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Designing the automatic transformation of visual 3 languages

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Abstract

The design process of complex systems requires a precise checking of the functional and dependability attributes of the target design. The growing complexity of systems necessitates the use of formal methods, as the exhaustiveness of checks performed by the traditional simulation and testing is insufficient.

For this reason, the mathematical models of various formal verification tools are automatically derived from UML-diagrams of the model by mathematical transformations guaranteeing a complete consistency between the target design and the models of verification and validation tools.

In the current paper, a general framework for an automated model transformation system is presented. The method starts from a uniform visual description and a formal proof concept of the particular transformations by integrating the powerful computational paradigm of graph transformation, planner algorithms of artificial intelligence, and various concepts of computer engineering. © 2002 Published by Elsevier Science B.V.

Keywords: System verification; Validation; Graph transformation; Model transformation; Visual languages; Planner algorithms; MOF; UML; Dependability

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1. Introduction

For most computer controlled systems, especially dependable, real-time systems for critical applications, an effective design process requires an early conceptual and

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¹ This work was supported by the Hungarian National Scientific Foundation Grant (OTKA T030804) and the Foundation for the Hungarian Higher Education and Research (FKFP 0193).

1 architectural validation prior to the implementation in order to avoid costly re-design
2 cycles. All relevant system characteristics have to be checked during this *system veri-*
3 *fication* phase in order to have a guaranteed design quality. These parameters identify
4 critical bottlenecks to which the system is highly sensitive.

5 The increasing need for effective design has necessitated the development of stan-
6 dardized and well-specified design methods and languages, which allow system, devel-
7 opers to work on a common platform of design tools. The *Unified Modelling Language*
8 (*UML*) is a visual specification language for pure software systems, as well as for em-
9 bedded real-time systems (systems reactively interacting with their environment). The
10 UML represents a collection of best engineering practises that have proven successful
11 in the modelling of large and complex systems. Recently, UML has been regarded as
12 the standard object-oriented modelling language.

13 1.1. Formal methods in system design

14 *Formal methods* are mathematics-based techniques offering a rigorous and effective
15 way to model, design and analyze computer systems. They have been a topic of research
16 (in projects like IOSIP [8], SafeRail [4], SpeciMen [6] or HIDE [2]) for many years
17 with valuable academic results. However, their industrial utilization is still limited to
18 specialized development sites, despite their vital necessity originating in the complexity
19 of IT products and the increasing requirements for dependability and Quality of Service
20 (QoS).

21 The use of formal verification tools (like e.g. PVS [13]) in IT system design is
22 hindered by a gap between practice-oriented CASE tools and sophisticated mathematical
23 tools. On the one hand, system engineers usually show no proper mathematical skills
24 required for applying formal verification techniques in the software design process.
25 On the other hand, even if a formal analysis is carried out, the consistency of the
26 manually created mathematical model and the original system is not assured. Moreover,
27 the interpretation of analysis results, thus the re-projection of the mathematical analysis
28 results to the designated system is problematical. From the engineering point of view,
29 the notion of dependability is a composite one necessitating the analysis of multiple
30 mathematical properties by using different verification tools.

31 The aim of our ongoing research is to provide a provenly correct and complete,
32 automated transformation between UML-based system models and formal mathe-
33 matical verification tools for an effective software design.

34 1.2. Mathematical model transformation

35 The step generating the description of the target design on the input language
36 of mathematical tools from the UML model of the system is called *mathematical*
37 *model transformation*. The inverse direction of model transformation (referred as *back-*
38 *annotation*) is of a similar practical importance as well when some problems (e.g. a
39 deadlock) are detected during the mathematical analysis. After an automated

1 back-annotation these problems can be observed in the same UML system model al-
2 lowing the designer to fix conceptual bugs within his well-known UML environment.

3 The practical application of transformation based design and verification necessitates
4 the analysis of the UML model from different aspects. This way a transformation envi-
5 ronment has to support the implementation of several transformations towards different
6 mathematical tools.

7 Several semi-formal transformation algorithms have already been designed and im-
8 plemented for different purposes (e.g. formal verification of functional properties and
9 quantitative analysis of dependability attributes [3]). Unfortunately, this conventional
10 way (i.e. experiences in the experimental implementation process) of model transfor-
11 mation raised several problems.

- 12 • The lack of unique and formal descriptions of the transformation algorithms resulted
13 in hand-written and rather ad hoc implementations (inconvenient for implementing
14 complex transformations).
- 15 • Any formal proof of correctness and completeness of these transformation scripts is
16 almost impossible, hence their uncertain quality remains a bottleneck of the entire
17 transformation based verification approach.
- 18 • Each model had to be verified individually although the transformation algorithms
19 have similar underlying algorithmic skeletons.

20 As a conclusion, a general and automated transformation method was missing, which
21 would generate the target models from a well-formed, high-level specification.

1.3. Research objectives

23 Our proposal for the previous problems is a general mathematical model transfor-
24 mation system supporting the automated generation of transformation code of a proven
25 quality for an arbitrary number of transformations. Such an automated model transfor-
26 mation system has to fulfil at least the following requirements [20]:

- 27 • *Requirement 1:* The easy-to-understand *description of source and target models*
28 (based on metamodels) in order to support a variety of transformations;
- 29 • *Requirement 2:* A visual but mathematically precise *description of transformation*
30 *rules* clearly indicating the correspondence between the elements of the UML visual
31 programming paradigm and the target mathematical notation;
- 32 • *Requirement 3:* An efficient *back-annotation* of mathematical analysis results (aiming
33 to visualize the results of the analysis in a UML notation);
- 34 • *Requirement 4:* An engine for *proving semantic correctness and completeness* of
35 transformations;
- 36 • *Requirement 5:* An *automatic model generation* from the visual transformation rules.

37 Transformations correctly proved necessitate a precise underlying mathematical struc-
38 ture for both source models (like UML) and target models (such as Kripke structures,
39 Petri Nets, computational tree logic, etc.). Additionally, model transformation and back-
40 annotation also have to be ruled strictly and precisely (Requirements 1–3).

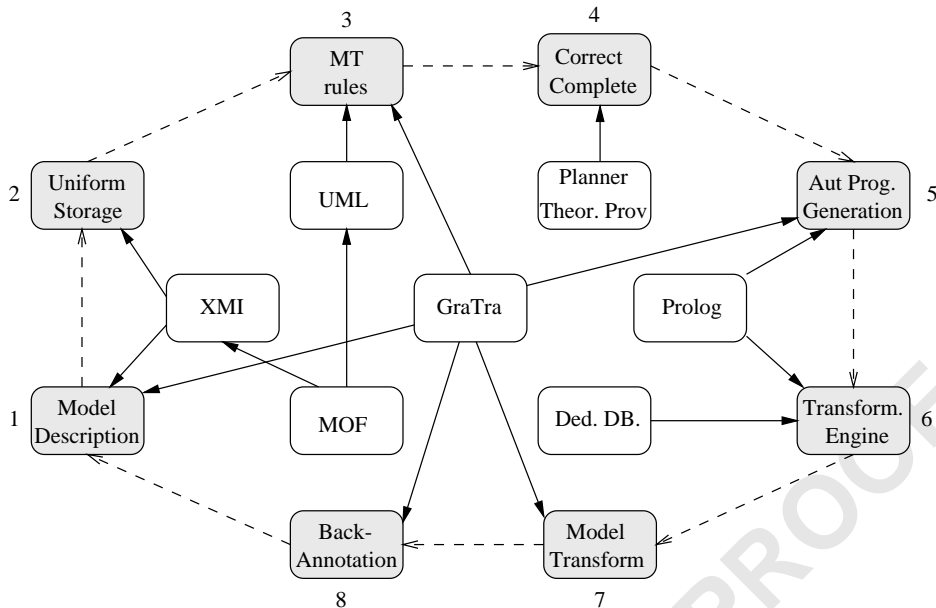


Fig. 1. An overview of VIATRA.

1 The quality of model transformation (Requirements 4 and 5) should be ensured by an
 2 automated proof method for correctness and completeness, which step will be followed
 3 by an automated program generation phase. The program derived takes a specific UML
 4 model as input and generates the language of a particular verification tool as the output.
 5 As a result, the quality bottlenecks originating in the former heuristic implementation
 (manual coding) could be eliminated.

7 1.4. VIATRA: a visual automated model transformation system

9 Our model transformation approach (which is an integration of different disciplines
 10 of artificial intelligence, and computer engineering) is based on formal mathematical
 11 background and provides a general transformation description language and methodol-
 12 ogy for a large scale of transformations.

13 The process of model transformation is characterized by a model analysis round-trip
 (illustrated by the sequence of rounded grey boxes in Fig. 1).

15 (1) *Model description*. A model transformation for practical applications necessitates
 16 on one hand a uniform and precise description of source and target models to
 17 improve the quality of such transformations. But, on the other hand, it should
 18 follow the main standards of the industry in order to be integrated to software
 design methodologies.

19 For this reason, the *Meta Object Facility (MOF)* metamodeling techniques
 are used in VIATRA. MOF metamodels provide graphical means to define

1 metaobjects for similarly behaving instances in various domains by combining the
2 expressive power of UML Class diagrams (concerning the structure) with the Ob-
3 ject Constraint Language (OCL) for describing semantic issues. MOF metamodels
4 are used as a basis for describing UML models (following the standard metamodel
5 of UML) as well as mathematical structures (by creating non-standard metamodels
6 for them).

7 A typical UML model contains more details than required for a specific mathe-
8 matical analysis (for instance, documentation or use case diagrams are frequently
9 of little importance). Thus, in the sequel, a UML model will only contain the
10 relevant pieces of information with respect to a specific analysis, and this re-
11 duced model can be obtained from the original user-created system model by some
12 filtering mechanism.

13 In VIATRA, filtering is expressed by metamodels. Exactly those constructs are
14 regarded as relevant (thus transformable) that is are included in the metamodel of
15 the source language (hence if specific constructs are irrelevant for one purpose,
16 they are simply omitted from the metamodel).

- 17 (2) *Uniform representation of models.* The front-end and back-end of transformations
18 (UML as the source model and a formal verification tool as the target model) is
19 defined by a uniform, standardized description language of system modelling, that
20 is, *XMI (XML Metadata Interchange)*. XMI is a special metamodel dependent
21 collection of XML constructs providing an XML representation for arbitrary (MOF
22 based) models.

23 XMI seems to be a natural choice as a large number of UML tool vendors
24 provide a facility to export their models into XMI, moreover, several academic
25 communities (e.g. the graph transformation community [19]) have started discus-
26 sion to settle on a general XML based interchange format for their tools.

- 27 (3) *Model transformation rules.* The visual specification of model transformations is
28 supported by *graph transformation* [1,15,8], which combines the advantages of
29 graphs and rules into an efficient computational paradigm.

30 A *graph transformation rule* is a special pair of pattern graphs where the in-
31 stance defined by the left-hand side is substituted with the instance defined by the
32 right hand side when applying such a rule (similarly to the well-known grammar
33 rules of Chomsky in computational linguistics).

34 Model transformation rules (in the form of graph transformation rules) are speci-
35 fied by using a visual notation of UML. However, for obtaining a tool-independent
36 transformation specification, the transformation rules will also be exported in an
37 XML based format, conforming to the evolving standard of graph transformation
38 systems [19].

- 39 (4) *Correctness and completeness.* Automated transformations necessitate an auto-
40 mated proof method aiming to verify that the generated target models are se-
41 mantically correct (correctness problem). Moreover, each construct allowed in the
42 source model should be handled by a corresponding rule (completeness
43 problem).

44 Instead of verifying the semantic correctness of individual target models we put
45 the stress on the *correctness and completeness of transformation rules*, i.e. starting

1 from a source model that fulfils some semantic criteria, the derivation steps should
2 always keep these properties invariant for the target design.

3 (5) *Automated program generation*. Even if the description of the transformation is
4 theoretically correct and complete, additionally, the source and target models are
5 also mathematically precise, the implementation of these transformations has a
6 high risk on the overall quality of a transformation system. As a possible solution,
7 *automatic transformation algorithm generation* is carried out for implementing
8 visual transformation rules and control structures.

9 (6) *The transformation engine*. As being a logic programming language based on
10 powerful unification methods, Prolog seems to be a suitable language for a pro-
11 totype implementation of the transformation engine. Thus, the XMI based models
12 and rule descriptions are translated into a Prolog graph notation serving as the input
13 data and the program to be executed, respectively. After a successful prototyping
14 phase, Prolog could be substituted with a more powerful but lower abstraction
15 level language (like C++ or Java).

16 (7) *Model transformation*. Model transformation is performed by executing the au-
17 tomatically generated Prolog program supplied with the Prolog description of the
18 source model. According to our experiments (see Section 4 for benchmark appli-
19 cations), the time required for the transformation is just a few percentage of the
20 total time spent on the formal analysis exploring the entire state space.

21 (8) *Back-annotation of analysis results*. The results of the mathematical model trans-
22 formation are planned to be automatically back-annotated to the UML based sys-
23 tem model. Thus, the system analysts are reported from conceptual bugs in their
24 well-known UML notation. Unfortunately, the current version of UML does not
25 directly support the representation of analysis traces. For instance, the sequence of
26 fired statechart transitions that leads to a deadlock (according to the verification
27 tool) completely lacks a fine-grained UML representation.

28 As model transformations are frequently projections in a mathematical sense,
29 thus, they cannot be inverted in general. Moreover, several formal analysis meth-
30 ods often perform another model transformation (e.g. a deadlock detection algo-
31 rithm may take the description of a transition system as input and may generate
32 a sequence of fired transitions as output). For this reason, back-annotation is not
33 equivalent with an inverse model transformation, as it only requires the identifi-
34 cation of related source and target objects.

35 1.5. Related results

36 In Section 1.3, we set up several requirements that has to be *simultaneously* fulfilled
37 by a general purpose model transformation system. Currently, a brief overview of
38 previous results (typically achieved in projects with different objectives and orientation)
39 is provided concerning these individual fields.

- 40 • *Model description*: Model transformations necessitate a formal specification of mod-
41 els in arbitrary domains with a special emphasis on defining a precise semantics
42 for UML. PROGRES [17] provides a general framework for graph models and their

1 transformations with typed graphs conforming to graph schemata. In FUJABA, UML
2 models are formally specified by combining UML and graph transformation [10],
3 while an algebraic presentation of models is used for defining the semantics of UML
4 in [11].

5 As a convenient handling of multiple metamodels (e.g. establishing correspon-
6 dence between source and target languages) are not addressed by these approaches,
7 reference graphs (and metamodels) are introduced in VIATRA.

- 8 • *General rule representation*: Model transformation rules require a visual, easy-to-
9 understand and platform independent notation. The idea of using UML as a specifi-
10 cation language of graph transformation rules (by collaboration and activity diagrams)
11 first appeared in [12]. Alternately, a general description of rules can be obtained on
12 an XML level [19]. In VIATRA, rules are specified in a (slightly different) UML
13 notation, and intended to be exported conforming to the evolving GTXL standard.
- 14 • *Correctness and completeness*: Traditional graph transformation approaches (e.g.
15 double pushout [5], single pushout [9]) elegantly deal with the soundness of a *single*
16 transformation step (proving that the resulting object is a graph). However, in model
17 transformation systems, the notion of correctness and completeness is related to an
18 arbitrary sequence of transformation rules.
- 19 • *Automatic program generation*: Using graph transformation as a programming lan-
20 guage forms the basic idea of PROGRES ([17]), which generates C code for the
21 implementation of graph transformation rules. VIATRA generates executable Prolog
22 code from high level UML based rule specifications as further verification steps will
23 be based on these Prolog term representations.
- 24 • *Model transformation approaches*: MTRANS [14] provides an XSLT based
25 framework for transforming MOF compliant models. Transformation scripts are spec-
26 ified in a purely textual language. Individual model transformations were designed in
27 RIVIERA [16], where UML models are transformed to the Maude language in order
28 to carry out formal analysis and verification. VIATRA is a general model transfor-
29 mation system for automating the creation of *different* models for formal verification.
- 30 • *Back-annotation, inverse transformation*: The triple graph grammar (TGG) approach
31 [18] provides a general bi-directional transformation mechanism for graph languages.
32 TGG uses correspondence graphs coupling the source and target objects. However,
33 in order to obtain bi-directionality, there is a loss in efficiency by having costly
34 graph pattern matching for both directions. Model transformation rules in VIATRA
35 are uni-directional (i.e. traditional graph transformation rules), thus back-annotation
36 can be more efficient by using simple reference relations instead of graph pattern
37 matching.

2. Model description

2.1. Running example

39 In order to simultaneously demonstrate the technicalities of model transformation and
40 the typical questions from the engineering background, we selected a small fragment
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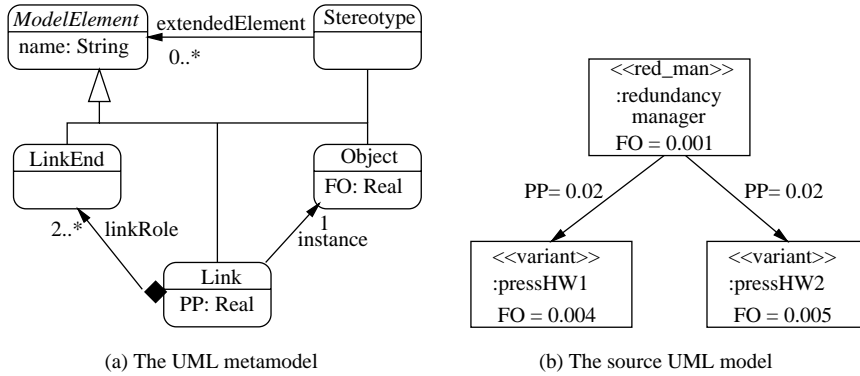


Fig. 2. The source language: UML object diagram.

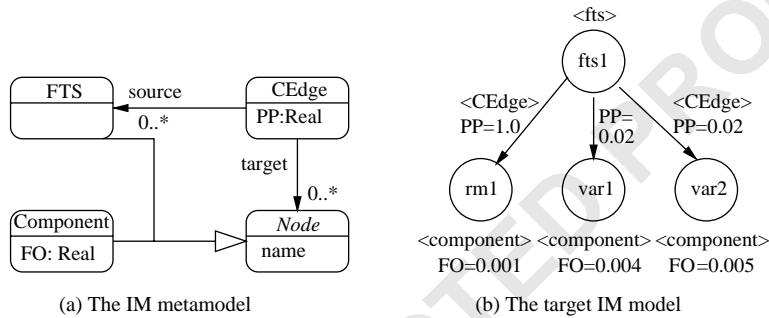


Fig. 3. The target language: IM hypergraph.

1 of a complex transformation as the basis of our running example. The complete trans-
 2 formation (discussed in details in [3]) generates stochastic Petri Nets from static UML
 3 models enriched with special dependability attributes (e.g. failure rate of components).
 4 Each static relation between high-level objects is regarded as a potential error propa-
 5 gation path. This Petri Net based analysis aims at the identification of dependability
 6 bottlenecks in an early phase of design.

7 The entire transformation is divided into two major steps. At first, a Intermediate
 8 Model (in the form of a simple hypergraph) is derived in order to extract important
 9 dependability attributes from UML models. Afterwards, the Petri Net model can be
 10 transformed straight from this intermediate hypergraph representation (without the use
 11 of original UML models).

12 In our running example, the transformation of fault tolerant structures will be
 13 performed from static UML models (depicted in Fig. 2) to this intermediate graph
 14 representation called Intermediate Model (IM in Fig. 3).

15 The simplified metamodel of UML (describing stereotyped objects and links
 between them with abstract classes printed in italics) is depicted in Fig. 2(a). The

1 metamodel is enriched with two dependability parameters: the fault occurrence rate F_0
 2 in objects and fault propagation probability PP of links (as potential propagation
 3 paths).

4 The sample source UML model (in a visual UML notation in Fig. 2(b)) repre-
 5 sents a fault-tolerant structure which consists of three objects, a redundancy manager
 6 (`redundancy_manager`) and two variants (`pressHW1` and `pressHW2`) identified by the
 7 corresponding stereotypes (`red_man` and `variant`) and the links between them. The
 8 redundancy manager is responsible for switching from one variant to the other when
 9 an error is detected.

10 The target IM metamodel in Fig. 3(a) specifies a hypergraph consisting of (i) nodes
 11 of type `FTS` representing the fault tolerant structure as a whole, (ii) nodes of type
 12 `Component` standing for system components, (iii) and edges of type `CEdge` indicating
 13 the “composed of” relation.

14 In the sample target IM hypergraph model in Fig. 3(b), (i) a single graph node
 15 of type `Component` is assigned to each variant object (`var1`, `var2`), (ii) two distinct
 16 nodes (`fts1` and `rm1` of types `FTS` and `Component`, respectively) are assigned to
 17 each redundancy manager, (iii) the `fts` node is in a ‘composed of’ relation with the
 18 remaining three nodes as indicated by the edges of type `CEdge`.

19 2.2. Graph models

20 In this section, basic concepts of graph transformation systems (such as graphs,
 21 graph transformation rules, transformation units, etc.) are applied to the special needs
 22 of model transformation built upon MOF metamodels in order to provide a precise
 23 (but still practice oriented) mathematical background. For the basic definitions (such
 24 as directed, typed and attributed graphs), the reader is referred to [1].

25 **Definition 1.** A *model graph* G is a directed, typed and attributed graph with the
 26 following structure (expressed e.g. by a corresponding schema graph).

- 27 • A graph node is associated with a unique identifier ld , and a type label τ_n .
- 28 • An edge has an own ld , a reference to a source ld_S and a target ld_T identifier, and
 29 a type label τ_e .
- 30 • Both nodes and edges may be related to attributes (represented e.g. as special
 31 graph nodes) with an ld identifier (referring to the graph element the attribute is
 32 related to), a type label τ_a and a data value V .

33 Model graphs may also contain n -ary relations between nodes (denoted as relations
 34 or hyperedges), but these relations are represented by a special class of model graph
 35 nodes connected to “original” graph nodes by special (reserved) types of edges. Model
 36 graph relations are closely related (in their use and functionality) to PROGRES path
 37 expressions with multiple source and/or target nodes.

38 From MOF models to model graphs: Model graphs are derived automatically from
 39 MOF based models. Each node and edge must have type labels corresponding to an

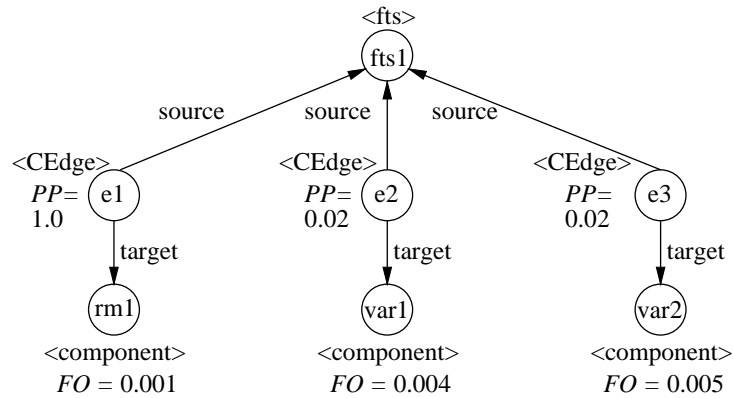


Fig. 4. Model graphs from MOF based models.

- 1 MOF construct. The most fundamental rules of this derivation are the following:
- 3 • Instances of an MOF Class (A) are mapped into model graph nodes with identically named types.
 - 5 • Associations in MOF based models are typically non-directed links between instances. However, model graphs are directed graphs, each (navigable) AssociationEnd of a MOF Association (E) between two MOF Classes (from A to B) is projected into a separate model graph edge. A further type restriction states that all the graph edges of type E have to connect a graph node of type A to a node of type B.
 - 7 • MOF attributes are directly mapped into model graph attributes.

11 With this respect, the model graph of Fig. 4. is an equivalent of the IM model of Fig. 3(b) (attributes are printed in italics).

13 *Reference graphs:* As the main goal of model transformation is to derive a target model from a given source model, source and target objects must be linked to each other in some way to form a single graph. For this reason, the following definition introduces the concepts of a *reference graph*. The structure of a reference graph is also constrained by a corresponding metamodel, which contains (i) references of existing source and target metamodel nodes; (ii) novel (so-called) reference nodes that provide a typed coupling of source and target objects, and (iii) reference edges connecting all these nodes.

15 **Definition 2.** A *reference graph* $G_{\text{ref}} = (G_s, G_t, \text{NODES}_{\text{ref}}, \text{EDGES}_{\text{ref}})$ contains a source and a target model graph (G_s and G_t , respectively), and an additional set of reference nodes $\text{NODES}_{\text{ref}}$ and edges $\text{EDGES}_{\text{ref}}$, where

- 23 • a *reference node* is a model graph node (thus associated with a unique identifier ld , and a type label T_n) of the reference metamodel.
 - 25 • a *reference edge* is a model graph edge (of the reference metamodel) that may lead from a reference node to either a source, a target or a reference element of a specific type.
- 27

1 As several models (such as statecharts, subnets in high-level Petri nets) are structured
 2 into a hierarchy, the previous definition of reference graphs can be extended by allowing
 3 reference nodes to relate (sub)graphs to (sub)graphs (in addition to single nodes). As
 4 a result, a more flexible reference structure is obtained, however, the reference graph
 5 is no longer a simple graph but a hierarchical graph.

2.3. Transformation rules

7 **Definition 3.** A **graph transformation rule** $r = (L, R, \text{App})$ contains a left-hand side
 (LHS) graph L , a right-hand side (RHS) graph R , and application conditions App .

9 The application of r to a host graph (graph instance) G replaces an occurrence of
 the LHS L in G by the RHS R . In general, this is performed by

- 11 (1) finding an occurrence of L in G (also denoted as graph pattern matching),
- 12 (2) checking the application conditions App (such as negative application conditions
 13 which prohibit the application of the rule in the presence of certain nodes and
 edges),
- 14 (3) removing a part of the graph G determined by the occurrence of L yielding the
 context graph D ,
- 15 (4) gluing R and the context graph D and obtaining the **derived** graph H .

16 The adaption of graph transformation rules to model transformations prescribe
 17 special requirements for the structure of these rules. As the target model is constructed
 18 from scratch, model transformation rules are frequently non-deleting, which ensures the
 19 pleasant property of being able to handle all the LHS matches parallelly.

20 On the other hand, when the deletion of certain graph objects is prescribed by a
 21 rule, we must ensure that distinct parallel matches do not conflict with each other. In
 22 our model transformation approach, parallelly executable rules cannot remove any part
 23 of the graph to avoid such problems.

24 Following the classification of different graph transformation approaches that can be
 25 found in [15], a model transformation rule is defined as follows:

26 **Definition 4.** A **model transformation rule** r_{mt} is a special graph transformation rule,
 27 where

- 28 • both graphs L and R are reference graphs;
- 29 • an occurrence of L in G_{ref} is required to be an isomorphic image of L ;
- 30 • all the dangling edges are deleted automatically;
- 31 • non-deleting rules are matched (and executed) parallelly as default.

32 A sample model transformation rule is depicted in Fig. 5. Please note that in order
 33 to improve the clarity of the illustrations, only a graphical representation of rules is
 34 indicated and the underlying model graph structure is omitted. Negative application
 35 conditions are denoted by objects embedded in a region painted gray.

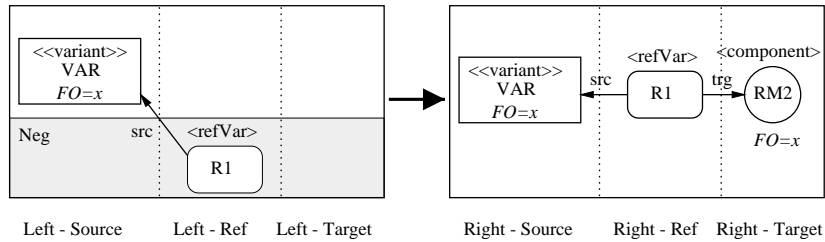


Fig. 5. A sample model transformation rule.

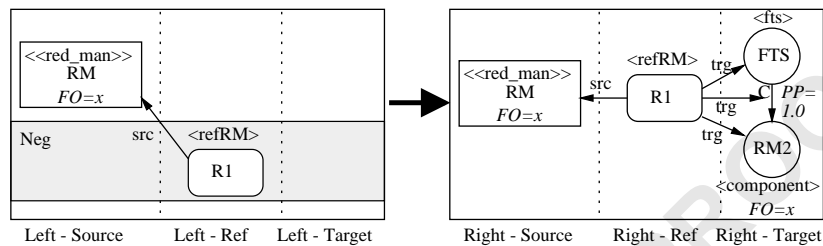


Fig. 6. Model transformation rule “ftsR”.

1 The LHS of this rule requires a UML object with the stereotype *variant* to be
 2 present on the source side without a reference edge to a reference node of type *refVar*
 3 (indicated by the negative condition), while there are no restrictions for the target
 4 design. According to the RHS, a new IM node of type *component* and a new reference
 5 node of type *refVar* is inserted and connected to the UML object by corresponding
 6 reference edges (of type *src* and *trg*). In addition to structural modifications, the
 7 value of an object’s attribute *FO* is also projected into the target design.

8 As possible industrial applications of model transformation surely consist of very
 9 large and complex models containing hundreds of rules, model transformation rules
 10 must be extended by a sophisticated structuring mechanisms that allow to compose
 11 them in a modular way. In the graph transformation community, the concepts of *trans-*
 12 *formation units* were introduced for this purpose (e.g. [1]), which units are adapted
 13 for structuring model transformations in VIATRA.

2.4. A sample transformation

14 Our sample model transformation is carried out by three transformation rules ap-
 15 plied in the specific order: *ftsR*, *variantR* and *linkR*. The process of our sample
 16 transformation is the following (characterized by the *parallel* application of rules in
 17 correspondence with the default semantics).

- 18 (1) Transform all the redundancy managers in the UML model into two connected
 19 IM nodes (*ftsR*; Fig. 6).

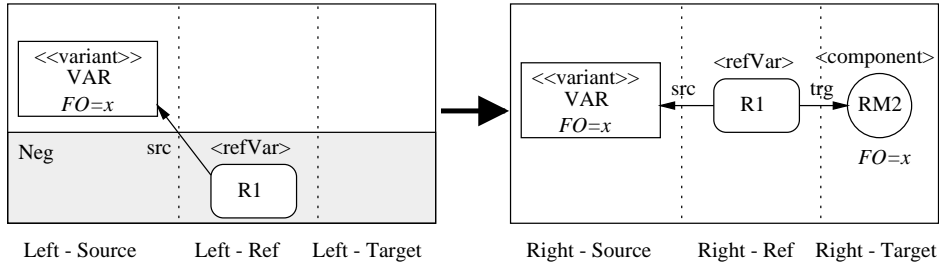


Fig. 7. Model transformation rule “variantR”.

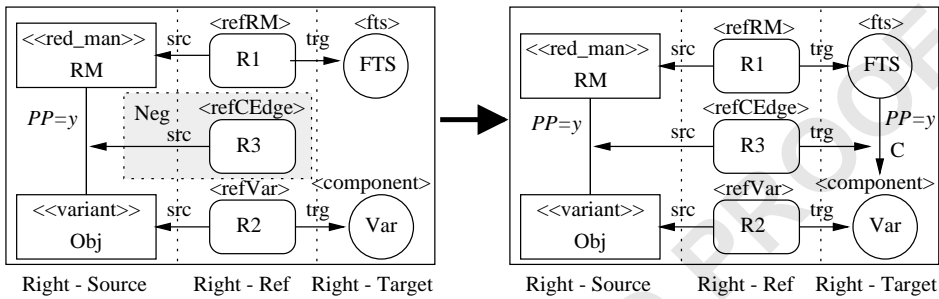


Fig. 8. Model transformation unit “linkR”.

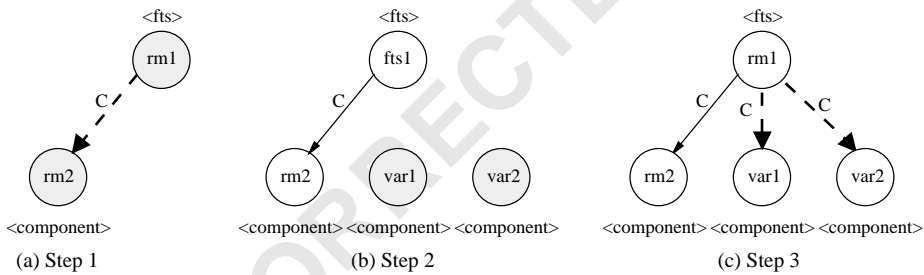


Fig. 9. Tracing the transformation step by step.

- 1 (2) Create a new IM node for each UML object with stereotype “variant” (variantR; Fig. 7).
- 3 (3) Link (by applying linkR in Fig. 8) each IM equivalent of variant objects with the corresponding equivalent of a node of type fts (i.e. fault tolerant structure).
- 5 By equivalent we mean related reference nodes and edges between the elements.

The construction of the target IM model is illustrated in Fig. 9. Nodes that have been created most recently are colored grey while new edges have dashed lines.

Step 1: An fts node and an component node are created by applying the transformation rule ftsR.

1 *Step 2:* The component nodes are constructed by applying transformation rule
variantR for the two occurrences of a source variant object.

3 *Step 3:* The fts nodes are connected to the component nodes (as a result of applying
linkR) by adding a new IM edge. Each pair of these nodes are linked only once, which
5 is ensured by the negative context condition on the LHS.

7 As a conclusion, we illustrated that model transformation can be specified by means
of graph transformation rules. In the following, we concentrate on the proven quality
of transformations (namely, correctness and completeness).

9 3. Correctness and completeness of transformations

11 The validity of some system requirement formulated in a temporal logics represen-
tation is typically verified by applying model checking or theorem proving techniques.
The proofs constructed by theorem provers are general in the sense that they hold in
13 any models of the specification. Model checkers, on the contrary, operate on given
model instances (i.e. finite representations of a general underlying theory). In this sec-
15 tion, the concepts of correctness and completeness for model transformation systems
(called *syntactic well-formedness* in the sequel) will be defined analogously on two
17 levels.

- 19 • *Model dependent approach:* In this first case, the well-formedness of individual trans-
formation instances (i.e. the transformation of a specific source model) are checked.
- 21 • *Metamodel/grammar dependent approach:* In this case, we are aiming to prove that
the transformation is correct for any instance of the source metamodel (i.e. any
sentence of the source grammar).

23 Before being able to discuss the correctness of model transformations, one has to
decide what a correct model and a correct transformation is.

- 25 • A first idea may be to prove the *semantic equivalence* of source and target models.
Unfortunately, many model transformations are projections (i.e. some constructs of
27 the source model are not transformed) thus semantic equivalence cannot be proven.
- 29 • In the future, we are planning to set up special *invariant criteria* that a transformation
must preserve, which criteria would be checked by of model checking or theorem
proving techniques.
- 31 • However, in the current paper, correctness is defined by means of visual languages
and graph grammars in analogy with traditional computational linguistics (thus on a
33 *syntactic level*).
 - 35 ◦ *Model dependent (simple) correctness* is defined by means of parsing the visual
sentences generated by a model transformation by using the graph grammar of the
target language.
 - 37 ◦ *Metamodel dependent (total) correctness* is stronger than the previous as it aims
to prove that *each model* generated by a model transformation system is a sen-
39 tence of the target language. As the structure of model transformation rules mainly
resembles to the structure of the source model, this problem is not at all trivial.

1 In the sequel, we suppose that a graph grammar exists for each metamodel (e.g.
 2 a graph grammar of UML or IM) which controls the construction of well-formed
 3 visual sentences. As the process of editing such models is not considered, we may
 4 also suppose that *no rules of these graph grammars prescribe the deletion of some*
 5 *elements*. Naturally, the structure of model transformation rules is not restricted in this
 6 sense.

7 3.1. Model correctness

8 Thus, in the current paper, a model is considered to be correct whenever it can
 9 be derived from the start graph (regarded as an axiom) by graph transformation rules
 10 (regarded as deduction rules).

11 **Definition 5** (Graph grammar). *Let $\mathcal{G} = (\mathcal{S}, \mathcal{R}_{\mathcal{G}})$ be a production system with the*
 12 *axiom \mathcal{S} (start graph) and deduction rules $\mathcal{R}_{\mathcal{G}}$ (graph transformation rules). This*
 13 *system is called a graph grammar (considering that all graph nodes are terminal*
 14 *nodes).*

15 **Definition 6** (Derivable). *Let $\mathcal{G} = (\mathcal{S}, \mathcal{R}_{\mathcal{G}})$ be a graph grammar. We call a graph \mathcal{M}*
 16 *(called model or sentence later) derivable from \mathcal{G} (denoted as $\mathcal{G} \vdash \mathcal{M}$) iff \mathcal{M} can be*
 17 *obtained from the start graph \mathcal{S} by a finite sequence of graph transformation steps*
 18 *using deduction rules $\mathcal{R}_{\mathcal{M}}$.*

19 **Definition 7** (Visual language). *Let \mathcal{G} be a graph grammar. The visual language (of*
 20 *the graph grammar), denoted as $\mathcal{L}_{\mathcal{G}}$, contains all the graphs that are derivable*
 21 *from \mathcal{G} .*

$$\mathcal{L}_{\mathcal{G}} = \{\mathcal{M} \mid \mathcal{G} \vdash \mathcal{M}\},$$

22 where \mathcal{M} is graph called (visual) sentence.

23 3.2. Transformation correctness

24 After discussing the correctness of models, correctness of model transformation will
 25 be introduced, built upon well-formed source models as axioms.

26 **Definition 8** (Model transformation). *Let $\mathcal{T} = (\mathcal{M}_{\mathcal{A}}, \mathcal{R}_{\mathcal{T}})$ be a graph grammar with*
 27 *the start graph $\mathcal{M}_{\mathcal{A}}$, called source model (a sentence of the source visual language),*
 28 *and model transformation rules $\mathcal{R}_{\mathcal{T}}$. \mathcal{T} is denoted as model transformation.*

29 **Definition 9** (Model transformation system). *A model transformation system is a*
 30 *tuple $\mathcal{M}\mathcal{T}\mathcal{S} = (\mathcal{A}, \mathcal{R}_{\mathcal{T}}, \mathcal{B})$, where \mathcal{A} and \mathcal{B} are graph grammars defining the source*
 31 *and target language, respectively, and $\mathcal{R}_{\mathcal{T}}$ is a set of model transformation*
 32 *rules.*

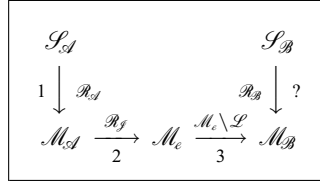


Fig. 10. Concepts of correctness.

1 **Corollary 10.** Let $\mathcal{M}\mathcal{T}\mathcal{S} = (\mathcal{A}, \mathcal{R}_{\mathcal{T}}, \mathcal{B})$ be a model transformation system. $\forall M_{\mathcal{A}} : \mathcal{A} \vdash M_{\mathcal{A}}, \mathcal{T} = (\mathcal{M}_{\mathcal{A}}, \mathcal{R}_{\mathcal{T}})$ is a model transformation.

3 Several models may be derived by a model transformation system from different
 5 source models. However, such a system is of little importance if these derived models
 7 are incorrect sentences of the target graph grammar. To express the difference, models
 that are derived by a model transformation system will be denoted as *model candidates*.
 This concept of correctness is illustrated in Fig. 10.

Definition 11 (Derivable as target). Let $\mathcal{T} = (\mathcal{M}_{\mathcal{A}}, \mathcal{R}_{\mathcal{T}})$ be a model transformation.
 9 A graph $M_{\mathcal{B}}$ (called model candidate) is derivable as target from \mathcal{T} (denoted as
 $\mathcal{T} \vdash_t M_{\mathcal{B}}$ or $\{\mathcal{M}_{\mathcal{A}}, \mathcal{R}_{\mathcal{T}}\} \vdash_t M_{\mathcal{B}}$) iff

$$11 \quad \exists M_c : (\mathcal{T} \vdash M_c) \wedge (M_{\mathcal{A}} \cup M_{\mathcal{B}} = M_c \setminus \mathcal{L}),$$

where \mathcal{L} is the set of all reference nodes and edges in M_c .

13 Model transformation rules build a common supergraph M_c containing the orig-
 15 inal source model $M_{\mathcal{A}}$ and the novel target model candidate $M_{\mathcal{B}}$, which are con-
 17 nected by reference nodes and edges \mathcal{L} . The target model candidate can be obtained
 from this supergraph if the original source model and the reference objects are
 removed.

In the following, the most important notions of model transformation systems
 (namely, correctness and completeness) are defined.

- 19 • Informally, a *model transformation is correct*, if the derived target candidate is a
 21 sentence of the target language (model dependent).
- 23 • A *model transformation system is correct*, whenever correctness holds for each
 source model (metamodel dependent).

Definition 12 (Correctness: model transformation). Let $\mathcal{T} = (\mathcal{M}_{\mathcal{A}}, \mathcal{R}_{\mathcal{T}})$ be a model
 25 transformation and \mathcal{B} be a graph grammar defining the target language. \mathcal{T} is correct
 (with respect to \mathcal{B}) iff

$$27 \quad \mathcal{T} \vdash_t M_{\mathcal{B}} \Rightarrow \mathcal{B} \vdash M_{\mathcal{B}}.$$

Such a correctness will also be denoted as simple correctness.

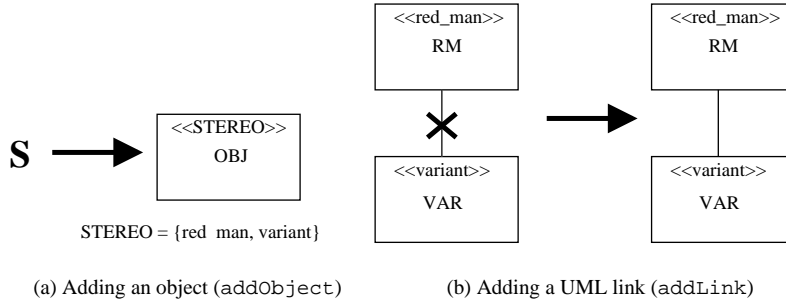


Fig. 11. Graph grammar of the source UML models.

1 **Definition 13** (Correctness: model transformation system). Let $\mathcal{M}\mathcal{T}\mathcal{S} = (\mathcal{A}, \mathcal{R}_{\mathcal{T}}, \mathcal{B})$ be a model transformation system. $\mathcal{M}\mathcal{T}\mathcal{S}$ is correct iff

$$3 \quad \forall M_{\mathcal{A}} : \mathcal{A} \vdash M_{\mathcal{A}} \wedge \{\mathcal{M}_{\mathcal{A}}, \mathcal{R}_{\mathcal{T}}\} \vdash_t M_{\mathcal{B}} \Rightarrow \mathcal{B} \vdash M_{\mathcal{B}}.$$

Such a system is also called total correct.

5 Completeness is also defined on two levels: finding an appropriate source model for a given target sentence and for each target model.

7 **Definition 14** (Completeness: model transformation). Let \mathcal{B} be a graph grammar, and $M_{\mathcal{B}}$ be a model of this grammar. A model transformation \mathcal{T} is complete (with respect to $M_{\mathcal{B}}$) iff

$$9 \quad \mathcal{B} \vdash M_{\mathcal{B}} \Rightarrow \mathcal{T} \vdash_t M_{\mathcal{B}}.$$

11 This process (finding one or more source models for a given target sentence) is also called *back-annotation* or simple completeness.

13 **Definition 15** (Completeness: model transformation system). Let $\mathcal{M}\mathcal{T}\mathcal{S} = (\mathcal{A}, \mathcal{R}_{\mathcal{T}}, \mathcal{B})$ be a model transformation system. $\mathcal{M}\mathcal{T}\mathcal{S}$ is complete iff

$$15 \quad \forall M_{\mathcal{B}} \exists M_{\mathcal{A}} : \mathcal{B} \vdash M_{\mathcal{B}} \Rightarrow \{\mathcal{M}_{\mathcal{A}}, \mathcal{R}_{\mathcal{T}}\} \vdash_t M_{\mathcal{B}} \wedge \mathcal{A} \vdash M_{\mathcal{A}}.$$

3.3. Examples on correctness and completeness

17 In the sequel, theoretical foundations are illustrated on our running example of the UML-IM model transformation.

19 At first, a model transformation system is created by source and target languages defined by graph grammar rules. Such a small grammar for handling the running example may be the following (shown in Figs. 11 and 12, where S is a placeholder for any empty LHS). Negative application conditions follow the traditional notation

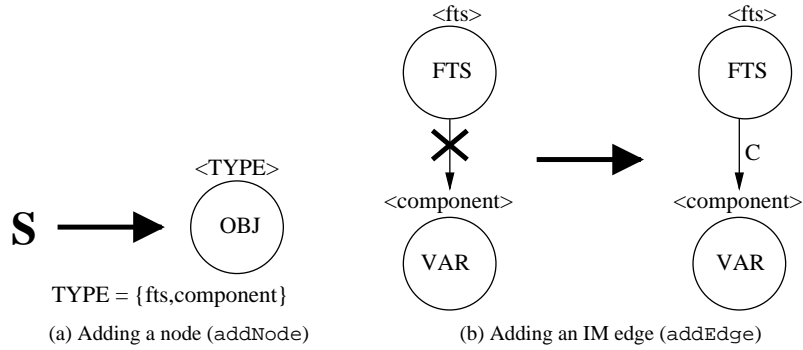


Fig. 12. Graph grammar of the target IM models.

- 1 (crossed edges) while typing constraints are interpreted as application conditions for
 2 the transformation rule.
- 3 • Let $\mathcal{M}\mathcal{T}\mathcal{S}$ be a model transformation system with source grammar \mathcal{A} of Fig. 11,
 4 target grammar \mathcal{B} of Fig. 12, and model transformation rules $\mathcal{R}_{\mathcal{T}}$ are the ones in
 5 Figs. 6–8.
- 6 • Let \mathcal{T} be a model transformation with source model $\mathcal{M}_{\mathcal{A}}$ of Fig. 2(b) and model
 7 transformation rules $\mathcal{R}_{\mathcal{T}}$.
- 8 • Let $\mathcal{M}_{\mathcal{B}}$ of Fig. 3(b) be a target model candidate.

9 **Proposition 16.** \mathcal{T} is correct (with respect to \mathcal{B}).

Proof. It is sufficient to show a sequence of derivations that is able to construct $\mathcal{M}_{\mathcal{B}}$
 11 from graph grammar \mathcal{B} . In other words, we have to show that the sentence $\mathcal{M}_{\mathcal{B}}$ can
 12 be parsed by using the inverse rules of grammar \mathcal{B} .

13 Let us consider the following sequence (in the given order within the same group),
 14 where $\text{addNode}(A,B)$ means to add the node B of type A, while $\text{addEdge}(C,D)$ adds
 15 an edge between nodes C, and D:

- 16 (1) $\text{addNode}(\text{fts}, \text{im1}), \text{addNode}(\text{component}, \text{im2}), \text{addEdge}(\text{im1}, \text{im2}),$
 17 (2) $\text{addNode}(\text{component}, \text{var1}), \text{addNode}(\text{component}, \text{var2}),$
 18 (3) $\text{addEdge}(\text{im1}, \text{var1}), \text{addEdge}(\text{im1}, \text{var2}).$

19 One can easily notice that the derivation process is similar to the one of Fig. 9. As
 20 a result, the same graph is constructed in each case. \square

21 **Corollary 17.** \mathcal{T} is complete (with respect to $\mathcal{M}_{\mathcal{B}}$).

Proposition 18. $\mathcal{M}\mathcal{T}\mathcal{S}$ is correct.

23 **Proof.** In this proof, each application of a model transformation rule will be related
 to a sequence of target grammar rules. Thus, when a model transformation rule is

Model transformation rules	Target grammar rules
ftsR	addNode(fts, FTS), addNode(component, RM2), addEdge(FTS, RM2)
variantR	addNode(component, VAR)
linkR	addEdge(FTS, VAR)

Fig. 13. Rule coupling for proving correctness.

1 applied, we try to apply the corresponding sequence of grammar rules. If the tar-
 3 get model candidate and the parallelly generated target model is isomorphic after
 each model transformation step then the model transformation must be correct as
 well.

5 In other words, starting from the target graph on the LHS of a model transformation
 rule, the target graph on the RHS of the similar rule has to be created by the graph
 7 grammar rules of the target language (empty target side is related to the \mathcal{S} start
 symbol).

9 Let us consider the following coupling of rules (depicted in Fig. 13).

11 As a result, the modifications performed by model transformation rules on the target
 model candidate are simulated by graph grammar rules of the target language, thus
 $\mathcal{M}\mathcal{T}\mathcal{S}$ is correct. \square

13 **Proposition 19.** $\mathcal{M}\mathcal{T}\mathcal{S}$ is not complete (unfortunately).

15 **Proof.** For a counterexample, let us consider a target model $\mathcal{M}'_{\mathcal{B}}$ with an individual
 node of type fts. Let us suppose that there exists a source model $\mathcal{M}'_{\mathcal{A}}$ which can be
 transformed to $\mathcal{M}'_{\mathcal{B}}$.

17 Such a source model must contain a redundancy manager object as it is the only
 object that is projected into an fts node. When performing the transformation of the
 19 redundancy manager, an additional node and edge will appear in the target model
 candidate.

21 As the graph grammar of the target language does not contain any rules that would
 be able to remove graph nodes and edges, the original target model must be a subgraph
 23 of the resulting model candidate. \square

25 Please note that if another set of model transformation rules were used (splitting
 ftsR into three rules: one is generating the fts node and the second one derives the
 component node, finally, the third one creates the link between those two), complete-
 27 ness could have been proven.

29 All the proofs presented here (especially the proofs of correctness) may serve as
 skeletons for further proofs in connection with model transformation systems. However,
 the problem of an automated verification still remains. In the following, the sketch of

1 such an automated proof method for syntactic correctness is presented, based upon
 2 planner algorithms of artificial intelligence.

3 3.4. Proving correctness by planner algorithms

4 *Planner algorithms* [21] are complex, hierarchical problem solving procedures subdi-
 5 viding the original problem into smaller parts before trying to solve them according to
 6 the “divide and conquer” principle. Finally, these partial solutions are merged together
 7 yielding the solution of the original problem.

8 **Definition 20.** A planner $\mathcal{P}\mathcal{A} : (\mathcal{I}, \mathcal{E}, \mathcal{O}) \mapsto \mathcal{P}$, is a structure where \mathcal{I} is the first-order
 9 logics formulae of the initial state, \mathcal{E} is the first-order logics formulae of the goal
 10 state, while \mathcal{O} is the set of permitted operations. The output is plan \mathcal{P} , which is a
 11 sequence of operations providing a trajectory from the initial to the goal state.

12 **Definition 21.** A planner operation $\mathcal{O} = (\mathcal{C}, \mathcal{A})$, where \mathcal{C} stands for the precondi-
 13 tions (first-order logics formulae), and \mathcal{A} for actions. Preconditions must hold before
 14 performing the specific operation. Actions may add or remove certain basic logics for-
 15 mulae (called facts) to the state space.

16 In the following, a planner will be constructed to prove correctness of model trans-
 17 formations.

- 18 • Basic facts are built up from model graphs (supposing the close world assumption,
 19 i.e. when all the true facts have to be listed explicitly).
 - 20 ◦ From a model graph node of type `type` with an identifier `id` the predicate `type`
 21 (`id`) is generated.
 - 22 ◦ From a model graph edge of type `type` with its own `id`, source `src` and target
 23 `trg` identifiers, the predicate `type(id,src,trg)` is generated.
 - 24 ◦ From a model graph attribute attached to the node identified by `id` with a name
 25 `name`, and having value `value`, the predicate `name(id,value)` is generated.
- 26 • Graph grammar rules (of the source and target language) are encoded into planner
 27 operations according to the following mapping:
 - 28 ◦ The LHS of a rule together with application conditions are encoded into a planner
 29 precondition.
 - 30 — LHS objects are encoded into positive predicates in the Prolog style, i.e. with
 31 (unbound) variables for `ids`.
 - 32 — Negative application conditions are (universally quantified) negative statements.
 - 33 — Further general conditions concerning uniqueness (and context) are added to
 34 the precondition of each operation. As our graph grammars do not contain
 35 deleting rules, postconditions are implicitly defined by the LHS objects and
 36 the additions prescribed by the RHS. This way, general postconditions such
 37 as the dangling edge condition need not be considered.
 - 38 ◦ the changes defined by the RHS of the rule are mapped into planner actions
 39 defining element additions (serving as new postconditions).

1 **Definition 22.** Let $\mathcal{A} = (\mathcal{S}, \mathcal{R}_{\mathcal{A}})$ and $\mathcal{B} = (\mathcal{S}, \mathcal{R}_{\mathcal{B}})$ to form the model transformation
 3 system $\mathcal{M}\mathcal{T}\mathcal{S} = (\mathcal{A}, \mathcal{R}_{\mathcal{T}}, \mathcal{B})$. The proof planner $\mathcal{P}\mathcal{A}_{\mathcal{T}}$ of correctness is sequence of
 5 $\mathcal{P}\mathcal{A}_i$ sub-planners (one assigned for each model transformation rule $\mathcal{R}_i \in \mathcal{R}_{\mathcal{T}}$) which
 7 are defined as follows:

- 5 • the initial state of $\mathcal{P}\mathcal{A}_i$ is defined by the left target side graph of the model trans-
 7 formation rule,
- 7 • a subgoal of $\mathcal{P}\mathcal{A}_i$ is defined by the right target side graph of the model transfor-
 9 mation rule.
- 9 • the operations are defined by the graph grammar rules $\mathcal{R}_{\mathcal{B}}$ of the target
 11 language.

11 **Proposition 23.** If a plan can be constructed for each \mathcal{R}_i then the model transforma-
 13 tion system $\mathcal{M}\mathcal{T}\mathcal{S}$ is correct.

13 **Proof (Sketch).** Speaking in graph transformation terms, we are aiming to prove that
 15 (i) whenever a model transformation (MT) rule is applied (to one specific match),
 17 (ii) and its effects can be simulated in general by applying a specific sequence of the
 19 target graph grammar (GG) rule on the target part of MT rule graphs, (iii) this specific
 21 sequence is applicable for the specific (isomorphic) match in the host graph thus deriv-
 23 ing the parsing steps of the host graph from parsing just the MT rule graph. (Please
 25 note the differences of rule and host graphs; graph grammar and model transformation
 27 rules). \square

21 According to our construction, performing a planner operation is identical to applying
 23 the related GG rule (without deletions). According to the assumption, there exist a
 25 sequence of GG rules that derives the right target graph (and not the image of it)
 27 from the left target graph of the MT rule. Such a sequence must not create additional
 29 graph objects (as side effects) due to the lack of deleting rules and the closed world
 31 assumption for the subgoal.

27 When an MT rule is applied, an isomorphic image of the initial and goal states are
 29 required to be present in the host graph. Thus, applying the same sequence of GG
 31 rules to that specific matching image, it will derive the image of the goal state (and
 nothing else).

31 Constructing a proof planner for correctness was only a demonstration. Similar plan-
 33 ners can be built for completeness as well by slight modifications.

33 4. Conclusion

35 In the current paper, our initial results towards a complex model transformation
 37 method was presented intended to perform mathematical model transformations in order
 39 to integrate UML-based system models and mathematical models of formal verification
 tools. Due to the large complexity of IT systems, model transformations are supported
 by an integrated environment composed of various fields of computer science (planner
 algorithms, graph transformation) and software engineering (UML, MOF).

1 For obtaining a higher quality of transformations, the syntactic correctness and com-
 3 pleteness of each transformation are proved, additionally, an executable Prolog code
 5 is derived automatically from high-level model transformation rules. As a result of
 an automated transformation and back-annotation of analysis results, a variety of for-
 mal verification tools will become available for system designers, without the thorough
 knowledge of underlying mathematics.

7 The following benchmark transformations have already been designed and imple-
 mented according to the model transformation concepts of VIATRA:

- 9 • Transforming the static aspects of UML models enriched with dependability para-
 11 meters into stochastic Petri Nets for dependability analysis in an early phase of
 system design;
- 13 • Transforming UML Statecharts into Extended Hierarchical Automaton that provide
 a formal operational semantics for these UML diagrams;
- Automatic Prolog program generation for visual control structures.

15 In our future plans, the reconsideration of the proof method and the implementa-
 17 tion of further model transformation are aimed at first. Semantic criteria that must be
 invariant to a model transformation may also be proved by using theorem provers and
 model checkers instead of planner algorithms.

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