_G}, \mathrm{target_G} \}$. For a graph homomorphism $\mathrm{m_L}$ from the graph L to the graph G, $\mathrm{L} \xrightarrow{m_{\mathrm{L}}} \mathrm{G}$, there is a mapping $\mathrm{m_L} : \mathrm{N_L} \longrightarrow \mathrm{N_G}$ from the set of nodes in graph L to the set of nodes in graph G and a mapping mapping $\mathrm{m_L} : \mathrm{E_L} \longrightarrow \mathrm{E}$ $_{\mathrm{G}}$ from the set of edges in graph L to the set of edges in graph G that preserve both source and target nodes. This means that there is a mapping from a source node in G that is equal to a source node in L and a target node in G is equal to a target node in L.

3.5.1 The Algebraic Approach

This approach are based on the concepts of composing graphs, modelled by pushouts of graphs and graph morphisms. This pushout approach comes in different variants, and we will look at two of these, namely the double-pushout (DPO) approach and the single pushout (SPO) approach[47, 48].

Historically, the first of the algebraic approaches to graph transformations, the double-pushout, was first introduced at the Technical University of Berlin in the early seventies by H. Ehrig, M. Pfender and H.J. Schneider[49]. They tried to generalize Chromsky grammars from strings to graphs. This allowed to define a graph rewriting step by the use of two gluing constructions. And by applying a graph rewriting step for the double-pushout approach is a pair of morphisms in the category of graphs where the arrows represents total graph morphisms, $\mathrm{L} \longleftarrow \mathrm{K} \longrightarrow \mathrm{R}$. This is true for each application rule in a graph transformation for the double-pushout approach. Where the graph K represents the common part and the two morphisms $\mathrm{L} \longleftarrow \mathrm{K}$ and $\mathrm{K} \longrightarrow \mathrm{R}$ use the algebraic construction, pushout to apply an application rule for a rewriting step. Hence the name double pushout and the use of two rewriting conditions.

3.5.2 Transformation Rules

For a transformation language to be able to execute graph transformations a set of application rules needs to be defined. Through these rules, a transformation interpreter can act accordingly. These rules can have many names, and are often referred to as productions or applications. For graph transformations, there can be an arbitrary number of rules. Its truly up to the users how they want to translate a language and how many rules that is needed to acquire this. A rule in a graph based approach to model transformation specifies two graphs. The left hand side (LHS) graph, also often referred to as a pattern graph specify a graph structure that is used to locate matching graph structures in a source model. The right hand side (RHS) graph, also referred to as the replacement graph specify a graph structure that should be produced for each matching graph structure located in a source model. There is also a special graph that is defined for a graph based approach to model transformations, and that is an intersection graph. The intersection graph specifies a graph structure that shares common graph elements that is part of both the RHS and the LHS graph. This intersection graph is essential for a graph based approach to include a double pushout or a pullback transformation technique when performing a model trasnformation. We will discuss the doublepushout approach in section 3.5.4. For these transformation rules to execute, there is an application control mechanism that determines the execution of transformation rules.

3.5.3 Application Control

In section 3.4.3 we discussed that a application control can be divided into locating matches and a control mechanism for scheduling transformation rules. Locating matches are in most cases part of an environments internal infrastructure and employ a non-deterministic searching algorithm that locate matches in a source model. Some graph based approach provides a rule scheduling mechanism that supports the possibility to specify the execution order of transformation rules. Scheduling mechanism controls the order that the transformation rules are executed. The most basic scheduling mechanism is a rule itself which corresponds to a single application of a transformation rule. But in most cases, a scheduling mechanism to control application of several rule.

3.5.4 Execution of rules

The basic idea for graph transformation for both the double-pushout approach and the single pushout approach is to apply an application rule r: L $\longrightarrow$ R. Where the rule represents a single rewriting step for graph transformations and L represents the left hand side of the rule and R represents the right hand side of the rule.

$$\begin{tikzcd} L \arrow[r, "\mathrm{r}"] \arrow[d, "\mathrm{m_L}"] & R \arrow[d, "\mathrm{m_R}"] \\ G \arrow[r] & H \end{tikzcd}$$

FIGURE 3.9: The basic idea for graph transformation by applying a rule r.

A production rule r, G$\xrightarrow{r,m}$H indicates a direct derivation to a derived graph H. In figure 3.9, the graph H is created by applying a single pushout for a transformation rule r. If there is a match m of nodes and arrows for a subgraph L in a source graph G, then this indicates a graph homomorphism from the subgraph L to the source graph G such that the graphical structure in G is preserved. For each rule r, there are some algebraic approaches to how we can achieve H. At this moment there are four approaches, the double-pushout approach (DPO) [47], the single-pushout approach (SPO) [48], the sesqui-pushout[50] and the pullback approach[51]. Where the two most common approaches used in graph transformation tools are the DPO and the SPO approach. There is one major aspect that separate these two approaches, and that is that the DPO approach has an application condition.

$$\begin{tikzcd}
L \arrow[d, "\mathrm{m_L}"] & C \arrow[l, "\mathrm{l}"'] \arrow[r, "\mathrm{r}"] \arrow[d, "\mathrm{m_C}"] & R \arrow[d, "\mathrm{m_R}"] \\
G & C' \arrow[l] \arrow[r] & H
\end{tikzcd}$$

FIGURE 3.10: Principles behind the double pushout approach.

This application condition, named the gluing condition[47] consists of two parts. Namely the dangling condition and identification condition. From figure 3.10, the dangling condition requires that if the transformation rule p specifies the deletion of a node in G, then it must also specify the deletion of all incoming and outgoing edges of this node in G. By applying this condition, we can be sure that there are no dangling edges after deleting a node in G. The identification condition requires that every element of G that should be deleted by applying a transformation rule p is only presented once in L.

A single transformation rule p in the DPO approach is given by a pair of graph homomorphisms from a common graph C. This common graph C is formed by taking elements that are present in both L (LHS) and R (LHS) of a transformation rule p. The graph H is created from the graph G, by deleting all elements that is matched from the pattern graph L, but none in C. To avoid dangling edges, the gluing condition must be satisfied before deleting these elements. This is the first part (1) of the DPO approach, namely the deletion of elements. The second part (2) is insertion of elements. From here we create a graph H off all nodes and arrows from the replacement graph R that is not presented in the common graph C. The DPO approach has the possibility to preserve elements from translating from the pattern graph L and the replacement graph R with the help of a common graph C.

For the SPO approach on the other hand, deletion has priority over preservation. Figure 3.9 is a representation of the practices of the SPO approach. Where nodes that are present in the pattern graph L but not the replacement graph R are deleted. And the incoming and outgoing edges of the deleted nodes that are not present in the replacement graph R is deleted.

An application condition in graph transformation indicates an additional graph morphism that provides a transformation rules with extra properties. These applications can represent either a negative application condition or positive application condition. Both instances of application conditions are very similar since they indicates some additional information for a transformation rule. A negative application condition express requirements that a specific graph structure is forbidden to be part of the located matching pattern. On the contrary a positive application condition express that a specific graph structure is required for a located matching pattern to be a valid match for a transformation rule. Figure 3.11 represents in this case a negative application condition[52] (NAC).

$$\begin{tikzcd} N \arrow[dr, dashed, bend right, "\mathrm{n_G}"'] & L \arrow[l, "\mathrm{n}"'] \arrow[d, "\mathrm{m_L}"] \\ & G \end{tikzcd}$$

Figure 3.11: A Negative application condition.

The figure contains three graphs and three graphs morphisms. Graph L represents the LHS graph, graph G represents the graph that should be translated while graph N represents a negative application condition. A negative application condition specifies that a certain graph structure should not be included in a located match. A positive application condition on the other hand requires that a certain graph structure is part of a located matching graph pattern. Note that a negative and positive application condition is basically very similarly represented but implemented differently. For example the double pushout technique for graph transformations in figure 3.12.

$$\begin{tikzcd} N \arrow[dr, dashed, bend right, "\mathrm{n_G}"'] & L \arrow[l, "\mathrm{n}"'] \arrow[d, "\mathrm{m_L}"] & C \arrow[l, "\mathrm{l}"'] \arrow[r, "\mathrm{r}"] \arrow[d, "\mathrm{m_C}"] & R \arrow[d, "\mathrm{m_R}"] \\ & G & C' \arrow[l] \arrow[r] & H \end{tikzcd}$$

Figure 3.12: Double pushout approach with negative application condition.

Before the double pushout can be used, there has to be located a matching graph pattern in G. The graph L will locate a matching pattern $\mathrm{m_L}$ in G, then check if there exist an application condition N, whether or not this application condition requires or forbids a special graph structure there will be a graph morphism $\mathrm{n_G}$ that states if a match is valid. This application condition filters the searching of graph patterns in G when a transformation rule is applied.

Chapter 4

Problem Specification

4.1 Problem Specification

The DPF Workbench already includes support for model transformations inn form of code generation. However, the environment does not include support for transforming a model between different modeling languages. One of DPF's strengths is that it is possible to formally define a Domain Specific Modeling Language by defining multiple levels of meta-models. The main goal of this thesis is to extend the DPF Workbench with exogenous model to model transformations. This leads to the main question for this thesis.

- Can we include tool support for model to model transformations for the DPF Workbench that translates a model specified over a modeling hierarchy to a model specified over another modeling hierarchy?

The solution to this is not written in stone, and there are several approaches to how we can solve this specific problem. The tool requires some manual implementation but there are several existing approaches available that provides model transformations as we mentioned in section 3.3. DPF specifications are basically graphs, more specific, they are directed graphs. This means that a DPF specification consist of a set of nodes, arrows and two functions that specifies source and target node of the edges. This makes a graph based approach to model transformations convenient, but we should also consider other approaches to model transformations.

- Can we integrate an existing model transformation environment with an editing tool for the Diagram Predicate Framework Workbench?

We want to introduce the DPF Workbench with tool support that includes model transformations. This has already been partially introduced to the workbench environment in Anders Sandven[53]'s master thesis. In his thesis he describe how he integrated a M2T transformation environment to the DPF Workbench. He integrated a model transformation environment, Xpand[54] that provides a template based approach to Model2Text transformation. For this thesis however, we want to verify that we can successfully introduce a model transformation environment that supports translation between different

DSML's. But first we have to find an applicable environment that can be integrated with the DPF Workbench. In section 4.2 we will explore three different model transformation tools that supports both exogenous and endogenous model transformations. One aspect of model transformations that is required to translate specifications in DPF is a set of transformation rules that describes how a target model is produced. This leads to a problem for the DPF, because a transformation rule requires modeling elements from some abstract syntax to specify a structural pattern that is used to locate matches in a source model.

- How can we include the abstract syntax of a modeling language that is specified by a corresponding linguistic meta-model and a corresponding ontological meta-model for a single transformation rule.

In 2007 Ralf Gitzel, Ingo Ott and Martin Schader published a paper where they amongst other subjects discuss the difference between Linguistic and Ontological meta-modeling. They provide a definition between the two, *"Linguistic metamodeling uses a metamodel to describe a language syntax without a concrete real-world mapping. Ontological meta-modeling uses metamodels to describe domain-specific hierarchies"*[55]. As it is, the MOF 2.4.1 standard does not allow for more than a four layered meta-modeling. DPF has an Ecore specified meta-model that describes the language syntax and a meta-modeling hierarchy that together with the language syntax defines the abstract syntax for specifications located in lower abstraction layers. Figure 4.1 provides a representation on how specifications are related both to a linguistic and an ontological meta-model regardless of abstraction layer.

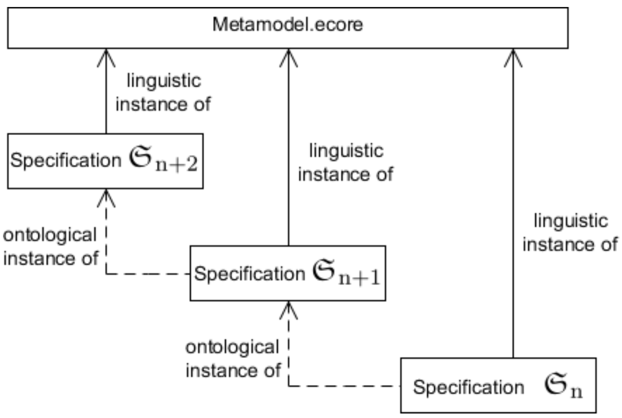


FIGURE 4.1: Relationship between layers of DPF specifications.

The "Metamodel.ecore" represents the linguistic meta-model that DPF provides to describe the language syntax for every single specification created by the DPF Model Editor. However, other than consisting of an underlying graph and a set of constraints, a DPF specification $\mathfrak{S}_n$ is also an instance of another specification$\mathfrak{S}_{n+1}$, and this is where it gets challenging. We can describe these specification models as ontological meta-models, since these models describes a domain specific modeling language through an arbitrary hierarchy of models. We have to find a way around this for our solution, because model transformation environments that utilize Ecore based models does not allow Ecore instance models to represent abstract syntax. This could serve a potential problem when integrating a model transformation environment with DPF. Modeling elements that DPF provides are created as nodes and arrows from an Ecore based meta-model, but are at the same time created according to modeling elements one abstraction layer higher.

We will discuss how we address and approach these problems in the next chapter. But first we will look at some related work on model transformations. We have considered the tools, The Attributed Graph Grammar System[37] (AGG) and Henshin[25] that provides a graph based approach to model transformation. We have also worked with ATLAS Transformation Language[56] (ATL), that provides a mixture of model transformation techniques and is therefore often referred to as a hybrid approach to model transformation. By analysing these three tools we want to find a model transformation environment that is best suited to be integrated with the DPF Workbench.

4.2 Three different model transformation environments

These model transformation tools use different approaches to how model transformations are applied. We have looked at tools that implement classical rewriting steps that utilizes the theory behind graph transformations and a tool that employs a hybrid approach to model transformations. For this survey we have tackled a specific exogenous model transformation example that translates an instance model of UML's activity diagram to an instance model of a Petri Nets[57] model. The next two figures provides the abstract syntax of the two corresponding languages. These figures are represented as Ecore models, that is EMF's interpretation of OMG's MOF. It is convenient to represent these meta-models as Ecore models since both Henshin and ATL specify transformation rules according to such models.

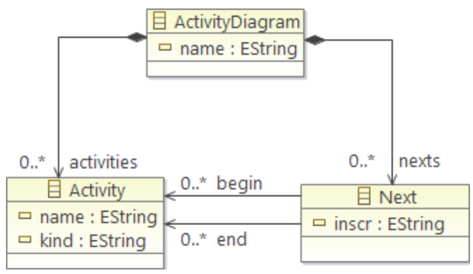


FIGURE 4.2: Abstract syntax that describes the source model.

Figure 4.2 represents a simplified version of a modeling language that is provided by the general purpose modeling language UML. The abstract syntax for the source model has an arbitrary number of activities and next modeling elements. An activity element can have a name and a kind while a next element can have an inscription and can either begin or end activities. The collection of activities and next elements are provided by a specific activity diagram.

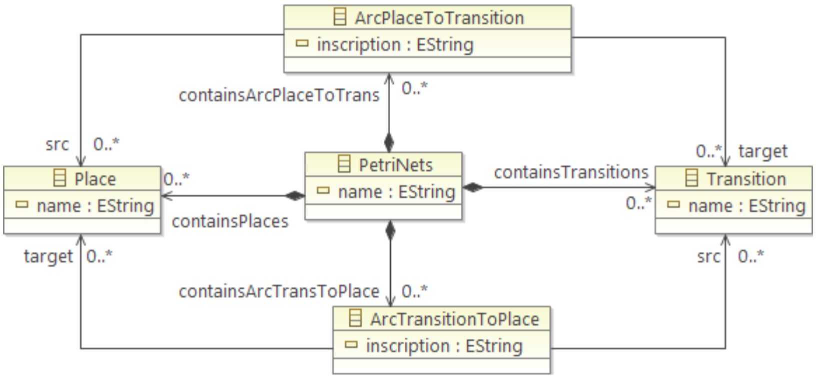


Figure 4.3: Abstract syntax that describes the target model.

The abstract syntax for the target model consist of places and transitions. A Petri net instance must have a place connected to a transition or the other way around, but a Petri net model can never have two of the same modeling types connected. For this test case we defined two nodes that specify if a connection is between a place and a transition or a transition and a place.

Note that these two meta-models are a simplified version of the abstract syntax for the corresponding modeling languages. For this test case we are more concerned with how the different model transformation environments refers to and utilizes the abstract syntax for defining transformation rules. For each tool regardless if the editor provides a graphical or textual syntax we discuss how to edit transformation rules, which is relevant for how we want to design a transformation tool for the DPF Workbench. We then consider how the different tools defines the abstract syntax for both the source and target model. Next we specify how transformation rules are created and if the tool provides any application control for these rules. We finish up by mentioning how the different tools applies a set ot transformation rules. In section 4.3 we consider the model transformation environment that provides a viable model transformation technology that could be integrated within the DPF Workbench.

4.2.1 The Attributed Graph Grammar System

AGG is a general development environment for algebraic graph transformation systems that provides a graphical editor for creating and modifying graphs. The editor provides a graphical user-interface with several visual editors for applying the principles of graph transformations. AGG also provide an interpreter and a set of validation tools. The system is an ongoing research activity of the graph grammar group at the Technical University Berlin and started in 1997.

Graphical Editor

The graphical editor of AGG, represented in figure 4.4, has several functions to help the user to define model transformations. In the top left corner of the graphical user-interface is a tree based editor that provides a set of transformation rules, type graphs, and source graphs. The source graph represents both the source and target model in a model transformation, and the type graph represents the abstract syntax for the modeling languages. The source-target relationship of a source graph is one and the same, but we will discuss this in future sections. For the purpose of this thesis we will refer to the host graph as the source graph, since AGG call these graphs for host graphs.

Each transformation rule has two visual editors, representing the left (LHS) and the right hand side (RHS), also referred to as the pattern and the replacement graph. The tree based editor also provides the possibility to attach application conditions to transformation rules. This is convenient if the user wants to specify constraints that restricts the pattern or replacement graph to be applied accordingly to a specific application condition.

Type graphs are described more in depths in the next section, but basically the type graph defines the abstract syntax for the source and the target model. The users can now create model instances that represents the concrete syntax of a specific modeling language. This representation of the abstract syntax are represented in a source graph and conforms to a corresponding type graph.

The transformation rules can also be extended with Java expressions. This means that the users can use Java primitives such as strings, integers or float numbers to form the pattern graph or the left hand side of the rule. However, the users can only bind attributes that are defined in a corresponding type graph.

Figure 4.4 also represents some node elements and association elements. These are meta elements that are initialized in a type graph and are used to model the source graph, the different transformation rules and the application conditions. Note that both the node elements and association elements in the figure has been scaled up for the purpose of this paper.

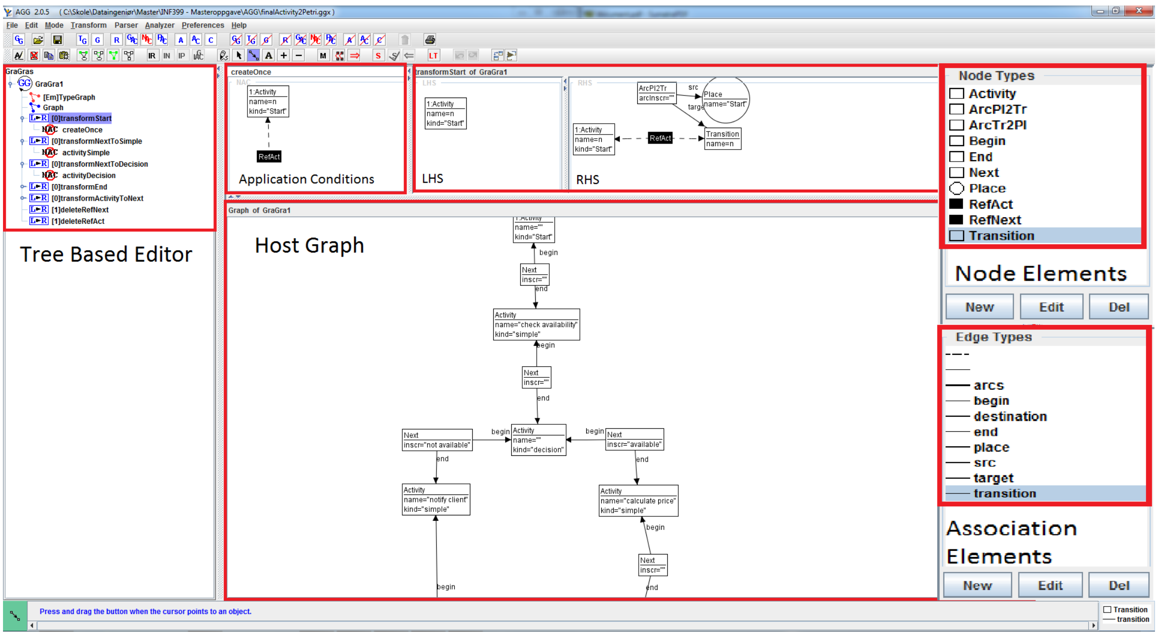


FIGURE 4.4: A model transformation for the AGG Editor.

Defining Meta-models

Before a source graph can be created, we have to specify the modeling language for the source model and the target model. In AGG both the source and the target meta-model are defined in one common type graph, that represents the abstract syntax for both the source and target model. If we want to prepare an AGG graph for a model transformation, we create a type graph with references between source modeling elements and target modeling elements. Because AGG is unaware of the relationship between these modeling elements unless we explicitly initialize them. The relationship between source and target modeling elements in the abstract syntax has two major purposes for an exogenous model transformation in AGG. The relationship specifies how source modeling elements correspond to target modeling elements and determines upon execution of the transformation rules that a matched pattern is only applied once.

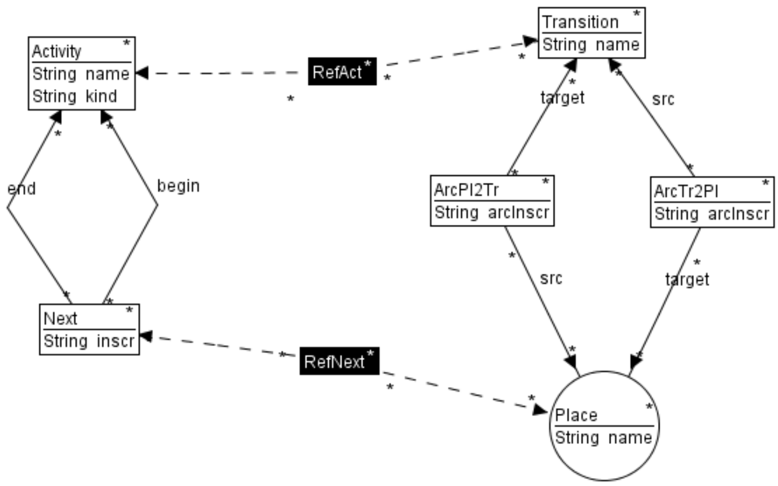


FIGURE 4.5: Type graph for activity diagram and Petri Net in AGG.

Figure 4.5 represents the type graph for our test case. The abstract syntax contains nodes and arrows that include a structural multiplicity constraint. The user defines nodes and arrows for each meta element for both the source and target model that other than defining the abstract syntax also defines the semantics of the two modeling languages. This is achieved by using either the Edge Type Editor or Node Type Editor, which are editors that defines either a node or an edge. The nodes and edges are given names and graphical properties such as colors and a visual representation. Nodes represents modeling elements from the two modeling languages while arrows represents the associations between these modeling elements. In the type graph we want to distinguish between associations and correspondences, and therefore we represent a correspondence between a source and target modeling element as a dashed arrow. The dashed arrow has the same properties as the association arrow between nodes, but the graphical representation is different. This makes the concrete syntax in the source graph easier to read when we are applying the transformation rules. In figure 4.5 we can see that a RefAct node is defined and is connected between the activity element and the transition element. The same initialisation is defined between the next element and the place element. This reference edge specifies that there is a correspondence between Activity and Transition and between Next and Place when the transformation rules are applied. For this type graph there is a structural multiplicity constraint for the nodes and edges. This means that there can be an arbitrary, or a zero to many number of instances of these nodes and edges in the source graph and the translated target graph.

Defining Transformation Rules

Now the type graph has been initialised and the instance graph of the source model has been created. But to be able to translate to a target model, we need to create a set of transformation rules. A transformation rule is initialised with an unique name, an empty LHS graph and an empty RHS graph.

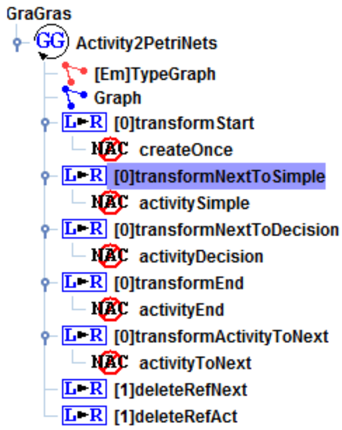


FIGURE 4.6: Tree based editor for transformation rules.

Whenever changes are made in the two graphs, AGG validates if the LHS or the RHS conforms to the type graph. The user is unable to insert elements in the two graphs that are not initialised in the type graph and the users are not allowed by AGG to create associations between nodes that are not initialised in the type graph. This is how the environment keep the source and target models consistent. In figure 4.6 we can see the tree based editor in AGG, that provides the type graph, the source graph and a list of transformation rules. When a new rule is created, both the LHS and the RHS are initialised. The users can then specify a graph structure that forms the LHS graph that AGG use to locate matching patterns in a source graph and a RHS graph, that represents the graph structure that the transformation system produces for each located match. AGG provides two visual editors for these corresponding graphs. However, there is also a graph that represents the intersection between the LHS and the RHS.

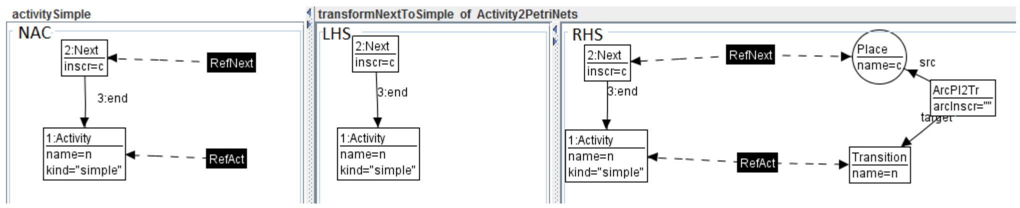


FIGURE 4.7: The LHS and RHS of a rule and a NAC attached.

Figure 4.7 is a representation of the rule transformNextToSimple with the LHS and the RHS graph. The LHS contains the graph structure that is used to locate matches while the RHS contains the graph structure that replaces the located matching pattern. For this rule the modeling elements that are represented in the LHS are also part of the graph structure in the RHS graph. Modeling elements that are part of both the LHS and RHS graph can be mapped together to specify for a transformation engine that these modeling elements defines a graph structure that is an intersection between the LHS and the RHS graph. In section 3.5 we introduced the concepts of single and double pushout of graphs for graph based model transformation tools. A double pushout of graphs includes this intersection graph for a transformation rule that makes it possible to preserve modeling elements that is part of both the LHS and the RHS and to make sure that the gluing condition is valid. Modeling elements that is defined in the LHS graph and not the RHS graph are removed when the AGG transformation engine applies a transformation rule. For example the transformation rule in figure 4.7 locates the graph structure that the LHS defines in a source graph and inserts a new graph structure that the RHS defines in the source graph. This transformation rule will not remove any modeling elements once applied since we have specified that the modeling elements in the the LHS graph are also part of the RHS graph. A rule can also specify application conditions that can either be a Positive Application Condition (PAC) or a Negative Application Condition (NAC). Figure 4.7 has a NAC, activitySimple that makes sure that the LHS of the rule is translated only once for each pattern match found in the source graph. This is because for each applied transformation rule we preserve the LHS graph structure and therefore is a potential match the next time the transformation rule is applied. However, the negative application condition requires that the matching pattern should not contain any references and therefore is not a valid matching pattern. Through the use of these application conditions, the users can create restrictions to how each transformation rule should handle matching patterns in the source graph. A transformation rule can have multiple application conditions attached.

Application Control for the Transformation Rules

In subsection 3.4.3 we specified that the application control of a model transformation environment handles the match location and rule application control. Locating matches in AGG are designed by some non-deterministic search algorithms that the users have no specific control over. AGG does however provide the users with the possibility to explicitly specify how the transformation rules are applied. By default, the transformation rules are applied non-deterministically. This means that there are no pattern to how the transformation rules are applied and the transformation rules can be applied differently on different runs. This option is quite useful if the set of transformation rules are independent of each other. AGG also provides other ways of applying rules such as applying rules by layers or by sequences. When the scheduling mechanism is set to be applied by rule layers, then AGG introduce the users with an integer that specify transformation rules on different layers. This integer will range from $0 \ldots n$, where the lowest number represents the highest property. If there are rules with the same layer number, then these rules are internally applied non-deterministically. If the rules are applied by sequence then the rules will be applied from the first element in the tree based editor and applying the rest of the rules in sequence.

Translating the Source Graph

In section 4.2.1 we described that when applying a transformation rule a matching pattern is located in the source graph, and a graph structure from the RHS is inserted in the same graph. This is special for AGG since the source graph represents both the source model and the target model in a model transformation. AGG's transformation system provides an in-place model transformation directly on the source graph. An exogenous model transformation that is specified in AGG usually include located matches from the source graph in the translated graph for each transformation rule. These modeling elements that represents the abstract syntax of the source model can then be removed through a set of transformation rules after the modeling elements that correspond to the abstract syntax of the target model is translated. This means that for an exogenous model transformation we should be careful when applying the transformation rules non-deterministically to avoid losing data. The user can now either press Start Transformation or perform the transformation one step at the time. For the first option AGG will apply one rule at the time until there are no more matching patterns located in the source graph. When AGG cannot find any more matches, the input graph is either correctly translated or there are errors in the rules. The other option gives the user the same result as the first option, but now the user can do one match at the time for each rule. AGG utilize both the single and double pushout approach when executing transformation rules[37]. Like we discussed in section 3.5 the single pushout approach removes the graph structure from the LHS and inserts the graph structure from the RHS in the source graph. If the rules specifies an intersection graph between the LHS and RHS graph then the double pushout technique is applied. AGG's transformation engine interpret a transformation rule and applies the transformation rule accordingly. Another model transformation environment that utilizes the concepts of graph transformations is Henshin.

4.2.2 The Henshin Project

The Henshin project[58] provides a transformation language and a tool environment for defining model transformations for the Eclipse Modeling Framework. The Henshin project is part of the Eclipse Model Framework Technology (EMFT), that acts as an EMF subproject for new technologies that extend and utilize EMF. The Henshin Editor was initially developed in a student project at Technical University of Berlin in 2010, and extended in the bachelor thesis [59] published by Johann Schmidt and the master thesis [60] published by Angeline Warning. The Henshin project provides a transformation language based on graph transformations that supports both endogenous and exogenous model transformations. With the help of a graphical editor, Henshin provides the user with an intuitive approach to defining transformation rules. The Henshin tool environment also provides a transformation engine and a state space generator.

Graphical Editor

Henshin model transformation environment is integrated as a plugin for the Eclipse Integrated Development Environment[61] and provides a graphical editor to create and modify transformation rules.

The users start out with using the Eclipse wizard to create an empty Henshin document. The Henshin document is based on the commonly known Extensible Markup Language (XML)[62]. If applicable a Henshin diagram file can be created based on the Henshin file that gives the users an intuitive approach to creating transformation rules.

The Henshin transformation file is represented in a tree based editor called the Henshin Model Editor. Figure 4.8 represents the editor that contains a list of transformation rules. These transformation rules are included under a Module element that represents the root element for a Henshin model transformation. For this specific example there are two external Ecore models included in the editor, more specifically the source and target meta-models. These meta-models are created based on the EMF standard for creating models and are independent of each other. Please note that a Henshin model transformation can include 0 . . . n models and therefore is not restricted to have exact one source and one target meta-model.

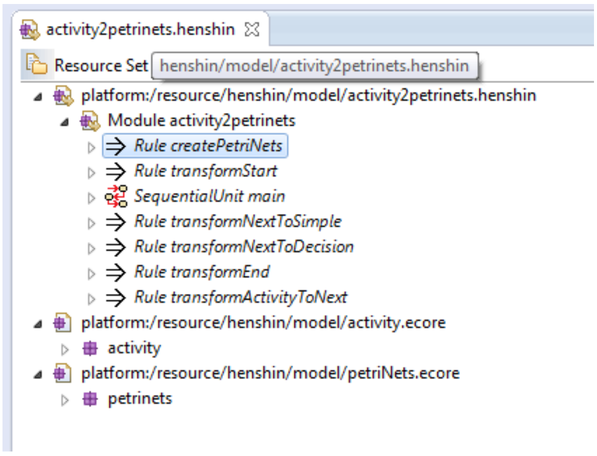


Figure 4.8: Tree Based Editor for rules in Henshin.

Defining Meta-models

The Henshin language requires a source and a target meta-model to be able to perform model transformations. The target meta-model can either be the same as the source meta-model or defined in another modeling language. Either way, before the users can start creating transformation rules, the meta-models has to be defined. To define these meta-models Henshin utilizes Ecore that is provided by the Eclipse Modeling Framework[63]. Ecore models can either be created using a tree based editor called

Sample Ecore Model Editor or by using a graphical editor. While the graphical editor is optional, the tree based editor is mandatory for creating Ecore models.

Initially the user has to create an EPackage element in the newly created Ecore model. Henshin interpret instances of this EPackage as EObjects and is what Henshin searches for when the user want to import an Ecore model. This EPackage element can have several child elements, like for example EClass, EEnum and EData type, but for this specific example we only needed the EClass modeling element. For each EClass modeling element the users can specify an EReference that connects two EClass modeling elements. This means that an EReference element defines relations between the nodes for the meta-models. To give an EClass element properties, the user can create an EAttribute element. This element can be typed, either by a predefined list of types or by defining user created EData types. For the purpose of this case study we only needed to name the different nodes and therefore we only needed the data type EString. Through the use of these Ecore modeling elements we can create the two meta-models from figure 4.2 and figure 4.3 that was previously presented in this chapter.

Defining Transformation Rules

Now we have defined the source and target meta-model for a Henshin module. We can now use elements from the two meta-models to create transformation rules in the Henshin transformation language. In Henshin, objects are referred to as nodes and links between objects as edges. From the meta-models these nodes represents the EClass elements and edges is a EReference between these EClass elements. A collection of these nodes and edges defines a graph structure. Each transformation rule in Henshin specifies two graphs that represent the LHS and the RHS. Note that the graphical editor provides an integrated view to creating transformation rules, and therefore Henshin handles assignment of modeling elements to the LHS and the RHS through the use of stereotypes. Figure 4.9 represents a visualization of the graphical syntax and includes a transformation rule, “transformSimpleActivity”. On the right side there is a tool bar that contains Henshin modeling elements and different EPackages. The first two EPackages represents modeling elements for the source and target meta-model. The Henshin Trace Model provides support for including traceable links for exogenous model transformations in Henshin that keeps track of the translated modeling elements during a model transformation. This model consist of a single class Trace, that has two references called source and target. These references are of type EObject and therefore can refer to any EMF object. The Trace model is generic and therefore supports creation of traceable links between any Ecore models.

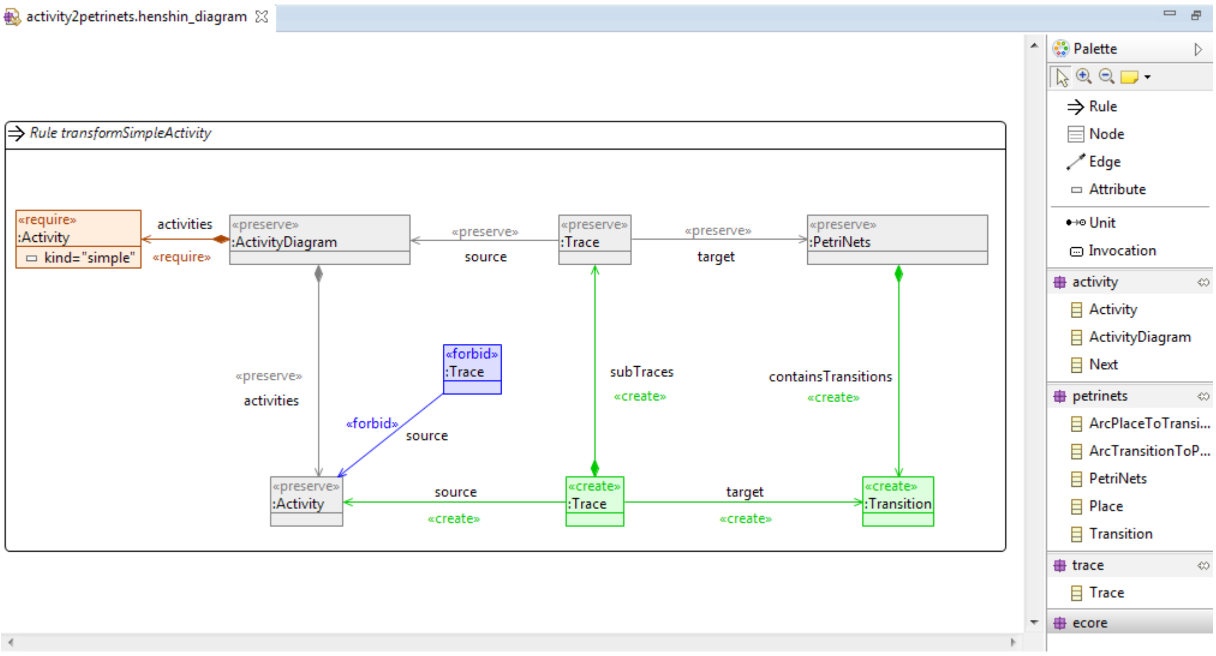


FIGURE 4.9: A rules represented in the Henshin graphical editor.

The Node, Edge and Attribute modeling elements are used to define the different transformation rules in Henshin. A new transformation rule in Henshin always have to start with creation of a new Rule element. Inside this Rule element the users are free to create nodes and define relationship between these nodes with edges. These modeling elements are required to be created accordingly to a corresponding meta-model. The nodes and edges defines a graph structure that is used to either locate matches in a source model or translate to target modeling elements. Note that the Node and Edge are special modeling elements for Henshin and are used to create the content of the transformation rules. The Node element has a type that correspond to an EClass while the Edge element has a type that correspond to an EReference. The Ecore models that are represented in figure 4.9 has a list of modeling elements that are typed by EClass. These modeling elements are a shortcut for Henshin that creates a Henshin node with a corresponding EClass type. The Attribute element can be used if attributes are defined for the classes that are imported. We will come back to the Unit element in the next section. Henshin distinguish if nodes, edges or attributes are part of the LHS and the RHS through the use of predefined stereotypes, or action types. Based on these action types Henshin automatically specifies if these modeling elements defines a graph structure that is used to locate matches in a source model or produce modeling elements for a target model. If the action type consist of the sequence “create”, Henshin knows that this element should be part of the replacement graph, or the RHS. While on the other side, the sequence “delete” should be part of the pattern graph, or the LHS. The “preserve” sequence is a bit more special, because nodes or edges in Henshin that is specified by this action type should be part of both the LHS graph and the RHS graph. This is done by putting the preserve element in both graphs and then create a mapping between these two elements to inform the Henshin Interpreter that this represents the same element. Henshin also has support for application conditions through the action types “forbid” and “require”, that are used for defining Negative Application Conditions (NACs) and Positive Application Conditions (PACs). These actions are supported for nodes, edges and attributes. The example rule in figure 4.9 use four of these action types. The modeling elements in gray represents modeling elements that are part of both the RHS and the LHS graph, while the modeling elements in green are specified in the RHS graph. This specific transformation rule will locate a matching pattern in a source model that is described by an Activity modeling element. The positive application condition specifies that Henshin only should locate matches that is of kind “simple”. The negative application condition specifies that a located match that is described by the Activity class should not have a traceable link. The NAC specifies that the transformation engine does not locate duplicate matching patterns. The first time a match is located a traceable link is established. Now this specific match is no longer a valid match since the NAC forbids the transformation engine to locate matches that already has established a traceable link to this modeling element. Note that we have a Trace and a PetriNets that is both a preserve modeling element. This is because these two are already translated by an already applied transformation rule. The transformation engine provides in-place transformations for exogenous model transformations and an already applied transformation rule has translated the Trace and PetriNets modeling element and are now part of the source model. The transformation engine can now include these translated target modeling elements in search patterns for other transformation rules.

Application Control for the Transformation Rules

Transformation units are used to administrate the different transformation rules. Henshin provides several different units with different properties. Note that a transformation rule is also a transformation unit. This means that it is unnecessary to create an unit in Henshin if a model transformation only consist of a single transformation rule. However, if there are more than one transformation rule there has to be a control mechanism that determines how these transformation rules should be applied. An Independent Unit applies rules non-deterministically, which is a good solution if the order of applying the transformation rules is not important and the rules are independent of each other. But if the transformation rules requires a very strict pattern and are dependent of other rules, then a sequential unit are a safe way to apply rules. The sequential unit forces the Henshin transformation engine to apply rules in a sequenital order. Figure 4.10 is an example of a sequential unit that will start applying rules at the black circle and follow the arrow through each given rule until it is finished.

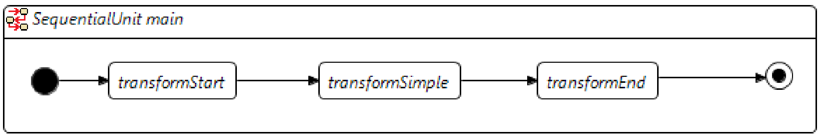


FIGURE 4.10: A SequentialUnit main that contains a sequence of rules.

If applicable a transformation unit can also consist of other units, for example if the user want to either iterate or loop through a transformation rule. The previous section described an example of a rule in figure 4.9. The sequential unit in figure 4.10 includes a LoopUnit “transformSimple” while the “transformStart” and “transformEnd” represents a single rule. The loop unit applies a single transformation rule until there are no more matches found in a source model. This is convenient for the rule, “transform-SimpleActivity” since we specified that the rule should only locate matches where there exist no traceable link. Henshin also has two other units that can administrate transformation rules, namely ConditionalUnit and PriorityUnit. The ConditionalUnit follows an if-else pattern, and is used if the user want Henshin to choose between two units.

Translating the instance model

Now that we have defined the source and target meta-model, created a set of transformation rules and initialised a control mechanism for these rules it is time to apply the transformation rules. For Henshin there is two ways to do this. In Henshin the default engine for executing model transformation is the Henshin interpreter. This interpreter can be invoked either by using the an Eclipse wizard or programmatically using the Henshin API.

Using the Eclipse wizard is done by opening the Henshin file in the Henshin Model Editor and right clicking the root object and apply transformation. This will open a wizard where the user can choose a transformation unit, which will either be a single transformation rule or some transformation unit that applies other units or rules. The user also has to select the instance model and can explicitly set parameters for the rules if this is applicable. Now the user has two choices, the first choice is to preview the result of the model transformation. This will either show the user a new window with the modifications to the model or a message that the rule or unit could not be applied. If the user press Transform instead of Preview, the model will be transformed and saved.

The interpreter can also be invoked programmatically, either as an Eclipse based application or as a simple Java application. Henshin provides an API that lets the users invoke the interpreter through the use of Java code and use the strengths of Henshin in their own program. There is a class HenshinResourceSet that lets the user load and save models and load a Henshin model transformation. When the instance model and Henshin module is loaded into the resource set, the transformation can be applied through the use of the Henshin Engine class. This is where Henshin finds and translates matches found in the instance graph. The user also has to specify the main transformation unit from the Henshin module. Both the engine and the unit can be loaded into the UnitApplication class. This class has a method that lets the user execute the model transformation. If the transformation was executed without errors, then the instance model can be saved with the translated changes.

4.2.3 ATL Transformation Language

ATL[32] (ATL Transformation Language) provides a model transformation language and is an implementation of the QVT[29] standard. It provides ways to produce a set of target models from a set of source models. ATL is maintained by OBEO[64] and AtlanMod[65] and was first initiated by the AtlanMod team, previously called the ATLAS Group, located at the University of Nantes in France. The initial version of ATL was created in 2004, where ATL later became part of the Eclipse Generative Modeling Technologies (GMT) [66]. The goal of GMT is to produce a set of research tools in the area of Model Driven Software Development. The ATL Integrated Development Environment (IDE) was later promoted for the Eclipse M2M project in January 2007.

There are developed several tools that has support for a declarative approach to model transformation. ATL is a hybrid model transformation approach, which is a transformation language that combines other model to model transformation approaches. For example, ATL provides transformation rules that can be either fully declarative or fully imperative or a mixture of both.

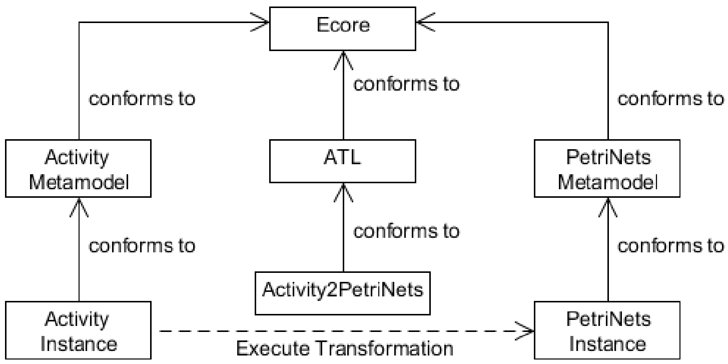


Figure 4.11: Model transformation process for Activity2PetriNets.

Figure 4.11 gives us an idea of how the ATL transformation from an activity diagram to Petri net are handled. We want to generate an instance model of PetriNets that conforms to its own meta-model. This is generated from a source model, Activity Instance that conforms to its respective meta-model. The created transformation Activity2PetriNets is expressed in the ATL transformation language, that conforms to its own meta-model. These three meta-models conform to the meta-model Ecore. So this makes Ecore a metameta-model to represent the meta-models of Activity, ATL and PetriNets.

ATL has to be configured properly before the user can execute a model transformation. In this configuration both the location of the source and target meta-model requires to be implicitly specified. The user also has to specify the instance model that should be translated, and create a new file that can be specified as the target instance model for the ATL run configuration. The user can then initiate the transformation by running this as an ATL transformation.

Textual editor

ATL can be compared to a programming language, because it basically is a transformation language that provides a concrete textual syntax. ATL is a text based transformation language, and is build around the Object Constraint Language (OCL) [14] with some additional predefined functions. ATL transformations is stored in a file extension called *".atl"*. These ATL files can contain different kind of ATL units and are defined in its own distinct ATL file. These different ATL units are ATL modules, ATL queries and ATL libraries. Libraries can be used to create independent ATL libraries that can be imported and used in different ATL units. The module unit specifies the different application rules for a model transformation and queries are used when the users want to compute primitive values from the source models.

Now that we have specified these three ATL units, we can shortly describe how we can use the ATL transformation language to create model to model transformations. For our case study, we only need the ATL modules. This unit enables developers to specify a set of rules that produces a set of target models from a set of source models. The source and target models of an ATL module must be consistent with their corresponding meta-models.

Defining Meta-models

Defining meta-models for the ATL language is defined by the modeling language Ecore. Since the meta-models are defined similar to Henshin, see section 4.2.2 for more details.

At first, the user start out with a blank ATL file. Since we are working in the ATL Integrated Development Environment for Eclipse, we want to start the document with defining the path to the source and the target meta-model. The reason for doing this is to achieve auto completion for modeling elements defined in the Ecore meta-models, which is convenient for the users when creating transformation rules.

activity2petrinets.henshin activity2petrinets.henshin_diagram Activities2Petrinets.atl

```
-- @path Petrinets=/activity2petrinet/petriNets.ecore
-- @path Activities=/activity2petrinet/activity.ecore

module Activities2Petrinets;
create OUT : Petrinets from IN : Activities;

rule Activity2StartPlace {
    from
        a : Activities!Activity (a.kind = 'start')
    to
        p : Petrinets!Place (
            name <- a.kind
        ),
        t : Petrinets!Transition (
            name <- a.name
        ),
        a_t : Petrinets!ArcPlaceToTransition (
            inscription <- '',
            src <- p,
            target <- t
        )

}

rule Activity2EndPlace {
    from
        a : Activities!Activity (a.kind = 'end')
    to
        p : Petrinets!Place (
            name <- a.kind
        ),
        t : Petrinets!Transition (
            name <- a.name
        )
}
```

FIGURE 4.12: Two simple rules for Activity2PetriNets in ATL.

Next the file is composed of a header section, where the user can give the module a name and specify the source and target meta-models. Note that the module name has to be identical to the name of the ATL file for the transformation engine to be able to extract the information.

We also need to specify the source and the target meta-model. From figure 4.12 we can see that the target meta-model is initialised with the keyword create, and the source meta-model is initialised using the keyword from. The user can also import some existing libraries if needed. This import section is however optional. Importing meta-models are handled a bit differently in ATL compared to Henshin. In ATL the meta-models are imported explicitly while in Henhsin they are imported implicitly before they can be used in modifying the transformation rules. For ATL the user has to configure where both the source and the target meta-model are located through a configuration page.

The next element is a set of rules that defines how the target models are generated from the source models. These rules are used to implicitly match source modeling elements and produce target modeling elements. In figure 4.12 we have examples of two rules, namely the rule for transforming the start activity and the rule for transforming the end activity. We can see that for each rule we specify what we want to translate from and what we want to translate to. We will describe transformation rules in more details in the next section.

The last element in a ATL module is a set of helper functions. This collection of helpers can be compared to Java methods and can be used to make the transformation rules easier to read.

Transformation Rules

A rule in ATL describes how a target model should be generated from a source model. In ATL there are three different types of rules, the matched rules and the lazy rules are both fully declarative while the called rules are imperative. These rules have an input pattern and an output pattern that consist of variables that specifies the different source and target modeling elements. The input pattern can have a list of source modeling elements that is part of a rule by defining a new variable for each different modeling element. Each input pattern element requires a mandatory type that corresponds to a meta-class defined in a corresponding meta-model. The output pattern defines how the target model elements are created from the input model.

The matched rules provides an declarative approach to creating transformation rules in ATL. The users can specify from which kinds of source modeling elements the target modeling elements can be generated from and how the generated target modeling elements should be initialized. A matched rule locates a match according to the type of the source modeling elements and generate target modeling elements from these matches. A new matched rule is defined by the keyword “rule” and has two mandatory and two optional sections. The mandatory sections specifies the input pattern and the output pattern while in the first optional section the users can declare and initialize local variables. Note that these variables can only be used within the scope of a rule. The second optional section includes an imperative section if the users want to specify the behaviour of a rule. The type that is introduced in the input pattern conforms to a meta-element in a meta-model of the source model. This rule will then generate target elements according to each match in the source model.

Figure 4.13 shows a simple rule, Activity2StartPlace that translates Activity source elements to some target elements. This rule specifies the keyword *from* for the input pattern and *to* for the output pattern. For this example we want to find matches for one source element that is of type Activity that conforms to the meta-model Activities. We also provide additional properties for this input source element, where we only want to find matches that conforms to the type Activity and has the name “start”. The rule specifies that we want to generate three target pattern elements p, t and a_t from this matching type. These generated target elements conforms to the meta-model Petrinets and specifies that these generated types should generate attributes from the source pattern element. The generated target model elements is initialized with attributes from the matched source pattern element.

```
rule Activity2StartPlace {
    from
        a : Activities!Activity (a.kind = 'start')
    to
        p : Petrinets!Place (
            name <- a.kind
        ),
        t : Petrinets!Transition (
            name <- a.name
        ),
        a_t : Petrinets!ArcPlaceToTransition (
            inscription <- '',
            src <- p,
            target <- t
        )
```

FIGURE 4.13: An example of a matched rule in ATL.

If applicable the users can add an optional condition for each rule to check for certain matches for this input element. This condition is expressed as an OCL expression and gives the user the possibility to restrict the searches of the source elements.

The second type for ATL rules are **Lazy rules**. These lazy rules will never be applied when a model transformation in the Atlas Transformation Language is executed unless they are applied at runtime by either a matched or a called rule. These lazy rules are created similar to the matched rules.

The third and final type for ATL rules are **Called rules**. A called rule has to be called from an imperative section from a rule. A called rule is created similar to a matched rule, namely with a *rule* keyword. One thing that is special with a called rule is that it does not have to match source elements from the source model. A called rule can for example include an imperative section for a matched or lazy rule that defines the semantics of the rule.

Execution of an ATL transformation

Figure 4.14 describes the architecture of the transformation language. From the figure we can see that we have an association between EMF and Ecore models. This are the meta-models that are expressed using EMF's Ecore model. These meta-models are then translated through a model handler that compiles these Ecore models to the ATL Virtual Machine, where these meta-models can be used both in creating ATL programs and in ATL's internal interpreter. The ATL compiler translates the ATL file into a new ASM assembler file that ATL can use to launch a model transformation. This assembler file contains the compiled code of the corresponding ATL file.

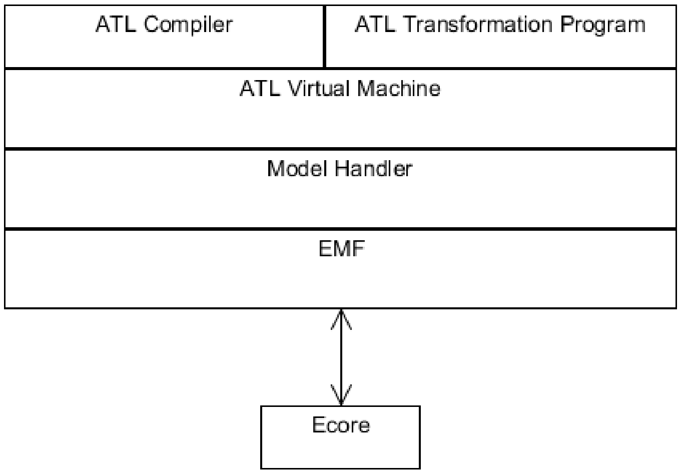


Figure 4.14: Internal infrastructure of for ATL.

The default semantics for executing a set of transformation rules specified in ATL can be described in three phases. Consider ATL User Manual[56] for more detailed information.

The first phase is an initialization phase. This phase consist of amongst other things to initialize the trace model and the module of an ATL transformation. The trace model in ATL has one important function, and that is to create a trace link that points to the matched source input elements and the corresponding generated target output elements. The traceable model in ATL works as an implicit tracing mechanism that specifies relationships between the source modeling elements and its corresponding target modeling elements by using a native type called ASMTransientLink[43]. For every time a transformation rule is matched to a source element, one ASMTransientLink is created that includes the name of the rule, a source modeling element and a target modeling element. These links are added to a collection that is stored internally for ATL. This means that the users of ATL cannot access these links after a model transformation has finished executing. However, as shown by Andrés Yie and Dennis Wagelaar[43], that gaining access to these ATL traces can be done explicitly by creating transformation rules that generates a tracing model based on the internal tracing information provided by ATL.

The next phase consist of finding matches in the source pattern based on the matched rules. This is done by the ATL transformation engine that applies a searching algorithm to locate valid matches. A match is valid when all input pattern elements are found amongst the source modeling elements and any OCL expression for that matched rule is valid. The transformation engine also allocates the target model elements based on the declared output pattern into memory. At this point the target modeling elements are only allocated, they are later initialized in the final phase. For each match found, there is created a traceable link that has a source link to the matched source modeling elements and a target link to the generated target modeling elements. The generated target elements are not given any attributes or properties in this phase. This phase creates target modeling elements from matches found and define traceable links that relates source and target modeling elements.

The final phase for executing an ATL module is to initialize the target modeling elements. At this stage each allocated target modeling element is given attributes and features that corresponds to the matched rule. The ATL transformation engine now use the traceable links to determine the matched source modeling elements and the generated target modeling elements. This operation is called resolveTemp, which returns the reference from the target modeling elements that where generated in the second phase to the corresponding source modeling element. Now that these three phases is finished the ATL transformation engine can execute the imperative code sections defined for the module and successfully finish a model transformation.

4.3 Model transformation environment for DPF

After working with the three model transformation environments in the previous section we decided go for a solution to integrate Henshin with the DPF Workbench. In this section we will describe why Henshin is best suited to be integrated with DPF. In this section we will describe why Henshin is the better choice of the three considered environments to be integrated with DPF. Henshin[25, 58] is a relatively new installment in the world of model transformations. Henshin was initially created three years ago, in 2010 and is marked as an Eclipse Incubation project. The purpose of the incubation phase is to establish a fully functional Eclipse plugin. In theory an integration of Henshin with DPF should be possible, since Henshin applies model transformations based on Ecore models and DPF specifications are basically represented as Ecore models. This presents a problem with integrating AGG with DPF since AGG does not employ Ecore modelsS. In EMF the root of all modeling objects is an EObject that has no references to a Java Object. AGG could be integrated with DPF, but the problem is that this would require an extensive amount of manual coding. We could use AGG as a general purpose graph transformation engine in a java application. We would have to create the source model as an AGG graph and a type graph based on the source and target modeling formalism that DPF provides. AGG provides an API that conveniently let us create type graphs, source graphs, transformation rules and application conditions.

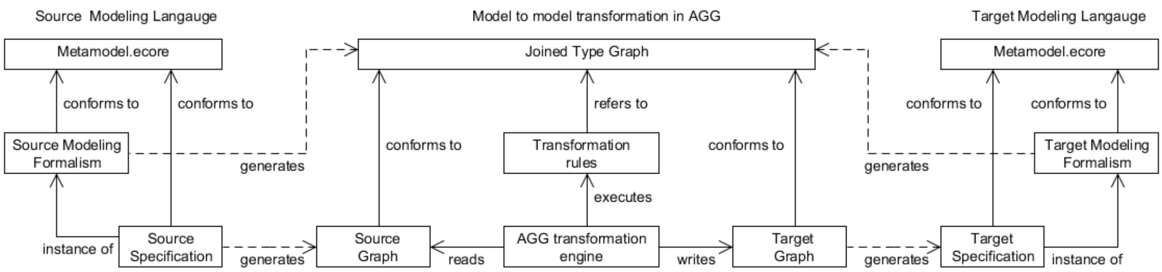


FIGURE 4.15: Proposed solution for integration of AGG with the DPF Workbench.

Figure 4.15 represents a proposed solution for how to integrate AGG together with the DPF workbench. The figure represents a source modeling formalism on the left side, a target modeling formalism on the right side and a model to model transformation done with AGG in the middle. The figure illustrates that we have to generate four models to be able employ AGG for a model to model transformation in DPF. First we create the abstract syntax for AGG source graphs by generating a joined type graph from a source modeling formalism and target modeling formalism. Then we have to generate the source specification into a source graph that at the same time conforms to the joined type graph. Note that we do not mention the transformation rules since we have to generate these regardless of what model transformation environment we integrate with the DPF Workbench. After the AGG transformation engine has executed the transformation rules we have to generate a target specification based on the translated target graph. This leads to some potential problems. The program that generates a source graph and a target specification has to be solid and not contain any flaws or bugs. Another problem is to keep the models consistent throughout the model transformation. How can we be certain that the target graph is consistent with the target specification? It is easy to lose consistency when changing a model manually from a target graph to a target specification. We could use AGG to do this, but that leads to many potentially factors that could go wrong. For both Henshin and ATL we are not required to do anything extra with these models. Since both environments has support for including Ecore models as meta-models and requires an instance model of an Ecore model as a input model to apply a model transformation. Therefore AGG can be integrated with EMF with some additional work, but Henshin and ATL is a more viable choice for DPF, since we can use the "Metamodel.ecore" as a meta-model and a source specification as input model directly in the other two environments.

Now we need to decide if we want to try and integrate the hybrid model transformation environment, ATL or the graph based model transformation environment, Henshin. In section 2.4 we discussed that a DPF specification is an extension of the Generalised Sketches formalism that is basically a directed graph. A model transformation in Henshin is based on the concepts of graph transformations and category theory. We can then be certain that Henshin can interpret a source specification as a directed graph. Henshin transformation language is also based on the two graph transformation styles single (SPO) and double pushout (DPO) that we discussed in section 3.5. And we recall that the DPO approach provides a dangling condition that ensures that a model transformation does not result in any edges that are missing a source or a target node. We want to create a tool for the DPF Workbench that provides the following.

- *Concrete Graphical Syntax.* We want to be able to create transformation rules based on the graphical syntax that the DPF Model Editor provides.
- *Generic.* We want our tool to work for an arbitrary source and target modeling formalism regardless of abstraction layer.

The tool is required to create a set of transformation rules based on some model transformation language and we want these transformation rules to be generic. This means that we create a set of transformation rules based on an arbitrary source and target meta-model. The only aspect of these meta-models that is consistent is that they contain a list of nodes and arrows. This means that regardless of abstraction layer a specification is specified by a set of nodes and arrows. The reason for why we decided to integrate Henshin within the DPF workbench is provided in the three following points.

1. We want to create a tool that use a simplified version of the DPF Editor to create transformation rules that provides a concrete graphical syntax. DPF models are already based on category theory and provides a graphical syntax.

2. Through the use of the Henshin meta-model we can generate a set of transformation rules that are based on the abstract syntax of the source and target specification. We can define a set of transformation rules in Henshin as a java application with the help of the API that Henshin provides.

3. We can utilize the concepts around graph transformation that provides a left hand side, a right hand side and an intersection graph. Through these three graphs we can in Henshin use the single or double pushout approach when applying a set of transformation rules.

The problem with integrating Henshin with DPF is that Henshin is based on the EMF technology, and therefore utilize OMG's MOF. Henshin supports out of the box model transformation that translate instance models that conforms to an Ecore based meta-model. These instance models provides the concrete syntax of a modeling language and are described by a corresponding meta-model that represents the abstract syntax. This meta-model is provided accordingly to the second layer of the Meta-Object Facility. This means that Henshin provides model transformation according to EMF's two layered modeling environment. DPF on the other hand provides initialisation of a potential endless hierarchy of meta-modeling, and therefore does not match the steps MOF provides to create the abstract syntax for a Domain Specific Language. We know that a transformation rule in Henshin requires references to meta-modeling elements from a source meta-model and a target meta-model. What makes a DPF specification special is that it is an instance model of both an Ecore based meta-model and another DPF specification. This means that a specifications concrete syntax is defined by the abstract syntax of a specification that is one abstraction layer higher. In DPF we can create an arbitrary level of meta-models and therefore two different Domain Specific Modeling Language can be defined in different abstraction layer hierarchies. The Henshin environment has strict guidelines on how models are imported and used. These models are required to be created accordingly to the Ecore model provided by EMF. Henshin can then utilize these models to create a graph pattern that structure both the LHS and the RHS graph of a transformation rule. The LHS graph contains a graph structure that is is used by the transformation engine to locate matches in an instance model that conforms to a specified Ecore model.

For our tool we can structure a set of transformation rules in Henshin based on this common meta-model, *Metamodel.ecore* that all specifications $\mathfrak{S}_{1...n}$ conforms to. We have to threat all specifications similar if we want the tool to provide a generic model to model transformation environment. The challenge with integrating Henshin in a language workbench that provides meta-modeling at arbitrary layers of abstraction is not in the source specification we want to translate, but in the specification that the source specification conforms to one abstraction layer higher. This proves to be a problem for Henshin, because we cannot import an instance model of an Ecore based meta-model into the Henshin model transformation environment. We can do changes to an instance model by using Henshin, but the transformation language can only import and utilize models that conforms to the Ecore meta-model. To solve this for DPF specifications we expand transformation rules in Henshin with application conditions. This means that we restrict the LHS graph to locate matching modeling elements in an instance source specification based on the abstract syntax that another specification provides. The next chapter provides an explanation of how we integrated Henshin for a transformation tool that provides model to model transformations for the DPF workbench.

Chapter 5

Implementation

5.1 Integrate Henshin with DPF

DPF is a framework where a domain specific modeling language can be defined over several layers of abstractions. A specification $\mathfrak{S}_{n+1}$ defines the abstract syntax for a specification $\mathfrak{S}_n$ at some abstraction layer. The semantic behavior for a DPF specification $\mathfrak{S}_n$ is defined through model transformations that can specify different changes done to the specification. There are already a natural model transformation provided in DPF, and that is when a new specification is created by the DPF Model Editor. A graph homomorphism is specified between modeling elements in the newly created specification and modeling elements provided one abstraction layer higher. In section 3.1.1 we described some model transformation examples according to different abstraction layers. DPF does not provide support for an exogenous model transformation that translates a specification described in one domain specific modeling language to a model expressed in another domain specific modeling language. A new specification will always be specified by a modeling language that corresponds to a modeling formalism $\mathfrak{S}_{n+1}$ one abstraction layer higher. These specification may either be a user created specification or the default specification provided by the framework.

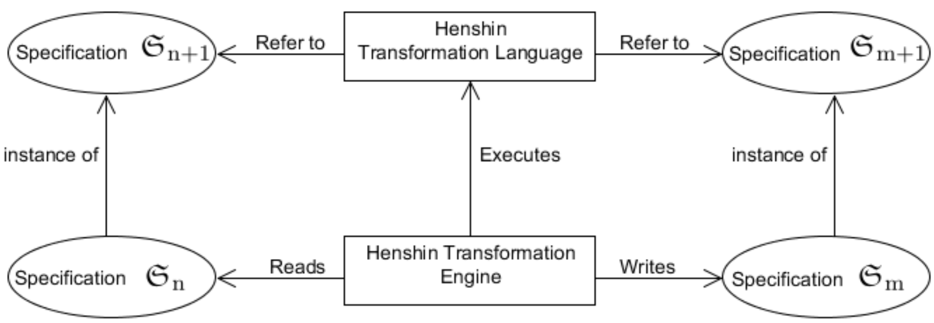


FIGURE 5.1: Using Henshin transformation language to translate a specification $\mathfrak{S}_n$.

Figure 5.1 explains at top level how we want to integrate the Henshin model transformation language with the Diagram Predicate Framework. Henshin provides a transformation language and a transformation engine. We use the Henshin transformation engine to read an instance specification $\mathfrak{S}_\mathrm{n}$ and write an instance specification $\mathfrak{S}_\mathrm{m}$. To achieve this the transformation engine executes a set of transformation rules written in the Henshin Transformation Language. These transformation rules refers to the abstract syntax that is specified in the modeling formalism $\mathfrak{S}_{\mathrm{n}+1}$ and the modeling formalism $\mathfrak{S}_{\mathrm{m}+1}$ that the source and target model conforms to.

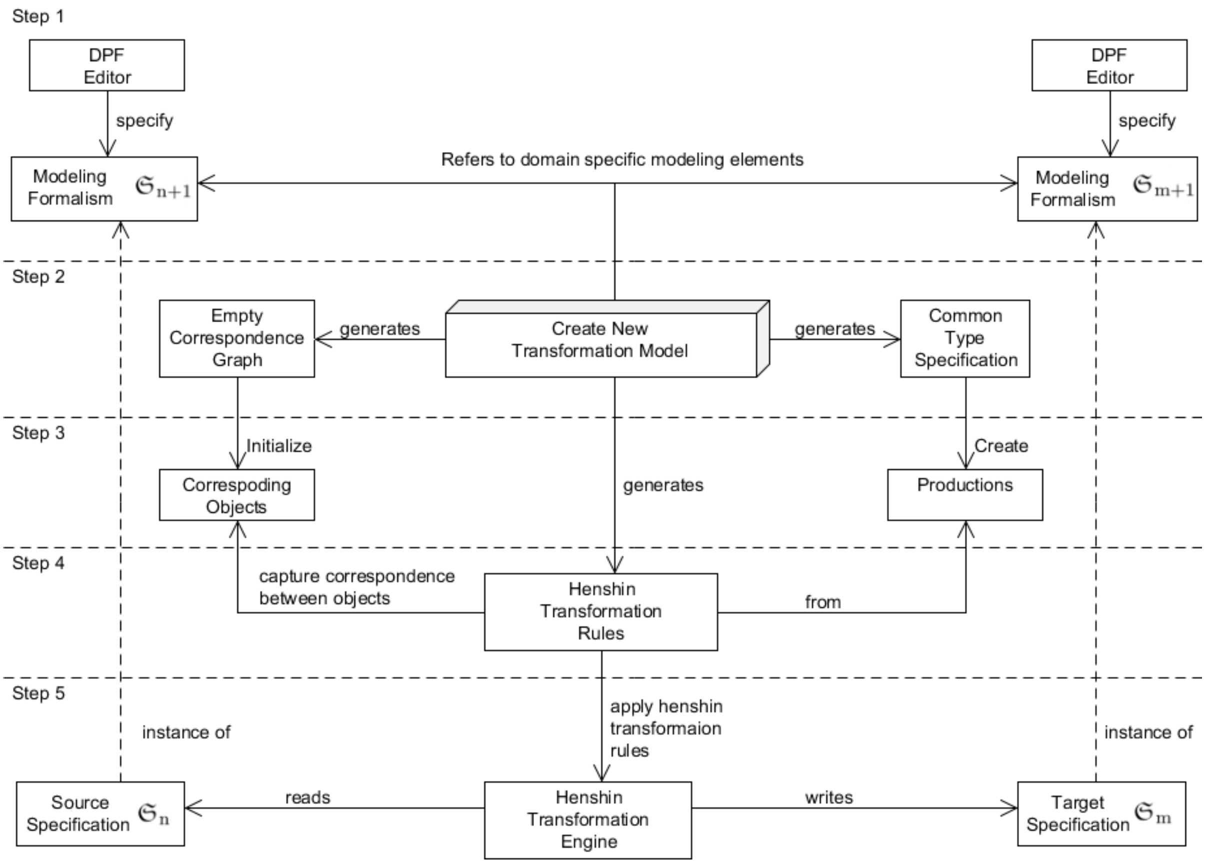


FIGURE 5.2: Progressively workflow for the problem solution.

Figure 5.2 provides a diagram that is extended from the previous figure 5.1. The diagram describes in five steps how the editor progress from creation to execution of transformation rules. The figure then explains that step 5 use the Henshin transformation engine that reads a specification $\mathfrak{S}_\mathrm{n}$ and writes a specification $\mathfrak{S}_\mathrm{m}$. But before we can apply the actual transformation we have to consider how the DPF Transformation Editor provides a set of Henshin transformation rules.

1. At the first step we still have to provide a source modeling formalism that contains a specification $\mathfrak{S}_{\mathrm{n}+1}$ and a target modeling formalism that contains a specification $\mathfrak{S}_{\mathrm{m}+1}$. These specifications has an underlying graph that contains nodes and arrow that represents the abstract syntax for the source and target specification.

2. Step 2 consist of creating a new transformation model in the DPF Transformation Editor. This new transformation model has references to a source modeling formalism $\mathfrak{S}_{\mathrm{n}+1}$ and a target modeling formalism $\mathfrak{S}_{\mathrm{m}+1}$. With both the target and source modeling formalism we create a $\mathfrak{S}_{\mathrm{n}+1} \cup \mathfrak{S}_{\mathrm{m}+1}$ specification that we use for typing purposes for the transformation rules. An empty correspondence graph is also generated.

3. Step 3 focus on creating the transformation rules through defining a set of productions, where one production represents one transformation rule. A single production specifies a LHS, RHS and an intersection graph that refer to this common type specification, $\mathfrak{S}_{n+1} \cup \mathfrak{S}_{m+1}$. At the same time corresponding objects are initialized by the user to specify the relation between source modeling elements and target modeling elements.

4. In step 4 we generate a set of Henshin Transformation Rules from these productions and capture the correspondence between objects by specifying traceable links.

5. In the final step we can apply these transformation rules to a Henshin transformation engine and produce a target specification $\mathfrak{S}_m$.

One major challenge was processing Henshin transformation rules from modeling elements that is represented in the source and target modeling formalisms. These five steps describes the workflow of the DPF Transformation Editor. In the next sections we will explore the most essential functionality of these five steps and explain how we can integrate Henshin with the DPF workbench. But first we will describe how a transformation rule is modelled in the Henshin model transformation language.

5.2 Henshin meta-model

The Henshin transformation language provides a meta-model that is an EMF based model and uses the Ecore meta-model for typing purposes[67]. Since this model is created based on EMF we know that EMF will generate interfaces and a factory that we can utilize to implement Henshin transformation rules in Java. We can specify a pattern graph and a replacement graph for each transformation rule based on the factory class that the Henshin API provides. In the following we will address what elements a transformation rule consist of based on the Henshin meta-model for a transformation rule represented in figure 5.3. The figure is obteined from a paper that Thorsten Arendt, Enrico Biermann, Stefan Jurack, Christian Krause, and Gabriele Taentzer published in 2010 on the Henshin transformation language where they provide the meta-model for defining a single transformation rule[67].

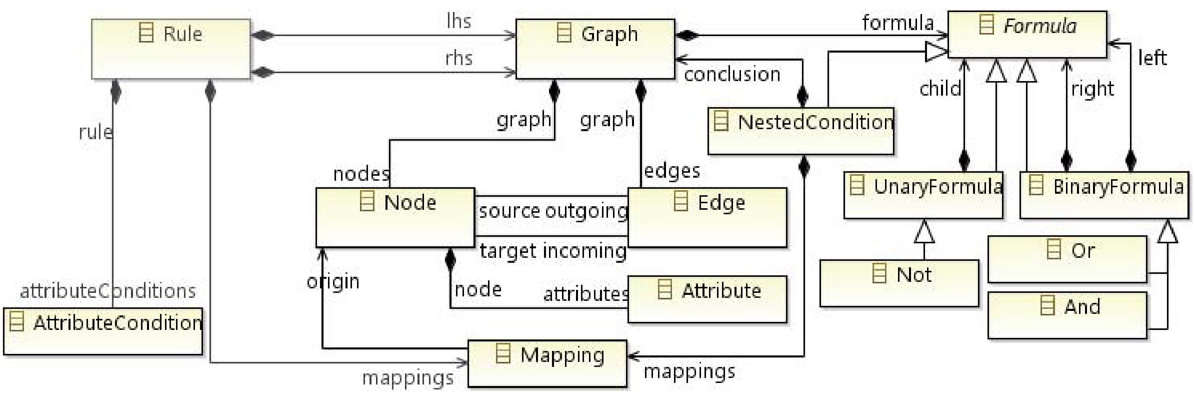


FIGURE 5.3: Henshin meta-model for a transformation rule.

A **Rule** in Henshin represents a transformation rule that has a name, a description and three properties. The first property disables or enables the transformation rule, while the two other properties lets the user enable or disable injective matching and the check dangling condition. The rule class works as the root for all other modeling elements that are represented in figure 5.3. A new rule defines a left hand side and a right hand side **Graph**. The LHS and RHS graph is formed by creating nodes and edges. Nodes refers to objects in an instance graph and edges refer to references between objects. An edge has a source and a target node, while a node can have a collection of incoming and outgoing edges. The nodes can also have a set of attributes attached. Nodes, edges and attributes all have two common properties, and the first one is that they all have a type.

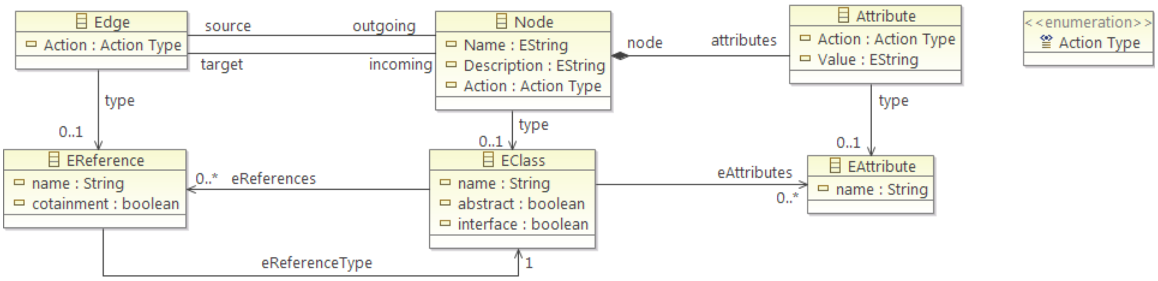


FIGURE 5.4: A simplified subset of the Ecore meta-model.

Figure 5.4 represents a small fraction of the Ecore meta-model and how Henshin modeling elements are typed by either an EClass, EReference or EAttribute. For example a Node that is typed by a specific EClass will only be matched to objects of this type in an instance model. These nodes and edges are represented under a graph and form a pattern. Together with the LHS and the RHS these patterns is either used to find matching patterns in a source model or to create the corresponding pattern for a target model. The second property that these three have in common is that they have an action type. Action types are predefined stereotypes for Henshin that specifies the semantics of a transformation rule. An action type could specify if a graph modeling element is part of an application condition, the RHS, the LHS or an intersection graph. A **Mapping** specifies how Henshin defines the intersection graph. This is Henshin modeling elements that should be included in both the LHS and the RHS graph. This means that these ojects should be part of the matching pattern, but should not be deleted. A mapping has two properties, namely an origin and an image. The origin property refers to a given node from the LHS graph, while the image property specify a mapping to a node in the RHS graph.

A rule can also specify a **Formula**, that determines restrictions for match searching for a specific rule. A Formula modeling element is a child of a graph and defines an application condition in Henshin. This formula class can either be defined as an u-nary logical operation, a binary logical operation or a nested condition. The first logical operation operates on a single operand while the second operates on two operands, where these operands are represented as a conditional statement that is either true or false. A rule can be applied to an instance model if and only if all application conditions are valid. We can basically have an unlimited nested formulas in Henshin, since a binary formula can have a right and a left **Formula**, that again can be a binary formula. Henshin however is only concerned whether this formula is valid or invalid when a specific transformation rule is applied. A nested condition provides a graph and a set of mappings to modeling elements that are part of the LHS or intersection graph. This graph is a child of a nested condition and contains nodes, edges and attributes that form a structural pattern that specifies the application condition. We can observe that transformation rules can have several number of application conditions. A binary formula can be of type **Or** or **And** and provides the possibility to nest other binary formulas. If the structure of a binary formula is the latter, then all the application conditions in a binary formula has to be valid for a located matching pattern.

5.3 DPF Transformation Editor

With the Eclipse Modeling Framework we created an Eclipse plugin where users can create and modify transformation rules. Figure 5.5 provides the structural data model that we use to generate code for the model implementation and the plugin implementation. The two classes Transform and Production are the two domain classes that together defines this domain specific modeling language that lets users create transformation rules. The Transform class represent the DPF Transformation Editor and has a source meta-model and a target meta-model, that corresponds to a source modeling formalism and a target modeling formalism. The editor interprets a model transformation as endogenous or exogenous if the target modeling formalism is equal or different to the source modeling formalism. We also have the file location on the storage unit for the source and target meta-model. The rules represents a collection of transformation rules. These rules are typed by a Production that represent one single transformation rule. A transformation rule has a name and contains a graph that is stored internally for each rule. This graph contains a pattern of nodes and arrows that the user can edit to form a LHS graph, a RHS graph and an intersection graph. These graphs defines several collections that contains nodes and arrows. These collections are utilized by Henshin to generate transformation rules.

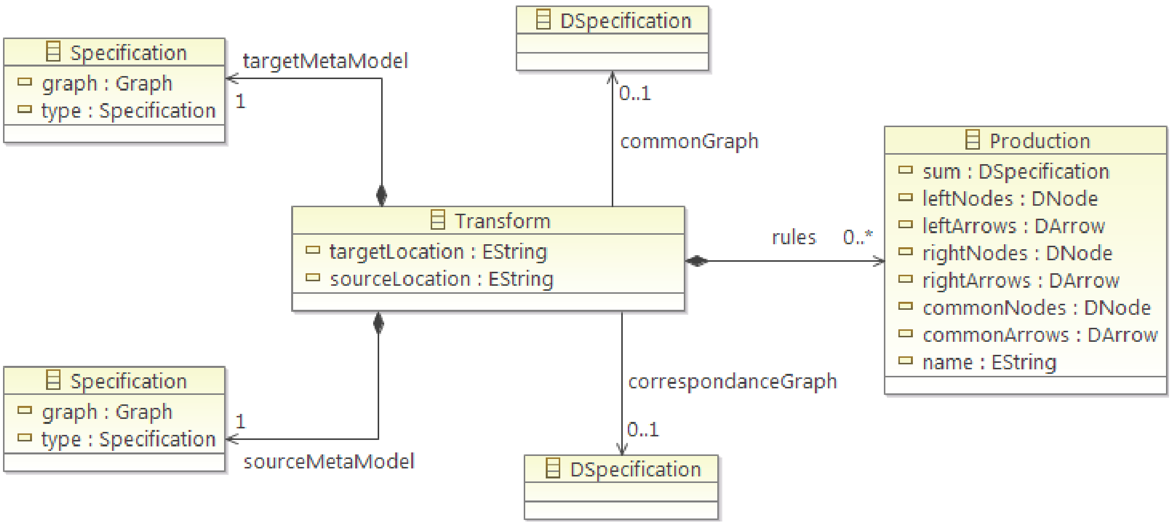


FIGURE 5.5: The domain model to create a DPF model transformation editor.

The user has to invoke the file creation wizard for the DPF Transformation Editor. Other than choosing a project folder and a name for this new editor file, the user has to specify what model is the source meta-model and what model is the target meta-model. If the user do not specify a target meta-model then the file creation wizard will interpret this as an endogenous model transformation.

The DPF Transformation Editor plugin has two editors that users can interact with. The first is the master editor for the plugin and contains a list of the transformation rules, where users can create, read, update and delete rules. The second editor is administrated by the master editor, and each time a new transformation rule is chosen, a simple version of the DPF Model Editor is opened with a corresponding transformation rule. This editor is created from the Graphical Editing Framework (GEF) and is a graphical editor that includes a toolbar. The toolbar is equal to the one used in the DPF Model Editor and contains modeling elements from the source and the target modeling formalism.

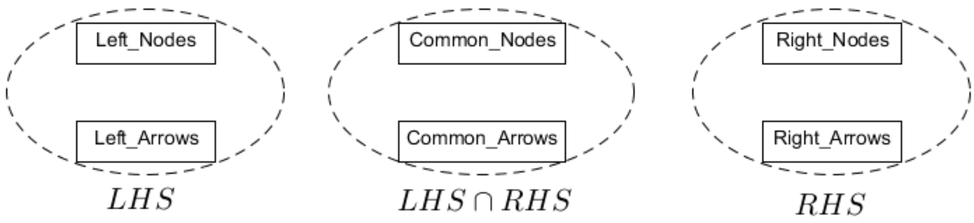


FIGURE 5.6: Three subgraphs for each transformation rule in the editor.

The nodes and arrows from a source and target meta-model are used to create the internal graph for each corresponding rule and uniquely map nodes and arrows to three subgraphs represented as lists. Figure 5.6 represents the left, right and common subgraphs, where each corresponding subgraph has a list of nodes and arrows. Each subgraph represents a different part of a transformation rule according to graph transformation. The left subgraph represents the LHS graph of a rule, while the right subgraph represents the RHS graph. The common subgraph represents the intersection between the pattern graph and the replacement graph. It is vital for the model transformation to work that all the nodes and arrows are mapped to one of these three subgraphs. This is entirely up to the user, because the nodes and arrows from the LHS graph have to be created in such a way that the graph can be matched in an instance graph.

Now that a list of transformation rules has been specified the user has to initialise the model transformation environment. This is done through three steps.

1. **Generate Correspondence Graph.** The user has to initialise a graph that contains the correspondence between objects. This is important since Henshin cannot envision how modeling elements from a source model are related to modeling elements from a target model. This relation has to be specified prior to generating Henshin transformation rules.

2. **Generate Henshin Rules.** Before we can use the Henshin model transformation language we have to provide a module that contains a set of transformation rules. And to achieve this we have to translate our transformation rules that we defined in the editor into Henshin executable rules.

3. **Apply Model Transformation.** By invoking the Henshin interpreter a target model can be produced by applying a set of transformation rules to a source model. The translated modeling elements can be assigned explicitly to a corresponding target modeling formalism after a model transformation is applied.

5.4 Generate Models

Two models are required to be generated before a set of transformation rules can be defined. These models are generated when a new model transformation is initialised for the DPF Transformation Editor. Each of these two models has a specific purpose for this integration of Henshin with the DPF Transformation Editor. The first DPF specification that is generated combines modeling elements from both the source and target modeling formalism while the second DPF specification specifies a correspondence between source modeling elements and target modeling elements. The creation process of the two models is similar, however the two models are created differently. Figure 5.7 illustrates how the two models are generated.

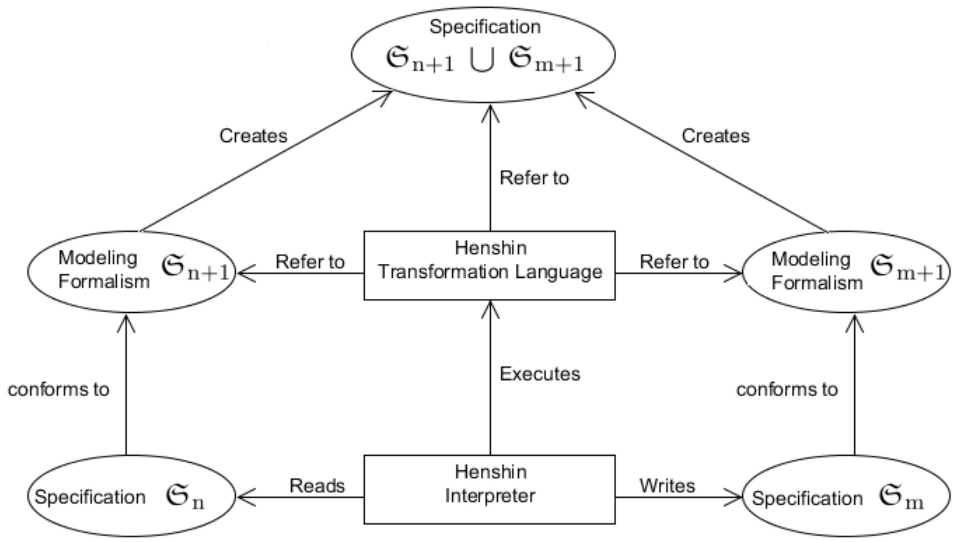


FIGURE 5.7: Combination of a source and target modeling formalism.

5.4.1 Modeling Elements for Application Conditions

This model is primarily used to create modeling elements for a production in the DPF Transformation Editor. The integrated view to creating transformation rules that the editor provides refers to this model for all created modeling elements. We generate this model based on the specifications $\mathfrak{S}_{n+1}$ and $\mathfrak{S}_{m+1}$ that are provided by the corresponding modeling formalisms. A traceable link modeling element is also specified and provides a source reference to source modeling elements and a target reference to target modeling elements. A traceable link is especially necessary if there is defined several nodes for a rule of the same modeling element. This DPF specification is then referred to when a set of productions are created according to the Henshin transformation language. An application condition is specified for every occurrence of a node or an arrow in a production. This is required for a Henshin rule to be able to include a modeling formalism in a search pattern.

5.4.2 Correspondence Graph

The Henshin transformation language refers to modeling elements from a source specification and a target specification when creating transformation rules. However, the Henshin transformation language is unable to figure out how source modeling elements are related to target modeling elements unless this is provided explicitly. We can create a new DPF model that presents all the nodes and arrows from the source specification $\mathfrak{S}_{\mathrm{n+1}}$ and the target specification $\mathfrak{S}_{\mathrm{m+1}}$ as nodes. We then provide a new modeling element that represents a bridge element between a source and a target modeling element. We can specify an arbitrary number of these modeling elements that binds nodes and arrows from a source model to nodes and arrows from a target model. This DPF model specify the correspondence graph between objects of a source and target meta-models. We can now refer to this DPF model when creating Henshin transformation rules to extract the corresponding objects. We use this correspondence graph or the trace object that we mention in section 5.4.1 to determine how we translate a source DPF specification. We create a trace object that has a source reference to every matching node and arrow that the transformation engine can locate and a target reference to the created nodes and arrows. In the next section these traceable links are considered in more detail together with how we generate a set of Henshin transformation rules.

5.5 Generate Henshin Rules

We utilize the meta-model represented in figure 5.3 to create transformation rules in Henshin. We start with creating the root element that is required for a Henshin model transformation and import EPackages that is needed to define the content of a transformation rule. We need to import two models if we want to translate a specification with Henshin. The first model is the corresponding language syntax for all DPF specifications and the second model is the meta-model for including traceable links in Henshin. We will describe the purpose of these traceable links in more detail in subsection 5.5.1. The transformation language requires models that defines the abstract syntax for an instance model to be able to specify modeling elements for both the LHS graph and the RHS graph of a transformation rule. We can use meta-elements provided by these two models when defining new nodes, edges and attributes in Henshin. These types are created accordingly to the Ecore meta-model, and are EClass for nodes, EReference for edges and EAttribute for attributes.

For Henshin we create one rule for each production provided by the DPF Model Editor, where the name of the rule is acquired from the production. Henshin provides a LHS, a RHS graph and a collection of mappings for each rule. We can create a graph structure for the LHS and the RHS based on subgraphs that each production provides. Modeling elements that form a pattern in the LHS are used to find a match in a source model, while modeling elements that form a pattern in the RHS are used to create new elements or replace these elements. Henshin also include an intersection graph for each rule. This graph is not represented as a physical graph like the LHS and the RHS are, but is represented as an underlying graph that is formed based on these two graphs. The intersection graph is represented by having elements in both the LHS and the RHS graph with mappings that distinguish that these elements are one and the same. Now we have the LHS graph, the RHS graph and the intersection of these two graphs that was mentioned in section 3.5. In this section we introduced double and single pushouts of graphs. Henshin has an arbitrary mixing of these graph transformation styles.

For each rule we created in the DPF Transformation Editor we have defined a pattern, that either corresponds to a left hand side, a right hand side or a common graph. This pattern consist of nodes and arrows that together form a graph. For each node and arrow, we create a Henshin node that is either typed as a Node or as an Arrow. An Arrow has to be represented as a Henshin node since it is defined in the meta-model for a specification as an EClass. Now we have to connect Henshin nodes with edges. An edge has three parameters, namely source, target and reference. In Henshin we create an edge with a source Henshin node and a target Henshin node. How the reference is typed depends on how the source and target node refer to each other in the specification meta-model. Figure 5.8 explains a simple example on how the relationship between a node and an arrow are handled for a specification.

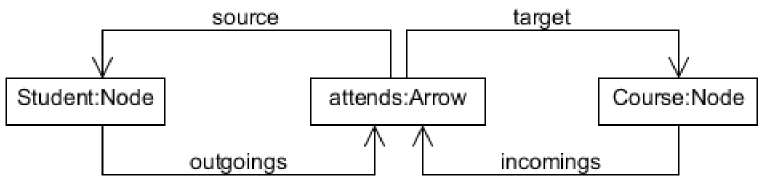


FIGURE 5.8: Example of how nodes and arrows are related for a specification.

An arrow that has a target and a source node, while every node has a list of both incoming and outgoing arrows. So this means that a Node and an Arrow have a similar relation in DPF models, where source and outgoings references represents the same relation but are typed differently. It is however easier to coupe with the arrows when creating transformation rules, since an arrow has an one-to-one relationship, with a source node and a target node. How the typing for an edge in Henshin is specified depends on the Henshin source and target node. These nodes are typed by a corresponding EClass type from the specification meta-model, that is a Node or an Arrow. An edge in Henshin can specify a relation between two other Henshin nodes depending on how references between Node and Arrow are typed. According to figure 5.8 we have two references between arrow and node and two references between node and arrow. If the source Henshin node for an edge is typed by Arrow then the available references are source and target. On the other side if the source Henshin node is typed by Node then we have a zero to many relationship in the two references incomings and outgoings. When we define relationships between two Henshin nodes we use the source and target reference. This is because this is an one to one relationship between two nodes and therefore we can always find the source and target node for a given arrow. This means for every Henshin node that are typed by Arrow we have to specify two relationships for this Henshin node. This is done by creating two edges in Henshin, where one refer to source node while the other edge refer to target node. This is achieved by specifying the Henshin node that is typed by Arrow as source for both edges and switch between source and target as reference for each target Henshin node.

At this moment the pattern on the left hand side and the right hand side are not specified by any types. The pattern conforms to the language syntax of DPF models, however this is the case for all specifications regardless of abstraction layer. A DPF specification is an instance of another specification, and this is where we can retrieve the types for every node and arrow. In the specification meta-model both the Node and Arrow class has a reference type to another Node and Arrow. Figure 5.9 represent how we want to employ application conditions in our Henshin rules to locate a matching pattern in a source specification $\mathfrak{S}_n$. Note that this figure represents a graph structure for a specification that is composed of nodes and arrows that include references to type nodes and arrows from the modeling formalism $\mathfrak{S}_{n+1}$. This figure does not represent a LHS of a transformation rule, but visualise how we want to locate matching modeling elements in a source $\mathfrak{S}_n$ based on a type node or a type arrow. The idea is to create an application condition for every node and arrow with their corresponding type node and type arrow. The node and arrow represents the matching pattern in a specification $\mathfrak{S}_n$ while the reference to a type node and a type arrow is how the Henshin transformation language can refer to the abstract syntax that the modeling formalism $\mathfrak{S}_{n+1}$ provides in DPF. The type nodes and arrows have an attribute called name that can be used to specify a positive application condition for a rule in Henshin. Positive application conditions are required to be valid when searching through a source model for a transformation rule to be applied.

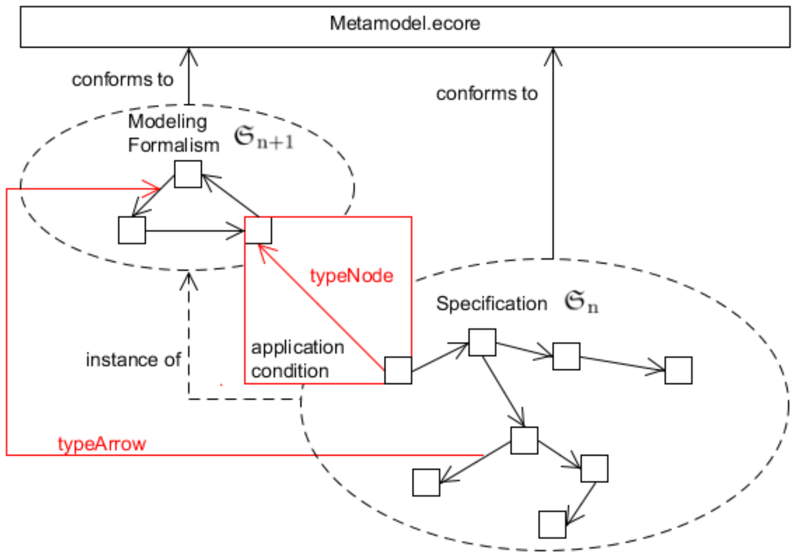


FIGURE 5.9: How we want to handle the abstract syntax one abstraction layer higher in the Henshin rules.

This also leads to an important change in our Henshin rules, because we have to include one more node and edge for every node and arrow. We have to create a new Henshin node that represent the type node and type arrow and an edge that define that this Henshin node is typed by another Henshin node. This is because when Henshin is locating matches in an instance graph we want the transformation language to locate matches for nodes or arrows that are typed by a specific node or arrow from a modeling formalism one abstraction layer higher. Figure 5.10 explains how we solve this in Henshin. We have a pattern graph or LHS on the right and an application condition graph on the left. This specific transformation rule in Henshin specifies a simple LHS graph that has an Arrow1 modeling element with a source Node1 and target Node2 elements. Note that the Arrow1 element is represented as a node and not as an arrow like the graph structures in figure 5.9. The reason for this is because an arrow is represented as an EClass in the linguistic meta-model for all specifications. Note that this LHS represents the graph structure that is used to locate matching patterns in a source model. For this example we want to locate all matching graph structures in a source specification $\mathfrak{S}_n$ that has an arrow with a corresponding source node and target node. At the same time we specify application conditions for this graph structure that correspond to a specific typeNode and typeArrow. For this example we focus on the Node1 modeling element.

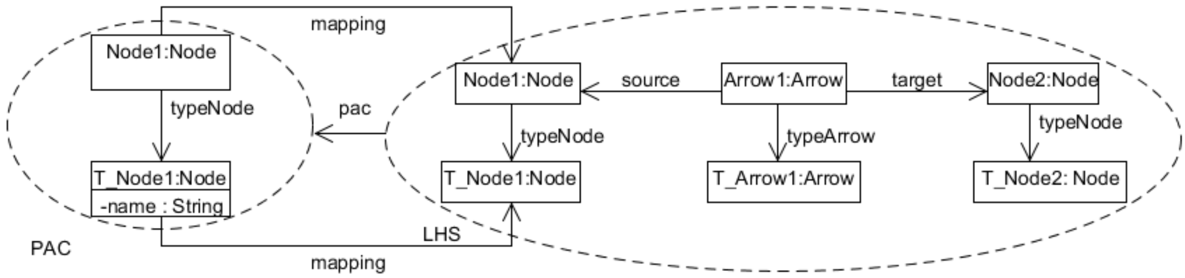


FIGURE 5.10: Defining a transformation rule that includes modeling elements from a specification one abstraction layer higher.

We discussed in section 5.2 that an application condition is represented as a Formula in Henshin, and to solve typing of nodes and arrows in DPF we need to create this Formula as a nested condition. This is because a nested condition provides a set of mappings and a graph, where we can define nodes, edges and attributes. To be able to map Henshin nodes is essential for creating an application condition. We need to make sure that an application condition is applied to a corresponding matched modeling element for a source model. This is achieved by mapping Henshin nodes that are part of the graph in a nested condition to Henshin nodes that are part of the graph pattern that is used to locate matches. If we refer back to figure 5.10 we can see that the pattern graph has a Node1 that are typed by a T_Node1. We then define a nested condition that contains these two nodes and a mapping from nodes in the application condition to the nodes in the LHS or intersection graph. Now we need to specify what an application condition should restrict when searching through matches, and this is the name attribute of the type node or arrow modeling element. This application condition can either be a positive or negative application condition. In this case we want the name attribute to be a positive application conditions that returns true for every matching type element located in a source model. We can specify several application conditions for a rule, and it depends on the graph structure of the LHS graph. We define a new application condition for each nodes and arrows that are part of the LHS graph, since these modeling elements can form a directed graph and each modeling element is typed by a modeling element from the source meta-model. All of these application conditions has to be true for a located match to be a valid match. Now we will explore how we also implement negative application conditions for our model transformation environment with traceable links.

5.5.1 Traceable links

As we discussed in chapter 3.2.7 a traceable link works as a footprint when executing a set of transformation rules. Henshin provides a traceable link implementation through the Henshin Trace model. This is a simple meta-model for defining traceable links and can be imported for any Henshin module. The Henshin Trace model provides an unique traceable link between a source modeling element and target modeling element. The source and target modeling elements can be any classes that conforms to the Ecore meta-model. We create a traceable link for every Henshin node we have included for the LHS graph. The nodes in the LHS graph are the source modeling elements for a Trace modeling element while nodes in the RHS graph are the target modeling elements. Now we have an unique link between a matched node from the LHS graph and a produced node for the RHS graph for every time a transformation rule is applied. These traceable links are represented in the replacement graph the first time that a connection between two nodes are initialised. This means that the traceable links are actually translated when a transformation rule is applied and stored in the translated graph. Next time we want to refer to a traceable link between modeling elements where a transformation rule has been applied we have to make sure that the trace object is created both in the LHS and the RHS with a mapping between them. Because together with a negative application condition this traceable link will make sure that we only translate located matches in an source model once. This can be achieved by defining a negative application condition that forbids Henshin to create a traceable link. We create a nested condition similar to the previous section, but for this case we want the application condition only to return true for all matches that does not contain this graph pattern. This is very convenient when applying a set of transformation rules, because we have already stated that a traceable link is created when a transformation rule locates a match in an instance graph. This means that we create unique traceable links between all nodes in the pattern graph that is matched in an instance graph and the nodes that we create. It has to be noticed that the source and target nodes of a traceable link has to be typed by the EClass modeling element that Ecore provides. We can now execute the set of transformation rules as long as we want and be safe that we will not execute matching pattern in an instance graph more than once. The reason that we can make this statement is because when we find a match for the first time then there exist no traceable link to these modeling elements. But once the transformation engine execute this rule, then a traceable link is initialised between the matching nodes on the left side and the corresponding modeling elements on the right side. Now the transformation engine cannot locate this specific match for a second time because we have restricted the transformation rule to not include matches that has a traceable link to the source node that are part of the LHS graph. Now we will describe more in detail how we apply these transformation rules.

5.6 Apply Model Transformation

5.6.1 Rule Application Control

Now that the DPF Transformation Editor has generated a set of Henshin transformation rules the transformation engine is ready to apply these rules to a source model. The Henshin module we generated in the previous section now contains a set of transformation rules that are defined accordingly to the the Henshin transformation language. The Henshin Transformation Engine can now execute this generated module by explicitly invoking the Henshin interpreter. The interpreter requires a module, a graph that contains the source model and a Henshin unit before it can be applied. For our solution we have created a transformation unit that executes a set of transformation rules in the same order that the DPF Transformation Editor provides, and is called a Sequential unit. A transformation unit in Henshin is an implementation of a rule application control system that we described in a more general term in section 3.2.3. A transformation unit in

Henshin is an executable part that the transformation engine can interpret and apply rules accordingly. It is important to specify that a transformation rule itself in Henshin is a transformation unit, and can therefore be executed by Henshin's transformation engine. But a Henshin transformation rule does not provide any control mechanism for it self or other rules when executed. A transformation rule will therefore only locate one single match if we invoke the Henshin interpreter on a single rule. This is one reason for why we want to specify a transformation unit that has some unique properties that a single transformation rule does not provide. Some Henshin transformation units have the possibility to have other transformation units as subunits. The Sequential unit that the module provides works as the master unit for applying the transformation rules. For each transformation rule we created in the previous section we define a Henshin Loop unit. This unit can only contain one single subunit, and that is a corresponding transformation rule. The Loop unit is executed for as long as there are any matching modeling elements in an instance graph and will locate matches an unlimited number of times unless we provide any mechanism to stop the unit. This is where the negative application conditions that we described in the previous section plays a vital role. Because the negative application condition specifies that a transformation rule will only be applied unless there exist no traceable links. The first time the transformation engine locates a match for a transformation rule it will create a traceable links that connects the matching modeling elements and the created modeling elements. Now the next time this specific match is located the application condition will not be valid since now there exist a traceable link that has a reference to a modeling element in the source model. We can now apply these repeatable units for all transformation rules as long as the input graph does not contain a traceable link for a matched modeling element.

5.6.2 The Transformed Model

For all matches found in a source model we do some changes depending on how the RHS graph is specified. These changes are specified as new DPF modeling elements after applying a set of transformation rules. The next step is to make sure that the produced modeling elements are type correct. This means that the target model is required to conform to a target modeling formalism. Figure 5.11 represents the result of a model to model transformation.

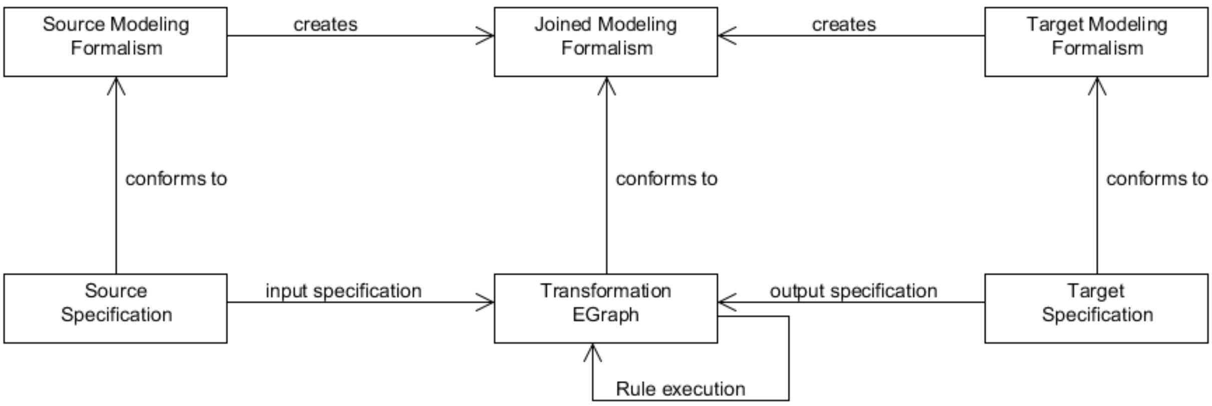


FIGURE 5.11: The transformed result of a model to model transformation.

The transformation EGraph represents the source model as we mentioned in the previous section. The Henshin interpreter will execute transformation rules on this transformation graph until there are no more valid matching pattern located in the source model. The produced target modeling elements that are included in the transformation graph after rule execution conforms to a joined modeling formalism. However, we want these modeling elements to conform to a target modeling formalism and not the joined modeling formalism. Section 5.5 describes how we can create a set of transformation rules in Henshin from the transformation rules in the DPF Transformation Editor. These transformation rules has a search graph structure with positive application conditions that determine the abstract syntax that a source modeling formalism one abstraction layer higher provides. Each Henshin node in a RHS graph of a rule that is specified has a reference to a target type node or arrow. For each application of a transformation rule we locate a match and create nodes and arrows with a corresponding type node and type arrow accordingly to the RHS. After the execution of all the transformation rules we can now extract these produced target modeling elements to a new target specification that conforms to a target modeling formalism. For each translated modeling element we can check if it has a corresponding type node or type arrow in the target modeling formalism.

5.7 Solution summary

So far we have extended the DPF Transformation Editor to support exogenous model transformation between different abstraction layering hierarchies. In this section we will summarize some of the features this solution provides.

- The DPF Transformation Editor provides an integrated view to define transformation rules. The different modeling elements that is created for a specific transformation rule can be mapped to either a left subgraph, a right subgraph or a common subgraph.
- Two DPF specifications are specified that the Henshin transformation language can utilize when creating transformation rules. One of the generated models specify the correspondence of objects and requires the user to define how a source modeling element relate to a target modeling element for a specific model transformation.
- The DPF Transformation Editor can invoke the Henshin interpreter to create a set of transformation rules according to the Henshin meta-model.
- A transformation rule in Henshin refers to the abstract syntax from a modeling formalism one abstraction layer higher by specifying an application condition for every occurrence of a modeling element in a transformation rule.
- We create a traceable link that includes a matched source modeling element and a corresponding produced target modeling element. This traceable link is used to be certain that the transformation engine does not locate duplicate matches and if already translated target modeling elements are defined in other transformation rules.
- We invoke the Henshin interpreter programmatically to apply the set of Henshin transformation rules to a source specification.

- After the transformation we extract the produced modeling elements from the translated graph to a specification and explicitly specify that the modeling elements conforms to modeling elements of a target modeling formalism one abstraction layer higher.

Chapter 6

Demonstrating the Tool

In this section a specific example of an exogenous model to model transformation is presented. It is similar to the case study that was covered in section 4.2. The source DSML is presented in the paper[18] and is defined according to two abstraction layers while the target DSML is defined according to one abstraction layer. This section will address the most significant parts of the workflow of a model transformation for the DPF Transformation Editor that was described in figure 5.2 in section 5.1.

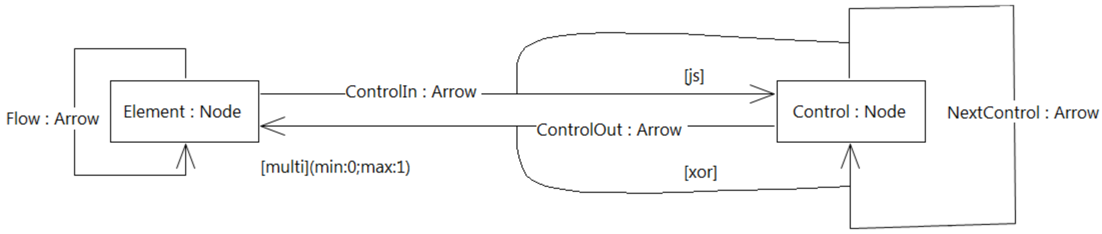


FIGURE 6.1: Modeling formalism at $\mathfrak{S}_3$ abstraction layer.

Figure 6.1 represents a modeling formalism for an activity diagram that is defined in abstraction layer $\mathfrak{S}_3$. The figure includes the two nodes Element and Control and the four arrows ControlIn, ControlOut, NextControl and Flow. The semantics of the model is specified by defining a couple of predicates for the arrows. The *[js]* specifies that a Control should have at least one incomming arrow from an Element or Control. The *[xor]* specifies that a Control can have either have an outgoing arrow to an Element or another Control both not to both. The multiplicity predicate specifies that a Control can only be connected with maximum one other Element. The specification $\mathfrak{S}_3$ together with the constraints that are defined specifies a modeling formalism for a DPF specification one abstraction layer lower.

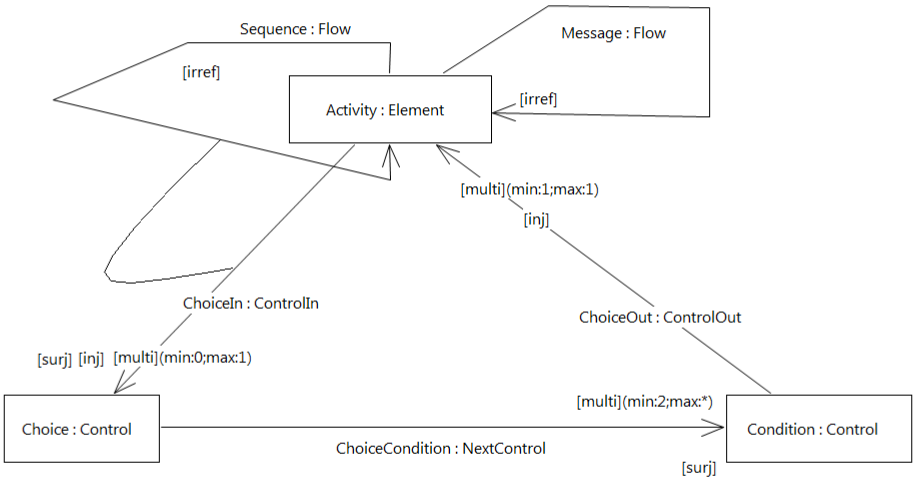


FIGURE 6.2: Source modeling formalism at $\mathfrak{S}_2$ abstraction layer.

Figure 6.2 represents a set of predicates for a specification $\mathfrak{S}_2$ that conforms to the modeling formalism specified in figure 6.1. This modeling formalism consists of one Element and two Control domain classes. The semantic of the modeling formalism is specified by a set of predicates and arrows between the three domain classes. The predicates for an Activity specifies that an Activity never can relate to itself but can relate to other Activity elements. A Choice and a Condition element is required to be connected with exactly one Activity element while a each Choice element requires a connection with at least two Condition elements. This modeling formalism represents the meta-model that describes the source DPF specification $\mathfrak{S}_1$ for this exogenous model transformation.

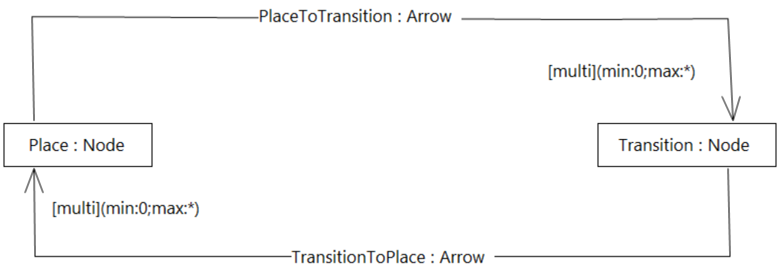


FIGURE 6.3: Target modeling formalism at $\mathfrak{S}_2$ abstraction layer.

Figure 6.3 represents the modeling formalism for a Petri net model and is the meta-model for the target DPF specification. The modeling formalism specifies that two domain classes Place and Transition can be connected to each other with a TransitionToPlace and a PlaceToTransition arrow. Note that both the modeling formalism presented in this figure and figure 6.1 conforms to the default DPF specification that is a Node connected with itself.

So far we have covered step 1 by defining a source and target modeling formalism of a model transformation in the DPF Transformation Editor. The next step is to define a new isntance of a model transformation that initializes an empty correspondence graph and the joined modeling formalism. Step 3 focus on creating a set of transformation rules and specify the corresponding objects between source and target modeling formalism.

Henshin requires this relation to be able to perform an exogenous model transformation. Figure 6.4 illustrates that all arrows in the source modeling formalisms should be translated according to a Place in the target modeling formalism.

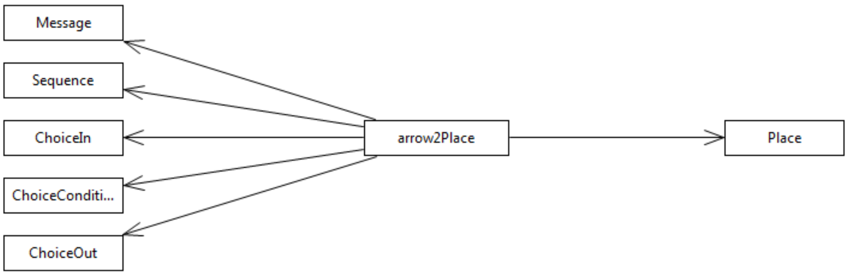


FIGURE 6.4: Correspondence of modeling objects in source and target modeling formalisms.

Note that this will jeopardize the semantics of the source and target modeling formalism by stating that an arrow should be translated to a node. However, to simplify an exogenous model transformation we specify that arrows from a source modeling formalism should correspond to a Place. The idea behind specifying the correspondence between objects is that the user is responsible for how a target specification is produced. The next part of step 3 is to define a set of transformation rules. Figure 6.5 defines that eight transformation rules is needed to translate an instance specification of the source modeling formalism.

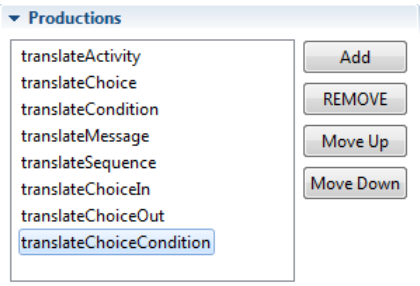


FIGURE 6.5: The set of transformation rules for this specific model transformation.

Figure 6.6 illustrates the two rules translateCondition and translateChoice. For the first rule we specify that a Condition modeling element from the source modeling formalism should be part of the searching pattern while a Trace and Transition modeling element are created for each located matching pattern.

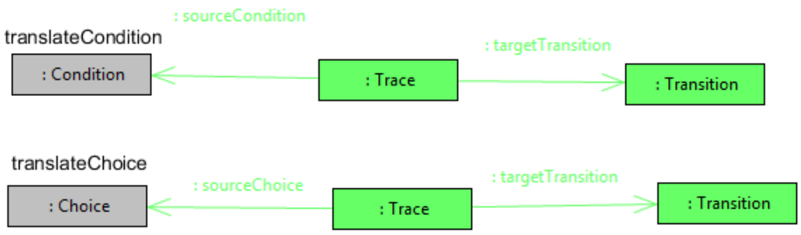


FIGURE 6.6: The transformation rules translateCondition and translateChoice.

Trace specifies the correspondence between source and target modeling elements and represents a traceable link with a source and target modeling element. Note that the color gray specifies that modeling elements belongs to the intersection graph while the color green specifies that modeling elements are part of the RHS graph. Figure 6.7 illustrates the integrated view for editing transformation rules in the DPF Transformation Editor. The Palette on the right side includes the modeling elements that is provided from the joined modeling formalism that was generated accordingly to step 2.

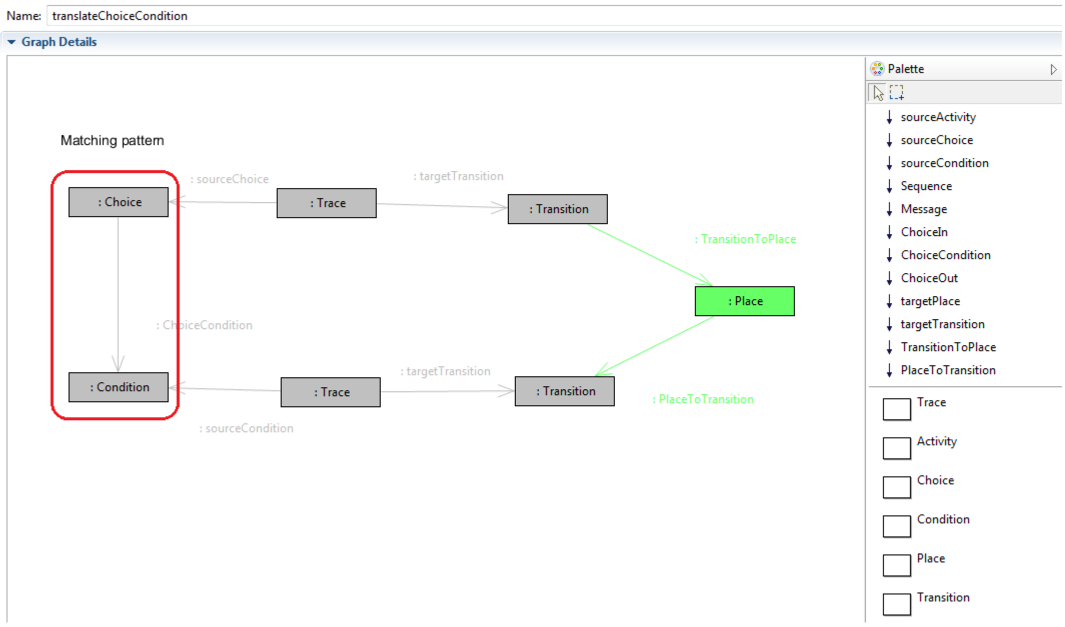


FIGURE 6.7: The integrated view for a specific transformation rule.

Before we describe the semantics of this specific transformation rules we should illustrate what matching pattern the rule searches for.

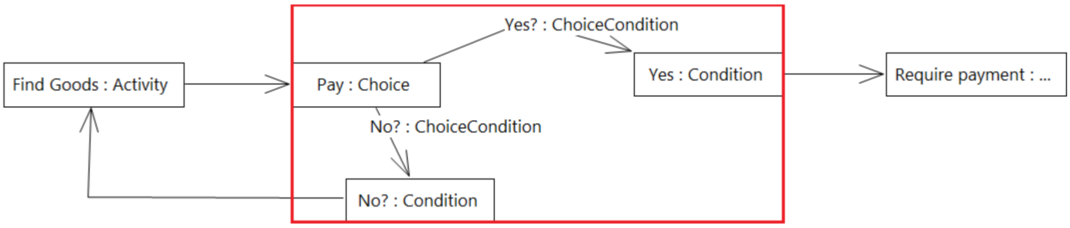


FIGURE 6.8: A small fragment of the source model for this specific model transformation.

Figure 6.8 represents a small fraction of the source model that will be translated. In this rule we want to locate a matching pattern that has a Choice connected with a Condition by a ChoiceCondition. Note that this specific rule will locate two matching pattern when applied. The first matching pattern is when the Choice is Yes while the second matching pattern is when the Choice is No. Back to the specific transformation rule, "translateChoiceCondition" in figure 6.7. We have a matching pattern that is part of the intersection graph. The matching pattern locates matches that has a Choice connected with a Condition by a ChoiceCondition. This rule will locate two different matches as shown in figure 6.8. The rule also specifies that a Place and two arrows are produced for every located matching pattern. One thing that is special for this rule is that two trace and transition modeling elements are part of the intersection graph. This is because these modeling elements already have been translated in the two transformation rules that were defined in figure 6.6. The two traces specifies that the two Transition elements corresponds to a Choice and a Condition element that is already translated for these matches. The newly created Place element are connected with the two already translated Transform elements with a TransitionToPlace and a PlaceToTransform arrow. The two final steps of the workflow of consist of generating a set of Henshin transformation rules from the eight rules in the DPF Transformation Editor and applying the Henshin rules to a source model.

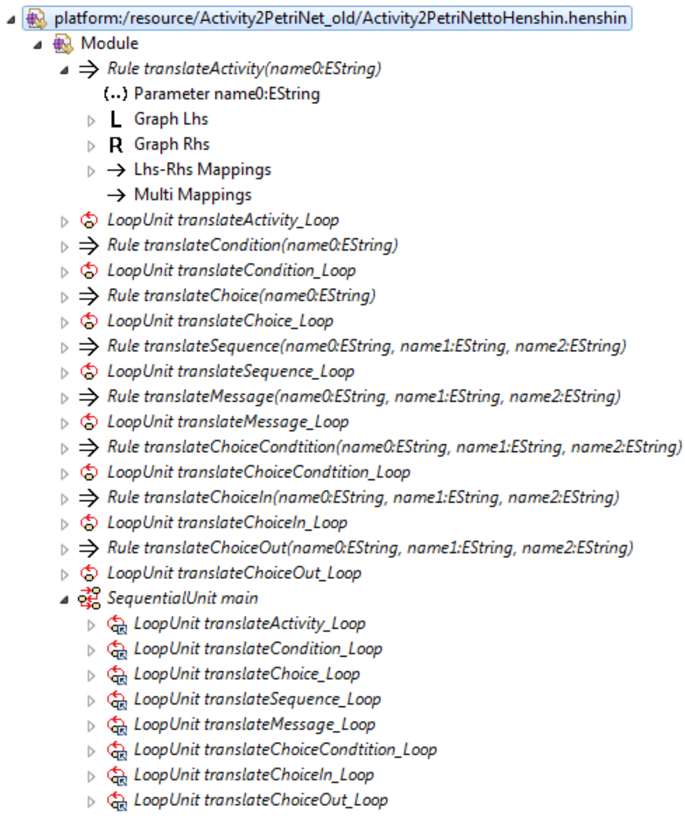


FIGURE 6.9: The eight transformation rules generated in Henshin.

Figure 6.9 represents a generated Henshin module with eight transformation rules. Each rule has a LHS, a RHS graph and a collection of mappings that forms the intersection graph. The parameter name0 for the "translateActivity" is used to pass along a variable from one matching modeling element to a produced target modeling element. Note that there are a collection of 17 items for this Module. The SequentailUnit, main represents the scheduling mechanism that specifies that 8 LoopUnits is applied in sequential order. Each LoopUnit has a corresponding transformation rule as subunit. The rules are applied until there are exist no more matching patterns. The main sequential unit can be applied to a source model and translate is according to the rules for a Henshin module. After the transformation we can extract the translated target modeling elements and explicitly assign these modeling elements to the target modeling formalism.

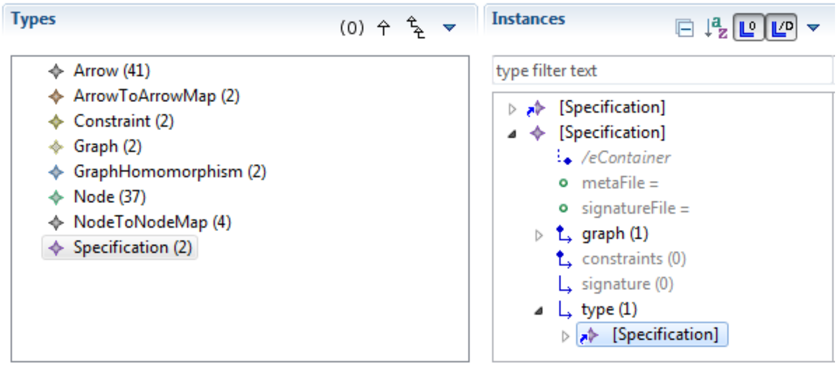


FIGURE 6.10: The result of this specific exogenous model transformation.

Figure 6.10 represents the translated DPF specification that conforms to a target modeling formalism. The Node and Arrows represents the translated modeling elements that is named according to matched modeling elements.

Chapter 7

Evaluation

7.1 Evaluation of Solution

We have successfully managed to integrate Henshin with the Diagram Predicate Framework to support exogenous model transformations. This is done by including an editor for the DPF workbench that communicates with the Henshin model transformation environment to provide a model to model transformation environment for DPF models. For the solution we have utilized the strengths of the environment that it implicitly does not support. If we refer back to figure 4.1 in section 5.1 we saw that a specification is an instance of a linguistic meta-model that Henshin has no problem interpreting. The problem arises for the ontological meta-models that describes the source model together with a linguistic meta-model. Suddenly there are two models that both provides some form of abstract syntax that Henshin is required to consider when defining the content of the transformation rules. Section 5 describes how we can explicitly solve this by extending the transformation rules with application conditions. Henshin utilizes EMF's Ecore modeling system when structuring both the left hand side and right hand side of a transformation rule. This means that Henshin supports the 2-layered modeling hierarchy that EMF provides. If we did not extend the transformation rules with application conditions accordingly to the source DSLs abstraction layer hierarchy, then Henshin would basically interpret that every DPF specification, regardless of abstraction layer is created accordingly to EMF's 2-layered approach to meta-modeling. Henshin would ignore the different modeling formalisms provided by several layers of abstraction and threat all modeling elements in a specification as a node and an arrow. This would lead to a set of transformation rules that refers to the abstract syntax of the highest abstraction layer that DPF provides. This is essentially what we want for the source model, but we want to define nodes and arrows according to the modeling formalism that is one abstraction layer higher and not the highest possible abstraction layers that is a node with an arrow connected to itself. We described in the previous section that we can introduce each node and arrow with its concurrent type from one abstraction layer higher as an application condition in Henshin. This way Henshin will only locate matches for nodes and arrows that gives a valid application condition. Without the application conditions the transformation engine could potentially locate matching patterns for every single node and arrow in a source specification for a single transformation rule. These application conditions could potentially get quite complex if the DPF Transformation Editor is extended with the possibility to specify negative and positive application condition.

The DPF Transformation Editor functions both as a support for the Henshin model transformation environment and as a solution for including support for exogenous model to model transformations in DPF. One could say that for this specific problem solution that Henshin is independent of the DPF Transformation Editor. However, this is not correct, because with the help of this tool we can make exogenous model transformations in DPF generic. This means that we could be able to transform a model specified in one DSML into a model specified in another DSML, regardless of abstraction layers. So in the case of creating transformation rules in the Henshin transformation language the DPF Transformation Editor could be considered to provide a support role. But when considering a generic model transformation for DSMLs on an arbitrary abstraction layering the tool's role is essential. Henshin can define generic model transformations when the source and target meta-model is Ecore based models, but for our case every single DPF specificaiton conforms to the same Ecore model. The DPF Transformation Editor provides the Henshin model transformation environment with a additional searching information through defining application conditions based on DPF specifications from higher abstraction layers.

The DPF Transformation Editor and Henshin provides a model to model transformation environment that translates a specification provided at an arbitrary layer of abstraction to another specification provided at an arbitrary layer of abstraction.

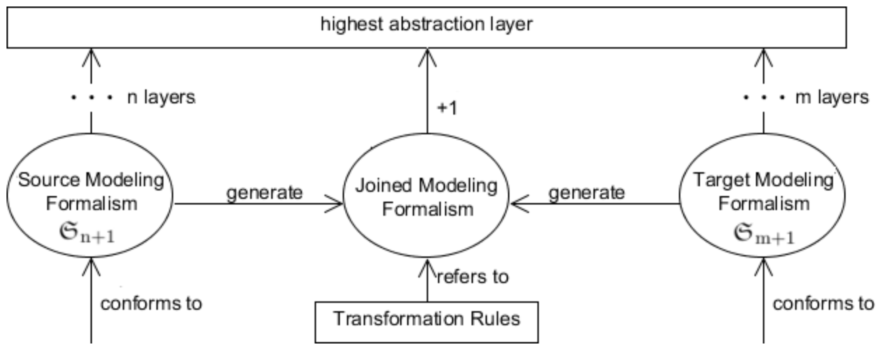


FIGURE 7.1: A simplified joined modeling formalism that transformation rules refers to.

Figure 7.1 explains that we create a joined specification from a source modeling formalism and a target modeling formalism from some abstraction layers. The joined specification is created independent of the two abstraction layers and is referred to when creating transformation rules in the DPF Transformation Editor.

7.2 Test case with the DPF Transformation Editor

7.3 Comparison with other editor tools

In this section we provide a comparison between the three model transformation environments that we worked with including the DPF Transformation Editor. In our solution we expanded the Henshin model transformation environment to be able to apply model transformations to a multi-layered meta-modeling environment like we discussed in section 7.1. It is natural that the DPF Transformation Editor will have similarities to the Henshin environment since our solutions builds heavily on this environment. But we can still compare our solution with both Henshin and other transformation tools. Table 7.1 provides an overview of the DPF Transformation Editor and the three other model transformation environments that we compared in section 4.2. We will consider only some of these elements since some of them will be explained in later subsections.

	AGG	Henshin	ATL	DPF Transform
Endogenous transformation	√	√	√	—
Exogenous transformation	√	√	√	√
Input Elements	1...n	1...n	1...n	1...n
Output Elements	1...n	1...n	1...n	1...n
Graphical syntax	√	√	—	√
Meta-modeling layers	2	2	2	∞
Separate meta-models	—	√	√	√
Integrated with EMF	—	√	√	√
Supports Java	√	√	√	√
Model transformation file size	200 kb	80 kb	4 kb	265 kb
In-place/out-place transformations	in-place	in-place	out-place	out-place

TABLE 7.1: Comparing model transformation tools.

All four tools supports an arbitrary number of both input and output elements. This means that if the tool takes a number of input models, then it produces the same number of target models. Take an ATL module as an example. It accepts a fixed number of models as input, and returns a fixed number of target models. This means that an ATL module can not generate an unknown number of target models. If there is one input model, then there will be one output model that conforms to a target meta-model.

Both AGG, DPF Transformation Editor and Henshin provides a graphical syntax to define the transformation rules. This is not the case for ATL, which uses a textual based approach. For ATL the users have to implement transformation rules in programming code. Tools that facilitates a graphical syntax could potentially be more intuitive than ATL since it is often easier to understand something when you can see the changes as miniatures.

The tools can be integrated with Java. For ATL the files containing the transformation rules have to be created before they can be used in a java application. In ATL this has to be an "atl" file containing a ATL module that has a list of rules. This is because the ATL transformation engine relies on a file extension with the name "atl". Both Henshin and AGG provides an API that can be used to create transformation rules, application conditions, type graph, source graph, etc. The DPF Transformation Editor is quite different since it utilize the convenience methods that the Henshin API provides. It is possible to specify transformation rules in the DPF Transformation Editor by implementation code, but the method to generate Henshin rules requires a single production that has a left, a right and a common subgraph, which we explained in section 5.

We can also se that the size of the transformation rules differ amongst the tools. The examples that are compared are different exogenous model transformations. This means that a model transformation for all tools includes a source and target meta-model and a file containing the transformation rules. By reading the table we can see that an exogenous model transformation in the DPF Transformation Editor uses 265 kb of the storage space. This number is so unbelievable small that it will never be noticed in any modern computers. But there is one interesting thing however, that the transformation rules defined in ATL is over 60 times smaller than the DPF Transformation Editor. What this basically means is that creating model transformations through the use of textual concrete syntax is less space consuming than through the use of graphical syntax. This is only logical since the graphical syntax based transformation languages requires more storage space simply because they use graphical elements to represent the transformation rules.

7.3.1 Editing Transformation Rules

In the DPF Transformation Editor we present the transformation rules in a list, where each transformation rule is extended with a simplified version of the DPF Model Editor and a toolbar that contains modeling elements from a source and a target meta-model. With these modeling elements we can create and structure a searching pattern and a replacement pattern for each transformation rules. It is logical that the searching pattern and replacement pattern create modeling elements that corresponds to the source and target meta-model, since this is an exogenous model transformation between two different modeling languages. In Henshin we can choose to create transformation rules in either the tree based Henshin Model Editor or in a graph based editor. The DPF Transformation Editor that we created provides an integrated view on transformation rules, similar to Henshin and GReAT. This means that we do not provide separate editors to implicitly edit the LHS and the RHS graphs for a transformation rule like for example AGG does. This is convenient since editing is now separated in a left hand and a right hand side editor. AGG can also include a third editing window, that specifies application conditions for the rule. At first glance AGG will most likely provide a more intuitive approach to editing transformation rules compared to the integrated view that Henshin and our solution provides. The users needs to understand the principles behind graph transformations when working with either tools, but AGG might present a more intuitive approach since the tool has a clear procedure on how to create and manage new application rules. However, AGG, Henshin and DPF Transformation Editor provides a graph based approach to model transformations even though they introduce different approaches to define transformation rules. The graphical editor that AGG and Henshin provides are different in such a way that the creation of rules are different. Both Henshin and AGG has a tree based editor, but the editor works differently amongst the two tools, see figure 4.6 and 4.8 for the two editors. The graphical editor for our solution is very similar to Henshin, but does not provide any three based editor. However, when generating to Henshin transformation rule it is possible to use the tree based editor and browse through the Henshin rules and application conditions. Keep in mind that changes done to the Henshin rules might jeopardize the execution of the transformation rules for DPF specifications.

ATL tool is definitely not as intuitive as the the graph transformation tools, however once you understand how to create transformation rules and how to work with the included meta-models, it is a good framework for working with model transformations. However, if a user do not fully understand the Object Constraint Language (OCL), ATL is rather a hard tool to work with. Because OCL has a very leveled learning curve, since it is a declarative programming language. We are more confident in working with imperative programming languages during our studies here in Bergen. ATL provides an editor where the users can use OCL to create and modify transformation rules. ATL has a very strict way of writing transformation rules, since the tool uses a textual based approach to create transformation rules. The user has to use the predefined stereotypes defined by ATL.

7.3.2 Meta-modeling

Meta-models are initialised and handled differently amongst the four tools. The initialisation of the meta-models for Henshin and ATL is similar. Both of these tools employ Ecore to create meta-models, since they are both integrated with EMF. For Henshin and ATL the user has to create one Ecore model for both the source and the target meta-model. Both of these meta-models can be imported into Henshin and ATL. One thing that is convenient with Henshin that ATL does not provide, is that Henshin provides a list of meta-models that is available for the user. These are meta-models that can be used either as source or target meta-model. If we want to translate a instance model to an Ecore model, we can in Henshin import this Ecore meta-model from a list and use it as the target meta-model.

AGG on the other hand uses a disjoint meta-model. This means that in AGG there is something called a type graph, and in this type graph both the target and the source meta-model are defined. AGG handles consistency similar to Henshin. AGG will restrict the user to only create nodes or arrows between nodes that are specified in the type graph. Figure 4.5 in chapter 3 shows that there are created references between two meta-models. Through the use of these references, AGG can create and modify transformation rules to facilitate an exogenous model transformation.

Through defining the abstract syntax is where our editor has its biggest advantage, since the three transformation tools that we worked with utilizes a two layered approach to modeling. First we create the abstract syntax through a meta-model and second we specify the concrete syntax through a instance model of this abstract syntax. This is also implicitly true for the DPF Transformation Editor, since every DPF specification, regardless of abstraction layer is represented as an instance model of a DPF specification one abstraction layer higher. There are some similarities to how we present meta-models like ATL and Henshin does for the transformation rules and that is through the Ecore model. There is one major difference however, and that is that our Ecore model is static and ATL and Henshin's meta-models are dynamic. And by dynamic we mean that the source meta-model and target meta-model represents the abstract syntax of some arbitrary modeling language. For the DPF Transformation Editor the source and target meta-model always corresponds to the same Ecore model and that is the common meta-model for all specifications. However, with the help of application conditions in Henshin we can define an abstract syntax that the transformation rules can refer to for an unlimited hierarchy layer of meta-modeling. So one could say that every DPF specification is an instance of a common modeling language while the abstract syntax for the modeling elements for this DPF specification are described by another DPF specification one abstraction layer higher.

7.3.3 Transformation Rules

We have seen that the creation of transformation rules varies over the four different tools. ATL provides a textual based approach and therefore requires multiple lines of code. The abstract syntax is represented differently for the four different tools. Henshin and ATL utilizes the Ecore model to create meta-models while AGG creates a type graph that contains the abstract syntax for both the source and target model. The DPF Transformation Editor requires two models that determines the abstract syntax. The first model is an Ecore model that represents the language syntax for all DPF specifications while the second model is provided at some abstraction layer and is an instance model of this Ecore model. The DPF Transformation Editor, AGG Henshin provides an editor with a graphical syntax, while ATL on the other side provides a text based editor for creating and modifying transformation rules. AGG separates the RHS, the LHS and the intersection graph in two separate editing parts while Henshin and the DPF Transformation Editor employs an integrated view with special techniques to distinguish between the different graphs. The four tools have a left hand side and a right hand side, but are represented differently amongst the rules. Henshin, the DPF Transformation Editor and AGG use graph patterns to represent the LHS and the RHS while ATL utilizes logical expressions both as declarative and imperative transformation rules. Both AGG and Henshin can specify both negative and positive application conditions that are attached to different transformation rules. For ATL these conditions are handled by OCL expressions, for example the if-then clause. This version of the DPF Transformation Editor does not support user created application conditions.

7.3.4 Rule Scheduling

ATL does the scheduling implicit, where the user has no control over the scheduling algorithm defined by the tool. The user can however influence the scheduling algorithm defined by the ATL transformation engine by designing the logic in the transformation rules to apply in a certain order. The transformation engine will first execute the declarative rules before applying the imperative section of a transformation rule. AGG and Henshin does however, give the users the possibility to influence how the transformation rules are applied. In Henshin and AGG rule scheduling is handled explicitly before applying the transformation rules, where the users can manipulate the execution order of the rule. For example the rules can be applied non-deterministic or in sequential order.To force the transformation in a sequential order could result in performance issues compared to applying the rules non-deterministically. AGG provides the users with the possibility to organize the transformation process into several phases or layers. These layers are numbered from $0 \dots n$, and the lower the number the higher the priority for the rule when it is translated. This gives the users the possibility to execute rules layer by layer. In Henshin these rule scheduling mechanisms are referred to as transformation units. For this tool it is possible to specify units that supports rule iteration, both by looping through rules until there are no more changes detected or by iterating through rules for a fixed number of iterations. In Henshin it is also possible to specify an amalgamation unit, that is an unit that provides a forall-operation for the matching pattern graph. This unit has a kernel rule and multiple underlying rules that are matched as often as possible. It is clear that Henshin provides the users with quite an variety of controlling the execution of rules.

The DPF Transformation Editor does not provide the user with any control regarding how to locate matches and how transformation rules are applied. We generate a Henshin module that contains a set of transformation rules. We can manipulate the execution order of these transformation rules, but the algorithm that Henshin uses to locate matching patterns in a source model is part of the internal infrastructure of Henshin and cannot be manipulated. We can however force the transformation rules to be executed in a given order. This version of the Editor has no support defining a schedule mechanism that specifies how the rules are applied and will for now only run the transformation rules sequentially. We can decide the priority of the rules by changing the order that they appear in the DPF Transformation Editor. Most of the transformation tools open to the public provides solutions to manipulate the scheduling mechanism, for example ATL provides the users the possibility to define rules as lazy rules and control how they are applied at runtime. While AGG and the Henshin environment lets the users specify the scheduling mechanism over a few predefined choices.

Another thing that is special about our integration of Henshin is that locating matches are handled differently. An application condition is initially meant to restrict a transformation rule when locating matches. If application conditions are not specified for a transformation rule in some 2 layered meta-modeling transformation tool we will still locate a matching pattern that correspond to modeling elements that are described in the abstract syntax. The application condition has a vital role in our integration of Henshin, because the application conditions are checked against the DPF specification that are one abstraction level higher. Without this application condition we would simply get a target DPF specification that has a list of nodes and arrows that conform to the highest level of abstraction in DPF. The highest level of abstraction in DPF is always a node and an arrow, that conforms to itself. So while a 2 layered meta-modeling transformation tool would find matches in a source model that correspond to the meta-model, the DPF Transformation Editor would find matches to the linguistic meta-model and not the ontological meta-model at some level of abstraction. One could state that an application condition for a 2 layered meta-modeling transformation tool is independent of the transformation rules while our version the transformation rules are dependent on the application conditions to be able to produce a correct target model.

7.3.5 Rule Organization

ATL organizes the transformation rules inside modules, and are therefore easy to reuse if applicable. This is convenient for users of ATL since this means that all created rules can be used to form new transformation rules. Henshin provides the user with the possibility to nest or reuse rules in different scheduling mechanism or transformation units as we discussed in the last paragraph. But Henshin and therefore also the DPF Transformation Editor does not provide the user with the possibility to reuse rules in the creation of new rules like in ATL.

7.3.6 Source - Target Relationship

The DPF Transformation Editor explicitly performs an out-place model transformation. This means that we create a target DPF specification with the translated modeling elements that is independent of the source model. We then make sure to specify all the nodes and arrows with its corresponding type from a modeling formalism one abstraction layer higher. AGG does this differently, since the source and target model are one and the same model. Matches are located in the source model, while the target model is updated accordingly. Henshin on the other hand provides in-place model transformations on the source model. However, when we invoke the Henshin interpreter engine programmatically we can either initialize variables that explicitly captures the transformed target modeling elements or check for changes before and after executing a set of transformation rules. Note that this can only be done when utilizing the Henshin interpreter programmatically. For an exogenous transformation in ATL it is mandatory to create a new separate file that contains the translated target modelings elements. Exogenous model transformation in ATL are therefore out-place model transformations.

7.3.7 Directionality

To provide a graph based model transformation with the possibility to translate in both directions is not a simple task. Because then the tool will have to provide arbitrary switching between source and target models, and therefore the LHS and RHS graphs will have to be changed according to the switch, which is rarely provided by graph approaches to model transformations. This means that the LHS and the RHS part of a transformation rules have to be switched out. This is not provided in the DPF Transformation Editor. One could do this in two steps, to first locate matches in a source model and produce a target model and then do another model transformation where the source and target part is switched. Both Henshin and AGG does not provide this since the corresponding RHS and LHS graphs are created according to the abstract syntax of the source and target model. These tools could also do two seperate model transformation in different directions, but then the two model transformations are independent of eachother and that is not how a bidirectional transformation is designed. Its obvious that all four tools are unidirectional, since they can be executed in one direction only. ATL operate on read-only source models and produce a write-only target model. The tools requires two model transformations to be able to transform in multiple directions. Where the source and target model and meta-models switch places. However, this is not how a bidirectional transformations work. A bidirectional model transformation is implemented as a couple of transformations that has one transformation for each direction.

7.3.8 Tracing

Tracing in the four tools provides an unique link between a source and a target model. The source represents the matched part while the target represents the produced or replaced part. The four tools provides dedicated support for traceability, however these traceable links are handled differently amongst the tools. For ATL the trace model works as a storage location and automatically creates trace links between source and target elements. These traceable links are internally used by the ATL transformation engine when executing a model transformation. However, we explained in section 3.4.7 that traceable links in ATL can be explicitly captured by creating transformation rules that generates a collection of traceable links in a separate trace file. Henshin does this differently, because tracing is controlled by the users. Henshin has a dedicated Trace Model that can be imported to the Henshin module as an Ecore model. Traceable links between modeling elements are automatically created when executing rules, but the user have to manually assign the traceable links inside the transformation rules. The traces in Henshin are translated when a rule is executed, and therefore the user has to be aware of this when using these traces in other rules, since this could lead to the creation of multiple traceable links between the same modeling elements. This is also why the Trace Model is required for Henshin to perform an exogenous model transformation. Because in Henshin a traceable link is translated as any other target modeling elements. This means that these traceable links are included in the searching model for future applied rules. If we want to produce new target modeling elements in other rules based on already translated target modeling elements the traceable links between source and target modeling elements are required for the models to remain consistent during a model transformation. The DPF Transformation Editor defines a traceable link with source and target modeling elements differently amongst nodes and arrows. For DPF models nodes and arrows are defined by the EClass modeling element that Ecore provides. Tracing in AGG plays a vital role to executing model transformations. Traceable elements are created similar to any other elements when initializing the type graph. With traceable links between the source and the target elements, AGG can be certain that elements are transformed. The traceable link in AGG ensures that a match in the pattern graph is only matched once. If we do not create a traceable link between source and target elements in AGG, the rules will be applied an endless amount of times. Tracing amongst the three different tools are different in such a way that it is required for exogenous model transformations for AGG and ATL. In ATL the traceable links are created automatically and cannot be controlled by the users, while in AGG the traceable links are created as bridges between source and target elements.

7.3.9 Translating the instance model

When ATL transformation language executes the application rules for the model to model transformation, a new model instance is created for the target model. This means that the source model is independent of the target model. Henshin and AGG on the other side performs in-place model to model transformations. This means that they both operate on an instance model of the source meta-model, and translates inside this instance model. On the other side, for ATL this is not needed, since both the source and target model are kept as separated files. This is also possible to achieve with Henshin if the user programmatically invoke the Henshin Interpreter. Henshin performs an in-place model transformation, but with the possibility to save the translated object in a separate file. The DPF Transformation Editor utilize the strengths of Henshin to perform an in-place model transformation of a source model and explicitly creates a target model based on the results of this source model. All four approaches can however give the same result. Inn AGG and Henshin the users just need to make sure to delete unwanted elements from the translated source model.

Chapter 8

Conclusion

There are several model transformation environments available that provides model to model transformations. These environments are designed accordingly to different approaches to model transformations. In this thesis we have explored three different model transformation environments that could expand the DPF Workbench with model to model transformation. We integrated a version of the DPF Transformation Editor that integrates the Henshin transformation language and engine to provide an exogenous model transformation environment for DPF. This is something to consider though, because even though the DPF Transformation Editor provides support for exogenous model transformations the language syntax of DPF remains the same before and after executing a set of transformation rules. This means that without the ontological metamodels we could not extend a tool with support for exogenous model transformations. However, since we can include modeling formalisms at different layers of abstraction with the help of application conditions, Henshin proved to be a viable transformation language that facilitates a model to model transformation environment for the DPF Workbench. In this thesis we have explained that Henshin can be extended with application conditions to perform model transformations on models described through arbitrary layers of abstractions.

- Application conditions to specify the abstract syntax from a DPF specification one abstraction layer higher.
- Requires a traceable link between each source and target modeling elements. This traceable link is utilized in three different aspects when integrating Henshin with the DPF Transformation Editor.
    1. Specifies that the engine only translates a matching pattern once.
    2. Defines a correspondence between source and target modeling elements.
    3. Reusable in other rules if the source and target element are used to define the LHS and RHS graph.

For an exogenous model transformation Henshin requires a traceable link between source and target modeling elements not only to specify the correspondence between two modeling objects, but also to reuse the source and target node of this traceable links in other rules. These modeling objects represents either a node or an arrow in a DPF specification. For a transformation rule when a traceable link is first established it is actually transformed like any other graph structure initialized by the RHS graph. Now we can use this traceable link if for example produced modeling elements are part of the LHS and RHS graph in other transformation rules. Note that to use a traceable link in other rules arises a potential dependency issue. The reason for this is because in this solution we designed the application control mechanism to apply transformation rules in a sequential order. If the application control utilizes a non-deterministic mechanism to apply rules then the target model would in worst case not produce any result. Since one rule requires a traceable link that should be initialized in another rule. However, to apply a set of transformation rules non-deterministically is convenient if the source model contains a dense graph, which should not be an issue since DPF specifications are human made.

The integration of Henshin with DPF allows for the possibility to translate a DPF specification to a DPF specification that conforms to another modeling formalism. The solution still requires more testing on different exogenous model transformation scenarios, but editor should be able to create a set of transformation rules in Henshin based on a source and target modeling formalism.

8.1 Future Work

There are still some work that is required to do before the DPF Transformation Editor becomes a mature system that can provides model to model transformations.

8.1.1 Endogenous Model Transformations

In this thesis we present an integration of Henshin that supports exogenous model transformations over different layers of abstraction, but the DPF Transformtaion Editor should be extended with endogenous model transformations. This can also be achieved by using Henshin, but an endogenous model transformation solution is done differently in Henshin compared to an exogenous model transformation. For Henshin we can utilize the double pushout approach to first locate a match, then delete modeling elements that are uniquely part of the LHS. The next pushout consist of inserting modeling elements that are uniquely part of the RHS. While these two operations are performed, modeling elements that is part of both the LHS and the RHS are preserved. This meant that we do not need traceable links to provide endogenous model transformation on DPF specifications in Henshin.

8.1.2 Making the Model Transformations constraint aware

The DPF Transformation Editor does at this moment not provide model to model transformation that is constraint aware for the source and target modeling formalism. Basically this means that we do not consider the constraints that is defined in the abstract syntax of the source and target meta-model. Figure 8.1 explains how we can do this.

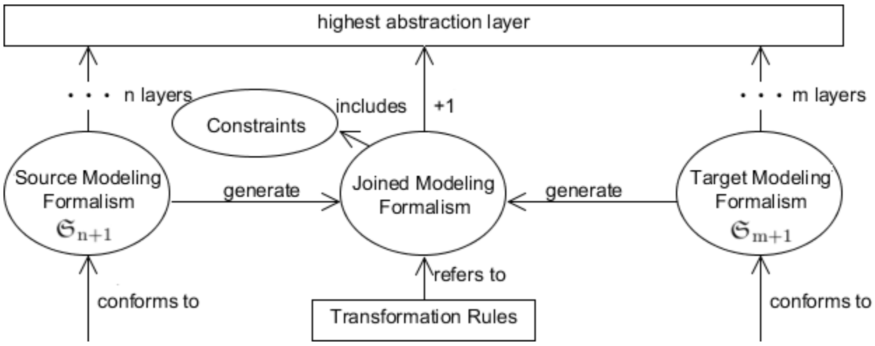


FIGURE 8.1: A simplified joined modeling formalism with constraints that transformation rules refers to.

We could extend the joined modeling formalism with constraints. This means that we have to create the constraints for both the source modeling formalism and the target modeling formalism in the joined modeling formalism. This means that we can make transformation rules in the DPF Transformation Editor that also includes the possibility to define the RHS with constraints based on constraints from the LHS. This is particularly convenient if we want to transform one modeling formalism into another modeling formalism.

8.1.3 Verification of target modeling formalism predicates

When the target model are finished with the transformation the corresponding predicates from the target modeling formalism requires verification. This can be achieved by searching through every single node and arrow in the target specification and make sure that the predicates are fulfilled with the target modeling formalism one abstraction layer higher.

Bibliography

[1] G. Premkumar and M. Potter, "Adoption of computer aided software engineering (case) technology: an innovation adoption perspective," *ACM SIGMIS Database*, vol. 26, no. 2-3, pp. 105–124, 1995.

[2] "OMG Unified Modeling Language^{TM} (OMG UML), Infrastructure." http://www.omg.org/spec/UML/2.4.1/.

[3] Rational, "Rational Unified Process: Best Practices for Software Development Teams," 1998.

[4] IBM Rational Software. http://www-01.ibm.com/software/rational/rup/. [Online; accessed 11-November-2013].

[5] The International Business Machines Corporation. http://www.ibm.com/ibm/us/en/. [Online; accessed 11-November-2013].

[6] K. Schwaber and M. Beedle, *Agile software development with Scrum*, vol. 1. Prentice Hall Upper Saddle River, 2002.

[7] K. Beck and C. Andres, *Extreme programming explained: embrace change*. Addison-Wesley Professional, 2004.

[8] R. France and B. Rumpe, "Model-driven development of complex software: A research roadmap," in *2007 Future of Software Engineering*, pp. 37–54, IEEE Computer Society, 2007.

[9] R. Brown, I. Morris, J. Shrimpton, and C. D. Wensley, "Graphs of morphisms of graphs," *the electronic journal of combinatorics*, vol. 15, no. A1, p. 1, 2008.

[10] M. Brambilla, J. Cabot, and M. Wimmer, *Model-Driven Software Engineering in Practice*. Morgan and Claypool, 2012.

[11] S. Cook and S. Kent, "The domain-specific ide," *UPGRADE, IX*, no. June, 2008.

[12] A. Rutle, *Diagram Predicate Framework A Formal Approach to MDE*. PhD dissertation, Department of Informatics, University of Bergen, Norway, 2010.

[13] "OMG Meta Object Facility (MOF) Core Specification Version 2.4.1." http://www.omg.org/spec/MOF/2.4.1/.

[14] "OMG. UML 2.0 OCL Specification, OMG Adopted Specification. Version 2.0." http://www.omg.org/spec/OCL/2.0/.

[15] J. Warmer and A. Kleppe, *The Object Constraint Language: Getting Your Models Ready for MDA*. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 2 ed., 2003.

[16] M. Blaha and J. Rumbaugh, *Object-oriented modeling and design with UML, Second Edition*. Pearson Prentice Hall, 2005.

[17] M. Fowler, *Domain-specific languages*. Pearson Education, 2010.

[18] Y. Lamo, X. Wang, F. Mantz, O. Bech, a. Sandven, and a. Rutle, "DPF Workbench: a multi-level language workbench for MDE," *Proceedings of the Estonian Academy of Sciences*, vol. 62, no. 1, p. 3, 2013.

[19] M. Fowler, "Language workbenches: The killer-app for domain specific languages," 2005.

[20] A. Rossini, *Diagram Predicate Framework meets Model Versioning and Deep Metamodelling*. PhD dissertation, Department of Informatics, University of Bergen, Norway, 2011.

[21] Z. Diskin and B. Kadish, "Variable set semantics for keyed generalized sketches: Formal semantics for object identity and abstract syntax for conceptual modeling," *Data & Knowledge Engineering*, vol. 47, no. 1, pp. 1–59, 2003.

[22] D. Duval, "Diagrammatic specifications," *Mathematical Structures in Computer Science*, vol. 13, pp. 857–890, 12 2003.

[23] Ø. Bech, "DPF Editor, A Multi-Layer Modelling Environment for Diagram Predicate Framework in Eclipse," 2011.

[24] T. Mens and P. Van Gorp, "A taxonomy of model transformation," *Electronic Notes in Theoretical Computer Science*, vol. 152, pp. 125–142, 2006.

[25] T. Arendt, E. Biermann, and S. Jurack, *Henshin: advanced concepts and tools for in-place EMF model transformations*. Springer Berlin Heidelberg, 2010.

[26] J. De Lara and E. Guerra, "Deep meta-modelling with METADEPTH," in *Objects, Models, Components, Patterns*, pp. 1–20, Springer, 2010.

[27] T. Levendovszky, L. Lengyel, G. Mezei, and H. Charaf, "A systematic approach to metamodeling environments and model transformation systems in VMTS," *Electronic Notes in Theoretical Computer Science*, vol. 127, no. 1, pp. 65–75, 2005.

[28] K. Letkeman, "Comparing and merging UML models in IBM Rational Software Architect," *IBM Rational, July*, 2005.

[29] "Meta Object Facility (MOF) 2.0 Query/View/Transformation Specification, Version 1.1." http://www.omg.org/spec/QVT/1.1/, 2011.

[30] Wikipedia, "Model transformation — wikipedia, the free encyclopedia," 2013. [Online; accessed 25-October-2013].

[31] The Eclipse Modeling Project. http://www.eclipse.org/modeling/. [Online; accessed 11-November-2013].

[32] F. Jouault, F. Allilaire, J. Bézivin, and I. Kurtev, "ATL: A model transformation tool," *Science of Computer Programming*, vol. 72, no. 1, pp. 31–39, 2008.

[33] The MMT project. http://www.eclipse.org/mmt/. [Online; accessed 11-November-2013].

[34] R. Dvorak, "Model transformation with operational QVT," *Borland Software Corporation*, 2008.

[35] G. Csertán, G. Huszerl, I. Majzik, Z. Pap, A. Pataricza, and D. Varró, "Viatra-visual automated transformations for formal verification and validation of uml models," in *Automated Software Engineering, 2002. Proceedings. ASE 2002. 17th IEEE International Conference on*, pp. 267–270, IEEE, 2002.

[36] D. Balasubramanian, A. Narayanan, C. van Buskirk, and G. Karsai, "The graph rewriting and transformation language: Great," *Electronic Communications of the EASST*, vol. 1, 2007.

[37] G. Taentzer, "AGG: A Graph Transformation Environment for Modeling and Validation of Software," in *Applications of Graph Transformations with Industrial Relevance*, pp. 446–453, Springer, 2004.

[38] J. De Lara and H. Vangheluwe, "AToM^3: A Tool for Multi-formalism and Meta-modelling," in *Fundamental approaches to software engineering*, pp. 174–188, Springer, 2002.

[39] K. Czarnecki and S. Helsen, "Feature-based survey of model transformation approaches," *IBM Systems Journal*, vol. 45, no. 3, pp. 621–645, 2006.

[40] K. C. Kang, S. G. Cohen, J. A. Hess, W. E. Novak, and A. S. Peterson, "Feature-oriented domain analysis (foda) feasibility study," tech. rep., DTIC Document, 1990.

[41] R. Prieto-Díaz, "Domain analysis: an introduction," *ACM SIGSOFT Software Engineering Notes*, vol. 15, no. 2, pp. 47–54, 1990.

[42] S. Dasgupta, C. Papadimitriou, and U. Vazirani, *Algorithms.* Tata McGraw - Hill Education, 2006.

[43] A. Yie and D. Wagelaar, "Advanced traceability for atl," in *1st International Workshop on Model Transformation with ATL*, pp. 78–87, 2009.

[44] H. Herrlich and G. Strecker, *Category theory.* Allyn and Bacon Boston, 1973.

[45] M. Barr and C. Wells, *Category theory for computing science.* No. 22, Prentice Hall New York, 1990.

[46] S. Awodey, *Category Theory.* Oxford University Press, 2006.

[47] A. Corradini, U. Montanari, F. Rossi, H. Ehrig, R. Heckel, and M. Löwe, "Algebraic approaches to graph transformation-part i: Basic concepts and double pushout approach.," in *Handbook of Graph Grammars*, pp. 163–246, 1997.

[48] H. Ehrig, R. Heckel, M. Korff, M. Löwe, L. Ribeiro, A. Wagner, and A. Corradini, "Algebraic approaches to graph transformation-part ii: Single pushout approach and comparison with double pushout approach.," in *Handbook of Graph Grammars*, pp. 247–312, Citeseer, 1997.

[49] H. Ehrig, M. Pfender, and H. J. Schneider, "Graph-grammars: an algebraic approach," in *14th Annual Symposium on Switching Automata Theory*, (New York, NY, USA), pp. 167–180, IEEE; Univ. Iowa, IEEE, 1973.

[50] A. Corradini, T. Heindel, F. Hermann, and B. König, "Sesqui-pushout rewriting," in *Graph Transformations*, pp. 30–45, Springer, 2006.

[51] M. Bauderon, "A uniform approach to graph rewriting: The pullback approach," in *Graph-Theoretic Concepts in Computer Science*, pp. 101–115, Springer, 1995.

[52] A. Habel, R. Heckel, and G. Taentzer, "Graph grammars with negative application conditions," *Fundamenta Informaticae*, vol. 26, no. 3, pp. 287–313, 1996.

[53] A. Sandven, "Metamodel based Code Generation in DPF Editor," 2012.

[54] Xpand. Project Web Site. . http://wiki.eclipse.org/Xpand. Accessed: 2013-11-11.

[55] R. Gitzel, I. Ott, and M. Schader, "Ontological extension to the MOF metamodel as a basis for code generation," *The Computer Journal*, vol. 50, no. 1, pp. 93–115, 2007.

[56] ATLAS group Lina and Inria, "ATL: Atlas Transformation Language, ATL User Manual version 0.7," 2006.

[57] K. Jensen, L. M. Kristensen, and L. Wells, "Coloured petri nets and cpn tools for modelling and validation of concurrent systems," *International Journal on Software Tools for Technology Transfer*, vol. 9, no. 3-4, pp. 213–254, 2007.

[58] The Henshin project. http://www.eclipse.org/henshin/. [Online; accessed 11-November-2013].

[59] J. Schmidt, *Entwicklung eines visuellen Editors zur Steuerung von EMF Modelltransformationen*. 2010.

[60] A. Warning, *Entwicklung eines visuellen Editors fr Anwendungsbedingungen und amalgamierte Regeln zur Flexibilisierung von EMFModelltransformationen*. 2010.

[61] Eclipse. http://www.eclipse.org/. [Online; accessed 11-November-2013].

[62] The World Wide Web Consortium (W3C). http://www.w3.org/standards/xml/. Accessed: 2013-11-11.

[63] D. Steinberg, F. Budinsky, M. Paternostro, and E. Merks, *EMF: Eclipse Modeling Framework 2.0*. Addison-Wesley Professional, Dec. 2009.

[64] OBEO Model Driven Company. http://www.obeo.fr/pages/atl-pro/en. [Online; accessed 11-November-2013].

[65] The AtlanMod ("Atlantic Modeling") team. http://www.emn.fr/z-info/atlanmod/index.php/Main_Page. [Online; accessed 11-November-2013].

[66] Generative Modeling Technologies. http://wiki.eclipse.org/index.php/GMT. [Online; accessed 11-November-2013].

[67] T. Arendt, E. Biermann, S. Jurack, C. Krause, and G. Taentzer, "Henshin: Advanced concepts and tools for in-place emf model transformations," in *Model Driven Engineering Languages and Systems* (D. Petriu, N. Rouquette, and y. Haugen, eds.), vol. 6394 of *Lecture Notes in Computer Science*, pp. 121–135, Springer Berlin Heidelberg, 2010.