Performance in Model Transformations: Experiments with ATL, QVT and Mistral

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Abstract

Model transformations are increasingly being incorporated in software development processes. However, as systems being developed with transformations and models grow in size and complexity, the performance of the transformations tends to degrade. In this paper we investigate the factors that have an impact on the execution performance of model transformations. We analyze the performance of three model transformation language engines, namely ATL, QVT Operational Mappings, and Mistral. We implemented solutions to two transformation problems in these languages, and compared the performance of these transformations. Additionally, we implemented these transformations in Java in order to evaluate the performance overhead imposed by the transformation languages. We extracted metric values from the transformations to systematically analyze how their characteristics influence transformation execution performance. In order to evaluate the effect of language constructs on transformation performance, we implemented different versions of the ATL and Mistral transformations in functionally equivalent ways but using different strategies. The results of this paper enable a transformation designer to estimate beforehand the performance of a transformation, and to choose among implementation alternatives to achieve the best performance. In addition, transformation engine developers may find some of our results useful in order to tune their tools for better performance.

Keywords: model transformations, metamodeling, ATL, QVT, Mistral, transformation languages, transformation execution performance

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1. Introduction

Since the introduction of Model-Driven Engineering, model transformations have become increasingly important in the software development process. Transformations are applied to problems that potentially involve huge models that need to be transformed. Examples of such problems are data translation and interoperability, refactoring of large code bases and model extraction. In order to be suitable for this task, transformation engines need to meet high scalability and performance requirements. In addition, transformation developers need to know the factors that determine the performance of transformations and need mechanisms to estimate and improve this performance.

Metamodels, models and transformation definitions all influence the performance of model transformations. The size and complexity of the input models are straightforward factors that affect transformation execution performance. In some model transformation languages, a certain transformation problem can be solved in multiple different but functionally equivalent ways. However, different constructs may influence the transformation execution performance either positively or negatively, and this needs to be investigated.

In this paper, we compare the performance of the transformation engines of three languages: ATL [14], QVT Operational Mappings [17] and Mistral [16]. The comparison is based on two carefully chosen example transformations that are executed for series of randomly generated input models with an increasing number of model elements. For each input model, we measured and compared the duration of the transformation execution. In addition we also implemented these transformations in Java, in order to evaluate the performance overhead imposed by the transformation languages. In order to analyze the effect of different language constructs on the performance of the transformation engines, we implemented one of the example transformations in five different ways in ATL and in two different ways in Mistral. Two version of the transformations have been implemented in Java (with and without SiTra [5]). We extracted metric values from the transformation definitions and analyzed the relation between these values and the performance results. This analysis should enable transformation implementors to estimate the performance of a given transformation, and to choose among alternative transformation languages (engines) and/or transformation language constructs. The results of this study can also be used by developers of transformation engines in order to improve the currently available tools.

This paper is structured as follows. Section 2 discusses the approach taken in this experiment. Section 3 elaborates on the metrics derived from the model transformations and their input. Section 4 gives the results of our model transformation experiments. Section 5 analyzes these results and draws some conclusions. Section 6 discusses related work. Section 7 gives our general conclusions and recommendations for future work.

2. Approach

The goal of this work is to compare the performance of the chosen transformation languages and their engines when facing input models of varying size and complexity, especially models that contain hundreds of thousands model elements. Transformation performance can be affected by several factors. In this paper we address the following factors:

Size of input model. As the number of input elements increases so does the number of the elements that are potentially matched by rules. This results in an increase of the elements to be transformed and in the overall execution time. We performed transformations on a series of models with increasing number of model elements.

Structure of input model. Models can be generally considered as graphs with a possibly complex interconnected structure of model elements. Model complexity may cause performance decrease, if complex navigation and matching needs to be done over a model. Some models may expose a simpler, tree-like structure. In order to study the impact of the structure of input models on transformations, we executed transformations over models with both simpler (tree-like and linear) structure, and more complex interconnection structures.

Transformation strategy. A given transformation problem may be solved in multiple alternative ways in a single language. Generally, different solutions may perform differently. We investigated the impact of the usage of different language constructs for a single transformation problem by implementing and executing five different but functionally equivalent solutions for the same transformation problem in ATL, and two for Mistral.

We compared the two model transformation tools that are part of the Eclipse M2M project (ATLAS Transformation Language (ATL) [13], Query/View/Transformations Operational Mappings (QVTo) [17], and a QVT-like language called Mistral [16]. The transformations implemented for these tools have also been compared with respect to performance with transformations implemented in Java, giving us a good indication of the performance overhead of using transformation languages.

2.1. Experimental Setup

We implemented two transformations in each language: the SimpleClass2SimpleRDBMS transformation and the RSS2ATOM transformation, both taken from the ATL zoo [18]. The input models in the SimpleClass2SimpleRDBMS transformation are graph-like class diagrams, while the input models of the RSS2ATOM transformation are tree-like. In this way we can compare how the structure of input models affects transformation execution performance.

SimpleClass2SimpleRDBMS Transformation

The SimpleClass2SimpleRDBMS transformation is one of the classical examples of model transformations, and has been implemented in many languages. This transformation takes a simplified class diagram as input and transforms this to a relational database model. The input model consists of *packages* that contain zero or more *classes* with *associations* between them. Classes can have zero or more *attributes*. Only classes that are marked as persistent are transformed to tables. Methods and other constructs normally found in class diagrams are not supported it this transformation. The resulting output model consists of *tables* that have *columns*, *primary keys* and *foreign keys*.

For the SimpleClass2SimpleRDBMS transformation, 62 models were generated using Epsilon [2]. About half of these models correspond to a general case scenario, in which some of the input classes are not marked as persistent and therefore are not transformed. The other models correspond to a worst case scenario, in which all classes are persistent and thus have to be transformed. The input models differ in the number of classes and the number of attributes per class. Attributes are restricted in such a way that the type of an attribute cannot be the class in which the attribute is defined.

The model transformations implemented per transformation scenario are functionally equivalent: the same input models are used for each transformation implementation, and the output models are, with a slight alteration in the order of the elements, identical.

The transformation was implemented in all three transformation languages (ATL, QVTo and Mistral) and in Java. We ensured that the output models generated by all transformations are identical. To be able to compare the languages, we tried to use similar constructs wherever possible. For example, the matched rules in the ATL transformation are encoded as mappings in QVTo.

RSS2ATOM Transformation

Unlike the graph-like structure of the SimpleClass models, Really Simple Syndication (RSS) models can be described as trees. An RSS model contains one *channel* (one root node), which in turn contains zero or more *item*s (child nodes). Consequently, an RSS model contains no cycles. Items in an RSS model have certain properties, like a title, description, a category, and a channel to which they belong.

The result of the RSS2ATOM transformation is a model with a similar tree-like structure, but as an ATOM model. Like RSS, the ATOM model consists of a single root node that contains *entries*. An ATOM entry is structured in the same way as the RSS item.

Similarly to the SimpleClass2SimpleRDBMS case, we implemented functionally equivalent RSS2ATOM transformations in each language. The generated output models are identical for each of the transformations for all of the input models.

Transformation Environment

In our experiments, we used the following transformation engines:

ATL. ATL plugin version 3.2.1.

QVTo. QVTo plugin version 3.1.0.

Mistral. Mistral version 0.9.

The plugins were run in a 64-bit Eclipse 3.7 SR1 Indigo environment, with 2GB of memory allocated to it.

The Java implementations of the transformations were executed using Ant scripts started from inside Eclipse without Virtual Machine forking, in order to allow a fair comparison with the transformations that run in Eclipse.

We executed all these transformations on the 64-bit Java Virtual Machine version 1.7 build 1, running on Microsoft Windows 7 Professional (64-bit version). The computer system was equipped with a quad core Intel Core i7 920 CPU, running at 2.67 GHz, and 6 GB of RAM.

The transformations were executed with several input models with increasing size. Transformations were run three times and the average time was taken. We executed the RSS2ATOM transformations 100 times. There was no significant difference in times for each run. The transformation execution process considered in our experiments starts at the moment the first metamodels are loaded and ends when the resulting model has been serialized.

2.2. Transformation Implementations

We implemented the SimpleClass2SimpleRDBMS transformation in ATL using different implementation strategies to study the effect of different language constructs on the performance of the transformation. We choose ATL to perform this experiment since it is a hybrid language that allows several alternative functionally equivalent implementations. The five alternative transformations entail the following changes:

Initial implementation (Transformation ATL). The initial implementation is a declarative transformation that inlines the navigation code over the input model in the bindings of transformation rules. It also uses the OCL operation `allInstances()` in order to obtain instances of class Association.

Move navigation to attribute helpers (Transformation ATL_a). In this transformation we moved the navigation expressions from the bindings to ATL attribute helpers. This causes the transformation to execute the navigation once, after which the result is cached for reuse. We expected that the performance should improved due to the reduced number of traversals over attributes of the classes.

Remove `allInstances()` (Transformation ATL_b). This transformation replaced `allInstances()` operation over associations with a matched rule. In this way each association is processed only once. Again, we expected an increased performance due to the lower number of visits for a single association.

Replace two matched rules with called rules (Transformation ATL_c). This transformation is hybrid since it contains both called and matched (lazy) rules. We replaced two matched rules from ATL_b with their functionally equivalent called rules. Furthermore, the transformation does not use the internal trace mechanism of declarative ATL when resolving classes to tables.

Implement imperatively (Transformation ATL_d). This transformation is purely imperative. It contains only called rules with imperative blocks and does not use the trace mechanism. Tracing is implemented by using a map-like structure available in ATL.

Transformations ATL_c and ATL_d are used to investigate the effect of mixing imperative and declarative constructs in a single ATL transformation. Overall, the five ATL transformations cover a wide spectrum of implementation options ranging from pure declarative to pure imperative implementations.

The SimpleClass2SimpleRDBMS transformation was implemented in Mistral in two different versions. We shall call these $Mistral$ and $Mistral_a$. Mistral is a declarative unidirectional transformation language. It was first reported in [16] and later on extended with reflective capabilities [15]. After a recent significant improvement of the engine it was possible to use the language in this experiment. Compared to ATL, Mistral offers only two types of rules: model element rules and helper rules. Model element rules are equivalent to matched rules in ATL with the possibility to instantiate OCL structures in the rule target. Helper rules are equivalent to ATL called rules. In contrast to ATL, Mistral allows modifications in both the source and target models and navigation over the target models.

Transformation $Mistral$ uses `allInstances()` to process associations whereas $Mistral_a$ uses a rule to process each association once. We expected that the avoidance of `allInstances()` will lead to a better performance. Transformation $Mistral$ is algorithmically equivalent to ATL_a, and $Mistral_a$ is equivalent to ATL_b.

We implemented two versions of each transformation (SimpleClass2SimpleRDBMS and RSS2ATOM) in Java, namely with and without SiTra [5]. SiTra is a library developed to facilitate the implementation of metamodel-based transformations in Java, offering facilities to define and execute transformation rules. SiTra stores the execution traces of these transformation rules, which avoids element duplication and allows one to reach already transformed target elements from source elements. For our SiTra-based version of our Java implementations we made some small adjustments to the original SiTra code[1] to allow the use of the code generated from the metamodels with the Eclipse Modeling Framework (EMF) tools [1].

3. Metrics

Software metrics have been extensively studied in the last decades. [12] Metrics can be used to get quick insights into the characteristics of a software artifact, among others. We have extracted metrics from the ATL and the QVTo transformations by using the metrics collection tool described in [6] and [8], respectively.

In this section, we describe the characteristics of the different transformations on the basis of the metrics extracted from the respective artifacts. We have used these characteristics to explain differences in the performance of the transformations later on in Section 5.

3.1. Java SimpleClass2SimpleRDBMS Transformations

In the Java implementations the programmer has to keep track of the order in which transformation rules are executed. In the SiTra-based version, we implemented the four inner transformation rules as specializations to the `Rule<Source,Target>` class provided by the library, while the high-level transformation controls the execution of these rules.

The Java implementation without SiTra has been strongly inspired by the SiTra version in terms of structure with one class for each transformation rule. However, in this implementation only tracing of the transformation from classes to tables is maintained (as a `HashMap<Class,Table>`), since this is the only tracing information necessary to perform the transformation. This has reduced considerably the overhead imposed by SiTra, which has an expensive tracing mechanism.

We refrain from giving an extensive account of the metrics of the Java implementations, since they cannot be compared with transformations implemented using transformation languages.

[1] from `http://www.cs.bham.ac.uk/~bxb/Sitra/download.html`

3.2. ATL SimpleClass2SimpleRDBMS Transformations

Table 1 shows the metric values that were extracted from the different ATL implementations for the SimpleClass2SimpleRDBMS transformation. For the metrics that require aggregation, we used the mean. An example of a metric requiring aggregation is *number of elements per output pattern*. The value we used in the analysis represents thus the mean number of elements in all output patterns.

The three declarative versions all consist of four transformation rules, whereas the imperative versions require more rules. From an understandability point of view, the declarative versions are preferred, since smaller transformations are expected to be more understandable [7]. Obviously, only the imperative versions of the transformation contain called rules. It is to be expected that only the imperative transformations contain an (imperative) `do`-section. However, also declarative transformation ATL_b contains a `do`-section. The reason for this is that this version of the transformation requires navigation of the target model, which is not possible in declarative ATL. The *number of elements per output pattern* is lower for the imperative transformations, since some of the features of the target model element are initialized in the `do`-section. From the metric *number of matched rules* can be derived that transformation ATL_d is indeed completely imperative. The imperative implementations contain only non-lazy matched rules and called rules. These implementations do not require an input filter to restrict the matching of a rule, because the rules are only invoked on the model elements they need to be invoked for and thus require no further restrictions.

The initial implementation, i.e., transformation ATL, contains no helpers. All other implementations do contain helpers, which are all attribute helpers. This is to be expected, since only the initial implementation has the navigation code in-line and in the other implementation it is moved to attribute helpers. In implementations ATL_b, ATL_c, and ATL_d, the `allInstances()` operator over associations has been removed, which requires one helper less. However, in implementations ATL_c, and ATL_d an extra attribute helper is required to implement the map-like structure for tracing. One of the differences between the initial implementation and the implementation where the navigation is moved to attributes (ATL_a) is the number of calls to `allInstances()`. From the metrics can be derived that they have been moved from rules to helpers. The `allInstances()` function is used to navigate a source model. Since navigation is the part that had been moved from rules to helpers, this shift is to be expected.

3.3. Mistral SimpleClass2SimpleRDBMS Transformations

We do not have a set of standard metrics for Mistral language. The metrics from the transformations are not necessary in our comparison since the only variation is using (not using) of `allInstances()` OCL operation. The number of rules is quite close to the number of rules in the transformations in other languages. Here are some indicative numbers.

SimpleClass2SimpleRDBMS $Mistral$**.** 1 model element rule, 3 helper rules.

SimpleClass2SimpleRDBMS $Mistral_a$**.** 2 model element rules, 3 helper rules.

RSS2ATOM. 2 model element rules, 2 helper rules.

3.4. QVTo Model Transformations

Table 2 shows the metric values extracted from the QVTo model transformations. Again, for the metrics that require aggregation we used the mean.

The metrics show that both transformations are small. The *SimpleClass-2SimpleRDBMS* transformation has slightly more complex mappings, since they use conditions and consist of more sub-elements. Neither transformation uses helpers. The *SimpleClass2SimpleRDBMS* transformation uses operations on collections, whereas the *RSS2ATOM* transformation does not. Apart from this, the metrics sketch a similar picture for both transformations. Also, the metrics show that the sizes in terms of the number of transformation functions of the QVTo implementations are similar to the sizes of the ATL implementations.

3.5. ATL RSS2ATOM Transformation

Table 3 shows the metric values that were extracted from the ATL implementation of the RSS2ATOM transformation. Again, for the metrics that require aggregation we used the mean.

From the metrics can be concluded that the RSS2ATOM transformation is a very small, completely declarative transformation.

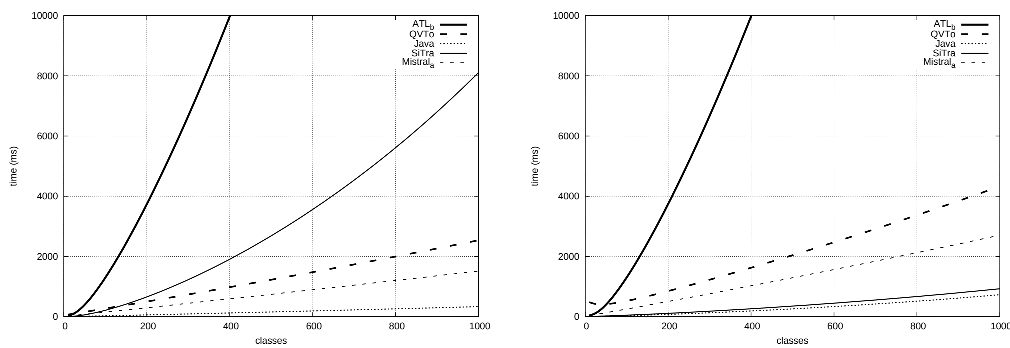
4. Results

We executed the model transformations, and in this way we obtained the execution time, measured in milliseconds, for each transformation and input model. With these execution times, we discuss and justify the performance differences of the transformations.

We first compare the different transformations using the SimpleClass2SimpleRDBMS transformation, after which we look at the alternative transformation strategies per language. Finally, we compare the different transformations using the RSS2ATOM transformation.

4.1. SimpleClass2SimpleRDBMS Transformations

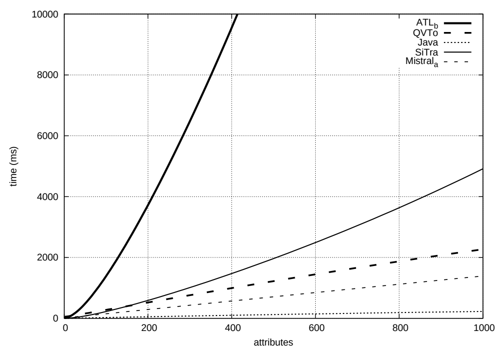
Figures 1 and 2 compare the aspects of increasing the model size and complexity for different transformation tools.



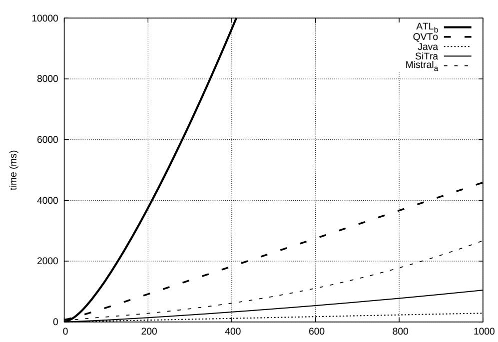
(a) General case (b) Worst case

Figure 1: Comparison between transformations in ATL, using the SimpleClass2SimpleRDBMS transformation (varying number of classes)

When increasing the size of the models, we observe a difference in performance between the general and the worst case. Four out of five transformations exhibit similar performances in both cases, however, the SiTra-based implementation requires nearly five times as much time in the general case than in the worst case for bigger models. This can be explained by considering the input models and the structure of the SiTra-based implementation. For the general case scenario, the models contain classes with some primary and non-primary attributes, and some associations. A foreign key has to be created for each attribute that has a type (Class) with at least one primary attribute, and for each association between persistent classes in case the destination class has at least one primary attribute. In the SiTra-based implementation, we perform queries to the trace information to retrieve the tables corresponding to the classes that had been generated before, and the SiTra package stores tracing information about each object generated during a transformation. The mechanisms to perform queries and store tracing information are not optimized in the SiTra distribution, which explains the poor performance. In the worst case scenario, the classes in the models have no primary attributes, therefore, these tracing mechanisms are not executed, resulting in faster execution times.



(a) General case



(b) Worst case

Figure 2: Comparison between transformation tools, using the SimpleClass2SimpleRDBMS transformation (varying number of attributes)

If we increase the complexity of the models, as illustrated in Figure 2, we see the same distribution of performance among the different transformations. The decrease in performance is nearly the same as when increasing the size of the input models. This is especially apparent in case of SiTra. When comparing the general and the worst case scenarios, we see that Java performs equally in either case. In the increased model size scenario, Java performed slightly worse in the worst case.

4.2. ATL SimpleClass2SimpleRDBMS Transformation Implementations

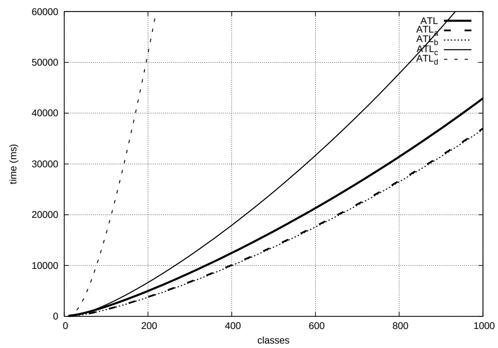
Figures 3 and 4 show the results obtained from running the different implementations of the SimpleClass2SimpleRDBMS transformation in ATL. Figure 3 shows the results for transformations run with input models with a fixed number of classes, and Figure 4 shows the results of using input models with a fixed number of attributes. The number of classes and attributes respectively are fixed to 100.

In our experiment, we assumed that a model with more classes is bigger, whereas a model containing more attributes and associations (with a class as their type) are more complex, because each such attribute and association actually defines a relation between classes. As such, Figure 3 shows the effect of increasing the model complexity, whereas Figure 4 shows the effect of increasing the model size.

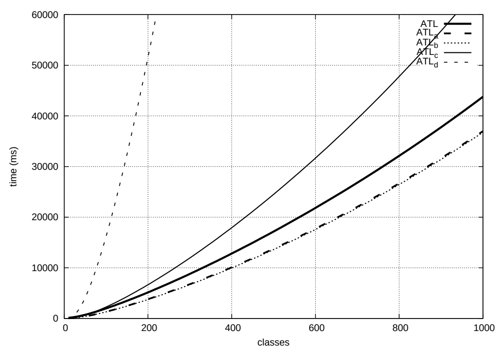
Figure 3 shows that the implementation style of the transformation indeed influences its performance. The two implementations that exploit ATL's caching are, as expected, the fastest performing transformations, with little difference in performance between them. The initial implementation is the third with regard to performance.

By considering the results of the hybrid transformation (ATL_c), we conclude that this implementation strategy had a negative impact on the performance of the transformation as a whole. The purely imperative transformation ATL_d is the slowest one.

Figure 4 shows a slightly different picture: the size of the input models appears to have an impact on the performance of the initial ATL implementation, which is now the second to worst performing transformation. The order of the other transformations is unaffected.



(a) General case



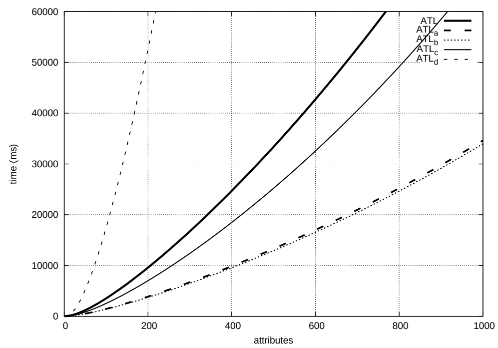
(b) Worst case

Figure 3: Comparison between transformations in ATL, using the SimpleClass2SimpleRDBMS transformation (varying number of classes)

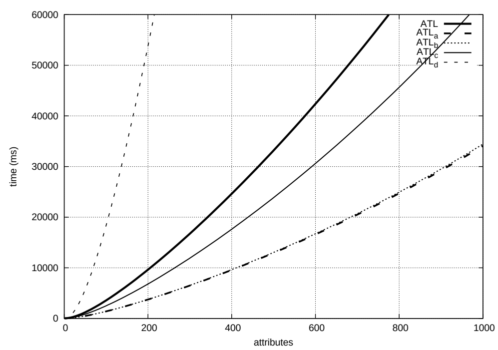
4.3. Mistral SimpleClass2SimpleRDBMS Transformation Implementations

Figure 5 shows the performance of the two Mistral transformations when increasing the number of classes, i.e. the size of the model, with a fixed number of attributes. Figure 6 illustrates the effect of increasing the number of attributes, i.e., the impact of an increasingly complex model.

The elimination of `allInstances()` has a positive impact on the performance of the Mistral transformation, as shown in Figure 5. In the general case, $Mistral_a$ is more than twice as fast as $Mistral$ as the models grow. In the worst case scenario, $Mistral_a$ performs slightly worse than in the general case, however, $Mistral$ requires over twice the time to complete the transformation for bigger models. This result was expected, as running `allInstances()` over increasingly large models were expected to impact the



(a) General case



(b) Worst case

Figure 4: Comparison between transformations in ATL, using the SimpleClass2SimpleRDBMS transformation (varying number of attributes)

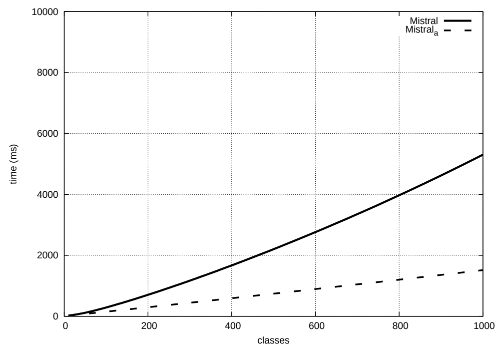
performance.

Figure 6 emphasizes that the complexity increase of the models has little effect on the performance with regard to implementation style. Both transformations perform similarly, with $Mistral_a$ performing slightly better.

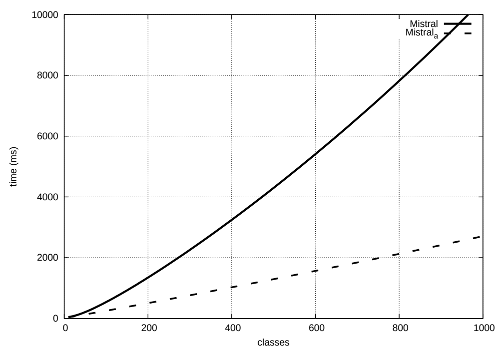
4.4. RSS2ATOM transformations

Due to the tree structure of the input- and output models, we could not evaluate the effect of model complexity, and general- and worst case scenarios for the RSS2ATOM transformation. For similar reasons, no alternative of transformation implementations have been created.

Figure 7 depicts the results obtained from the RSS2ATOM experiment. Unlike the SimpleClass2SimpleRDBMS transformation, the SiTra-based transformation is now the worst performing one for bigger models. In the previous



(a) General case



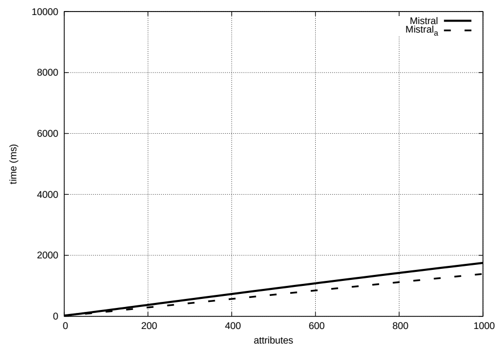
(b) Worst case

Figure 5: Comparison between transformations in Mistral, using the SimpleClass2SimpleRDBMS transformation (varying number of classes)

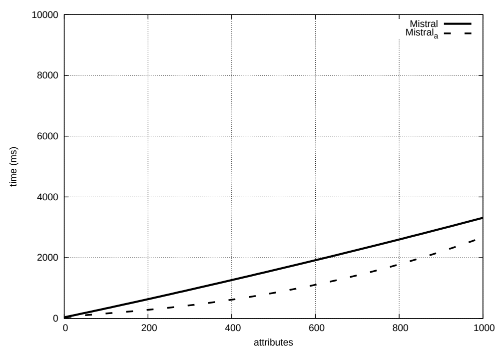
experiment, this transformation was the second best or second worst performer, depending on the transformation scenario. As a result, ATL is now no longer the slowest tool. Our baseline Java implementation is the fastest performing transformation, followed by the Mistral transformation.

4.5. Statistical Analysis

To acquire more insights into the influence of the different implementation strategies of the $SimpleClass2SimpleRDBMS$ transformation, we performed a statistical analysis to relate the metrics presented in Table 1 with the performance results presented in Section 4.2. Therefore, we analyzed correlations between the extracted metrics and the time it took to perform a model transformation. Since we cannot assume that our data is distributed normally, we use a non-parametric correlation test. In this case, we used



(a) General case



(b) Worst case

Figure 6: Comparison between transformations in Mistral, using the SimpleClass2SimpleRDBMS transformation (varying number of attributes)

Spearman's rank correlation test. This test returns two values, viz., significance and correlation coefficient. The significance of the correlation indicates the probability that there is no correlation between two variables even though correlation is reported, i.e., the probability for a coincidence. The correlation coefficient indicates the strength and direction of the correlation. A positive correlation coefficient means that there is a positive relation between metric and quality attribute and a negative correlation coefficient implies a negative relation.

Declarative versus Imperative. The main difference between the declarative and the imperative implementations of the transformation is the use of matched rules versus the use of called rules. Another difference is the use of `do`-sections in the imperative version. Therefore, we analyzed the correla-

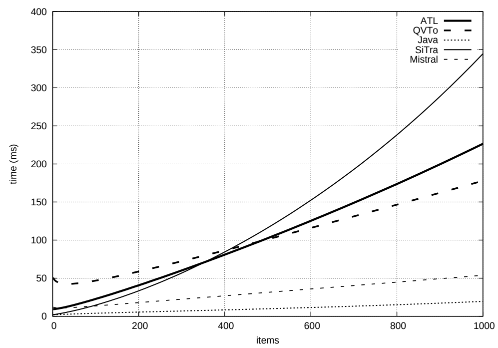


Figure 7: Transformation tools compared using the RSS2ATOM transformation

tions between transformation time and the metrics *number of matched rules*, *number of called rules*, and *number of rules with a* `do`*-section*. The results are shown in Table 4.

The results show a negative correlation between the number of matched rules and execution time. This means that more matched rules lead to a lower execution time and thus better performance. The results show a positive correlation between the number of called rules and `do`-sections, which indicates that these constructs negatively affect performance. Unfortunately, the results are not significant. A possible explanation for this is that there are too few subjects in the analysis and that the differences among them are too small. This may be solved by considering a larger transformation, where the differences are larger and that allow for more hybrid implementations.

Moving Navigation to Attributes. The main difference between the initial implementation and the the other ones, where the navigation is moved to the attributes, is the number of attribute helpers. Therefore, we analyzed the correlations between transformation time and the metric *number of attribute helpers*. The results are shown in Table 5.

The results show a negative correlation between the number of attribute helpers and execution time, meaning that using attributes has a beneficial effect on performance. Similar to the declarative versus imperative case, the results are not significant. This may be solved by considering hybrid implementations as well, e.g., with only half of the navigation moved to attributes.

Usage of ***`allInstances()`****.* In transformation ATL_b, the `allInstances()` operations have been removed. Our expectation is that this is beneficial for performance. Therefore, we analyzed the correlations between transformation time and the metric *number of calls to* ***`allInstances()`***. The results are shown in Table 6.

The results show a positive correlation between the number of calls to `allInstances()`. This confirms our expectation that the use of the `allInstances()` operations negatively affects performance. However, again, it must be noted that the results are not significant. Also this may be solved by considering hybrid implementations as well, e.g., with only half of the calls to `allInstances()` removed.

5. Discussion

After obtaining the metrics from the model transformations and have executed the transformations to gather performance data, we can analyze them in order to find a correlation between metric values and the speed at which the transformation can be run.

5.1. Comparison of Transformation Implementations

Comparing the different ATL transformations along each other, we see that the relative difference does not change when either varying the number of classes or the number of attributes. However, when looking at both these cases, we see that when varying the number of classes, the ATL transformation is the third performing implementation, however, when varying the number of attributes, this implementation is the second to last to finish executing. From this we can conclude that the negative impact of increasing the complexity of the input models is stronger than that of increasing their size for this specific implementation.

In the results from our Mistral experiments we do not see a change in relative results between the two implementations: the $Mistral_a$ implementation is the fastest performer in any of the four scenario. What we can conclude from the data, is that increasing the size of the models has a greater impact on the $Mistral$ implementation, than increasing the complexity. This can be explained when considering the number of calls to `allInstances()`: this is an expensive method to use, and it is called more often and returns more results when using more model elements. Since the number of model elements remains the same when only increasing the complexity of the input models, the number of calls to `allInstances()` remains unaltered, resulting in a better performance.

5.2. Comparison of Transformations

The data shows that the pure Java implementation of the transformations is indeed the fastest one. Depending on the input models, the SiTra-based implementation may be the second performer, but can also be one of the slower ones.

The performance of the Mistral transformation is less than that of Java, but depending on the input models and thus the performance of the SiTra-based implementation, it finishes either second or third.

The slowest performing transformation transformations are in ATL. An explanation for this can be sought in the way the ATL engine works: the transformation implementation is first compiled to an intermediate byte code form, which in turn is interpreted by the ATL Virtual Machine. Furthermore, it has previously proved that the ATL Virtual Machine has performance problems regarding collections. [11]

QVT Relations

As was the case in [19], we experimented with the QVT Relations model transformation tool medini QVT [4] too. However, due to some issues, the results of these transformations could not be incorporated in our results.

Firstly, the medini QVT tool consists of an older 32-bit version of Eclipse (3.5) bundled with the medini plugins. Since we executed the rest of the model transformations on the latest version of Eclipse (3.7), the results would not have been comparable.

Secondly, due to the working of medini[2], the maximum amount of memory is allocated fast, even for smaller models. This causes memory problems for the larger models, which can thusly not be executed.

6. Related work

The basis for this work lies in [10] and [19]. Here, the model transformation tools ATL, QVT Operational Mappings and QVT Relations are compared in a similar fashion as in this paper. The authors conclude that

[2]Every matched element is printed to the console.

from the three model transformation tools, ATL is the fastest performer, followed by QVTo and QVTr. The difference with the current work is the environment in which the transformations were run and which tools were used. In this paper we used newer versions of the tools and a newer version of Java. Also, more memory was allocated for the execution of the model transformations.

Transformation Tool Contest (TTC) [3] is a series of events where solutions to transformation problems are submitted and compared. The transformation problems focus on various qualities, e.g. expressivity, evolvability, performance, scalability and the ability of the tools to solve certain problems, e.g. state space generation. The tool contest is a valuable source of insight about the strong and weak points of transformation tools. However, there is still no clear focus of achieving real comparable results, statistical soundness and relation to metrics over models and transformations. This event can be considered as a potential host for well-defined experiments.

In [9], van Amstel et al. define quality attributes and metrics for measuring them. Metrics are subdivided into size-, function-, module-, and consistency metrics. The first deals with the size of the transformation, the second deals with the complexity of functions, the third measures the complexity of modules as a whole, the last measures covers the degree to which a transformation contains conflicting information. Metrics from these four categories are related to quality attributes and their effect, either positive or negative, is mentioned. Understandability, modifiability, reusability, reuse, modularity, completeness, consistency and conciseness are named as being of importance for the quality of model transformations. The conclusion made by the authors is that the metrics should be tested through an empirical study.

Based on the quality attributes defined by the previous work, [20] defines more metrics, divided into three categories: unit metrics, rule metrics and helper metrics. The first contains the subcategories module metrics and library metrics, the second covers matched rule, lazy matched rule and called matched rule metrics, the last does not have any subcategories. In total, 81 metrics are defined. When comparing this set against the set of metrics defined in [9], the authors note that the difference in the number of metrics can be explained by the size and complexity of the ATL metamodel, from which the metrics were derived.

7. Conclusions and Future Work

We presented a comparison of the performance of the execution engines of three transformation languages: ATL, QVTo, and Mistral. Furthermore, we looked at implementation of transformations using pure Java and a SiTra-based Java implementation We studied how the size and complexity of the input models affect the performance. Furthermore, we compared five different ATL transformations and two different Mistral transformations that solve the same problem in order to study the effect of different language constructs on the performance.

Overall, our pure Java implementation is the fastest among the transformations. For the alternative ATL transformations we found that a declarative style of implementing the transformation was the fastest, if calls to `allInstances()` were avoided. This is also the case for the Mistral alternatives.

We provided metrics that can be used to measure how declarative an ATL transformation is. These metrics can be used by transformation developers when estimating the expected performance of a transformation. Our experiments run on models of up to a million of elements and give an indication of the expected time for the used transformations.

There are several works that define metrics over model transformation programs. However, the research on how to relate basic metric values to more abstract and complex transformation qualities is still in a very early phase.

Our work can be extended in several directions. We did not use metrics that indicate how complex a model is. Our intuition is that a graph-like model is more complex than a tree-like model. There are metrics for this characteristic and they should be correlated with our results.

We ran our experiments on two toy-like examples. To obtain more realistic results, the experiments should be repeated on real-life models that go beyond a million of elements.

Not all the language features have been studied. For example, we could have studied how usage of inheritance in ATL influences performance. The same is valid for QVTo where navigation can be separated from the mappings by the means of queries. In the experiments, all the rules contained simple source patterns. It is well known that pattern matching is a complex operation. The effect of the complexity of the source patterns needs to be studied.

The results reported in this paper are valid for the current versions of the transformation engines. Alternative implementations may produce better results. For example, some transformation engines are implemented as a compiler and others as an interpreter. We believe that the results in this paper will be useful to the language designers to improve the current state of their tools.

There are languages that are not covered in this paper. Our work should be extended by covering more transformation languages.

[1] Eclipse Modeling - EMF), `http://eclipse.org/modeling/emf/`

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

[3] Transformation tools contest, `http://is.tm.tue.nl/staff/pvgorp/events/TTC2011/CfC.pdf`

[4] ikv++ technologies ag: medini qvt, `http://projects.ikv.de/qvt/`

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Metric	ATL	ATL_a	ATL_b	ATL_c	ATL_d
# Transformation rules	4	4	4	6	7
# Matched rules	4	4	4	1	0
# Non-lazy matched rules	1	1	2	0	0
# Lazy matched rules	3	3	2	1	0
# Called rules	0	0	0	5	7
# Rules with an input filter	1	1	2	0	0
# Rules with a `do`-section	0	0	1	5	7
# Helpers	0	2	1	2	2
# Attribute helpers	0	2	1	2	2
# Operation helpers	0	0	0	0	0
# Calls to `resolveTemp()`	0	0	2	0	0
# Calls to `allInstances()`	1	1	0	2	2
# Calls to built-in functions	10	10	11	17	22
# Elements per output pattern	1	1	1	0,67	0,57
# Parameters per called rule	0	0	0	0,8	0,86
# Statements per `do`-section	0	0	1	1,4	1,43
# Bindings per rule	2,5	2,5	2,5	1,67	1,43
Avg. helper cyclomatic complexity	0	1	1	1	1
# Operations on collections per helper	0	1	1	1	1
# Operations on collections per rule	6	4	3,33	2,8	2,8
# Avg. rule fan-in	1,5	1,5	1,25	1,33	1,29
# Avg. helper fan-in	0	3	5	5	7
# Avg. rule fan-out	1,5	3	2,5	3	3,29
# Avg. helper fan-out	0	0	0	0	0
# Calls to `resolveTemp()` per rule	0	0	0,5	0	0
# Calls to `allInstances()` per rule	0,25	0	0	0,33	0,29
# Calls to `allInstances()` per helper	0	0,5	0	0	0

Table 1: Metrics from the different ATL versions of the SimpleClass2SimpleRDBMS transformation

Metric	SimpleClass2SimpleRDBMS	RSS2ATOM
# Mappings	5	7
# Mappings with condition	1	0
# Helpers	0	0
# Calls to `resolve` expressions	6	0
# Elements per mapping	68,8	43,86
# Parameters per mapping	0	0
# Variables per mapping	0,8	0
# Operations on collections per mapping	1,4	0
Cyclomatic complexity per mapping	1	1
# Elements per helper	0	0
# Parameters per helper	0	0
Cyclomatic Complexity per helper	0	0
Avg. mapping fan-in	1,2	1,29
Avg. helper fan-in	0	0
Avg. mapping fan-out	0,6	1
Avg. helper fan-out	0	0
Avg. `resolve` from mapping fan-in	1,2	0

Table 2: Metrics from the QVTo transformations

Metric	RSS2ATOM
# Transformation rules	7
# Matched rules	7
# Non-lazy matched rules	2
# Lazy matched rules	5
# Called rules	0
# Rules with an input filter	0
# Rules with a `do`-section	0
# Helpers	0
# Attribute helpers	0
# Operation helpers	0
# Calls to `resolveTemp()`	0
# Calls to `allInstances()`	0
# Calls to built-in functions	0
# Elements per output pattern	1
# Parameters per called rule	0
# Statements per `do`-section	0
# Bindings per rule	3,1
Avg. helper cyclomatic complexity	0
# Operations on collections per helper	0
# Operations on collections per rule	0
# Avg. rule fan-in	1
# Avg. helper fan-in	0
# Avg. rule fan-out	1
# Avg. helper fan-out	0
# Calls to `resolveTemp()` per rule	0
# Calls to `allInstances()` per rule	0
# Calls to `allInstances()` per helper	0

Table 3: Metrics from the ATL version of the RSS2ATOM transformation

	Transformation time	
	Correlation Coefficient	Significance (2-tailed)
# Matched rules	-0,55	0,349
# Called rules	0,55	0,349
# Rules with a `do`-section	0,017	0,769

Table 4: Spearman correlations

	Transformation time	
	Correlation Coefficient	Significance (2-tailed)
# Attribute helpers	-0,13	0,830

Table 5: Spearman correlation

	Transformation time	
	Correlation Coefficient	Significance (2-tailed)
# calls to `allInstances()`	0,69	0,244

Table 6: Spearman correlation