Evolution specification evaluation in industrial MDSE ecosystems

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Evolution Specification Evaluation in Industrial MDSE Ecosystems

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Abstract—Domain-specific languages (DSLs) allow users to model systems using concepts from a specific domain. Evolution of DSLs triggers co-evolution of models developed in these languages. When the number of models that needs to co-evolve increases, so does the required effort to do so. This is called the co-evolution problem.

We have investigated the extent of the co-evolution problem at ASML [1], provider of lithography equipment for the semiconductor industry. Here we have described the structure and evolution of a large-scale ecosystem of DSLs. We have observed that due to the large number of artifacts that require co-evolutionary activity, manual solutions have become unfeasible, and an automated approach is required. A popular approach for automating co-evolution is the operator-based approach. In this paper we have evaluated the operator-based approach on a large-scale industrial case-study of twenty-two DSLs and 95 model-to-model transformations with a revision history of over three years, and have revealed deficiencies in existing operator libraries. To address these deficiencies we have presented a top-down methodology to derive a complete set of operators.

I. INTRODUCTION

Domain-specific languages (DSLs) offer an efficient way to model complex systems in terms of familiar domain concepts. The relative ease with which model driven engineering (MDE) allows new DSLs to be created is allowing DSLs to be adopted more quickly in industry [2]. The amount of industrial case-studies in literature suggests that MDE is being adopted in industry [3], [4]. For example at ASML, where DSLs are being used for specification of servo-control applications and execution platforms for the TWINSCAN lithography machine [5].

DSLs are created by specifying their abstract syntax using meta-models[6] that dictate the concepts and structure of a language. Due to this centralized specification of language concepts and structure, meta-models have become, by design, a hotspot in the development process: artifacts such as models, model-transformations, editors, and even Java code (e.g., the EMF-API when using Eclipse EMF as an implementation technology) depend on the meta-models. This also means that when meta-models evolve, related artifacts such as models [7]–[10], model-transformations [11], [12], text editors, and graphical editors [13] must reflect changes made to the meta-models. This is known as the co-evolution problem [14].

Manual updating of models triggered by evolution of meta-models is not only difficult but also costly. One can imagine that, in some cases, the induced co-evolutionary effort that would be inferred by a meta-model change is so significant that the meta-model change would be postponed or even not executed at all. This causes developers to encode new domain concepts into existing ones, jeopardizing the primary strength of DSLs: modeling in a specific domain.

The contributions of this paper are threefold. First, we provide insights into how scale affects (co-)evolution in an ecosystem of DSLs used for systems engineering. We study how evolution and co-evolution are dealt with in a large-scale industrial model-driven system engineering (MDSE) ecosystem of twenty-two DSLs. Second, we investigate if an operator-based approach is suitable for dealing with evolution and co-evolution at this large scale. We investigate to what extent current operator libraries are able to specify (co-)evolution in our industrial case-study. Lastly, we investigate what extensions to operator libraries are necessary in order to completely specify (co-)evolution in practical use-cases. Rather than extending one of the existing operator libraries in an ad hoc way to fully cover co-evolution, we present a top-down methodology to derive a complete set of atomic operators. In this way, every meta-model evolution can be specified.

The remainder of this paper is structured as follows: In Section [II] we elaborate on MDE ecosystems and the added challenges they pose with respect to (co-)evolution. In Section [III] we explain the industrial context of our research, and in Section [IV] we look at the MDSE ecosystem case study in this industrial context. In Section [V] we analyze the application of the operator-based approach to our industrial case study, and identify shortcomings. We discuss how to mitigate these shortcomings in Section [VI]. In Section [VII] we discuss related work in our field. Finally, we conclude this paper by sketching directions for future work, and summarizing our conclusions in Section [VIII].

II. (CO-)EVOLUTION IN MDSE ECOSYSTEMS

A. MDSE Ecosystems

In an MDSE ecosystem, meta-models are the central artifact, defining language concepts and structure. Many artifacts
B. Co-Evolution

With respect to model conformance [16], changes that make up the evolution of a meta-model may be classified into three different categories [7]:

1) **Non-breaking changes** (NBC), which do not break model conformance;
2) **Breaking-Resolvable Changes** (BRC), which break model conformance, but can be co-evolved in a fully automated fashion.
3) **Breaking-Unresolvable Changes** (BUC), which break model conformance, and require additional information for successful co-evolution of models to take place.

The main challenges in model co-evolution arise with respect to BUCs, as they introduce ambiguities. For instance, in Figure 2 it is unclear whether X.name is renamed to X’.id or Y’.name, or if no rename (but adds and deletes) was performed. Due to the size of industrial use-cases (i.e. hundreds to thousands of model instances) manual resolution of these ambiguities is no longer feasible, and automation is required.

A number of approaches have been proposed to address the co-evolution problem [17]. An approach that has been extensively studied is the operator-based approach [10], where a library of co-evolutionary operators is supplied to represent the modelers intent with respect to model evolution [18]. This approach is not only applicable to MDE, but has also been used in the context of databases [19]. Each operator specifies a meta-model evolution, along with a corresponding model co-evolution. For instance, the modification in Figure 2 could be described using the operators Rename(X.name, “id”) and CreateAttribute(Y, “name”, EString) [18]. The practical applicability of such an approach relies heavily on the set of available operators, such as those proposed by Herrmannsdörfer et al. [3], [4], [18].

When dealing with an MDSE ecosystem as mentioned in Section 1 the magnitude of the co-evolution problem increases further. Evolution of a DSL may affect more artifacts than just the conforming models. This has been illustrated in the upper segment of Figure 1. When a DSL evolves (∂(DSLA)), its conforming models must co-evolve (∂(alpha)).

Fig. 1: Abstract representation of evolution in an MDSE ecosystem.

Additionally, model-to-model transformations might need adaptation (∂(A2B)) in order to deal with newly added concepts in the new models instances (alpha’.DSLA’). Lastly, DSLB might include domain concepts from DSLA. Just as models from DSLA need to co-evolve to capture the evolution in DSLA, models of DSLB including concepts from DSLA might also need to co-evolve (∂(beta)).

**III. Industrial Context**

Our research takes place at ASML [1], provider of lithography systems for the semiconductor industry. Over the last years, ASML uses model-driven engineering (MDE) in several parts of its development process.

ASMLs lithography systems consist of numerous servo control systems that are developed using MDE according to the Control Architecture Reference Model (CARM) [5]. CARM consists of multiple layers to describe the control logic and their execution platforms of the TWINSCAN lithoscanner at several levels of abstraction. CARM is multidisciplinary in nature, requiring expertise of mechatronic engineers, electrical engineers and embedded software engineers. Multiple abstraction layers as well as the multidisciplinary character of CARM necessitated development of a set of DSLs each targeting a different domain (cf. Figure 3). Dependencies between the DSLs, as well as the shared environment where they are developed and evolve, make the set of DSLs into a software ecosystem [20], [21].
The CARM ecosystem is divided into three main components: the modeling stack, the analysis stack and the deployment stack [5].

The modeling stack (Figure 3, left) allows for the specification of control applications for the litho-scanner at various levels of abstraction, and is modeled according to the Y-chart paradigm [22], which is a guideline for system decomposition. The platform layer (slate blue) has languages for modeling logical and physical properties of the platform. Finally, the mapping (orange) dictates how the application (green) is mapped to its execution platform.

The analysis stack (Figure 3, top right) allows for early predictability in the designs from the modeling stack, and plays a key role in scheduling the application onto the multi-processor platforms. Therefore, the analysis stack includes DSLs that can be analyzed by external verification and simulation tools such as POOSL [23], SDF [24], and ESITrace [25].

Finally, the deployment stack (Figure 3, bottom right) was designed to facilitate the disclosure of all relevant information to the clients on each TWINSCAN machine to initialize and execute the process controllers as well as configuring their execution platforms.

All DSLs in the CARM ecosystem are defined in terms of EMF Ecore class diagrams [26], [27] and OCL constraints [28]. The languages consist, on average, of 60 to 80 concepts with outliers on both the high end (400 concepts) and the low end (10 concepts). Some languages share common functionality, or contain strongly related concepts. In these cases, DSL specifications include domain concepts from other DSL specifications. To bridge the gap between the different domains, model-to-model transformations are used.

The models in CARM that are subject to co-evolution are mostly input and output models of model-to-model transformation unit tests. Whereas the models used during the development process, and on the lithography machine itself, are “reconstructed” from several artifacts in the software archive. The number of unit-test models are in an order of magnitude of hundreds, whereas the development models are in an order of magnitude of thousands. In the future, when the development models are no longer reconstructed, but become the primary source of specification, the co-evolution problem will increase in size.

IV. EVOLUTION OF INDUSTRIAL MDSE ECOSYSTEMS

The DSLs in CARM evolve and become larger over time, as can be seen in Figure 4 in which the number of distinct modeling elements per language has been plotted over time. This evolution, gives rise to a large amount of co-evolutionary work with respect to the hundreds of model instances.

Furthermore, as a result of the language dependencies mentioned in Section III co-evolution in the CARM ecosystem becomes more challenging than co-evolution in a collection of models in one DSL: changes made to a particular DSL might propagate to artifacts conforming to other DSLs. For example, the Basics DSL offers functionality for the declaration of connectable components using a variety of different communication ports and connections between them. These concepts are common throughout the application layer. Say we would
remove a particular type of port (e.g., a dataPort) from the language definition, then models from all languages in the application layer might be affected and require co-evolution. Additionally, transformations that transform the dataPort concept might need to be updated, as they contain redundant information (i.e., how to transform a dataPort). This rippling effect of co-evolution as a consequence of language dependence can be observed in Figures 4a and 5. In Figure 4a, plotting the DSL structure of the Basics DSL over time, there is a large evolution around revision 4098. In Figure 5, the number of changed models of the ControlBlocks DSL has been plotted per revision. Here we see a large number of modifications around revision 4100 (visualized as light blue hexagons), relating to the evolution of Basics.

The need to co-evolve more models than those conforming to the meta-model being evolved makes meta-model evolution extra costly. Indeed, in some cases the induced co-evolution effort leads to meta-model evolution being postponed or to new domain concepts being encoded into legacy concepts. The latter practice jeopardizes the primary strength of DSLs: modeling in a specific domain. Advantages and promises of MDSE are, hence, being put at risk by the co-evolution costs.

This conclusion is further supported by the continuous change of the DSLs illustrated by Figure 4 akin to Lehman’s law of continuing change [29].

To reduce the effort induced by meta-model evolution, a way-of-working similar to the butterfly method for database schema evolution [30] can be adopted. In that approach, a situation is created where both old and new concepts are supported, but modeling using legacy concepts is ceased. This way of working is illustrated in Figure 6. Using this approach, the immediate co-evolution pressure is decreased, as all models still conform to their meta-models. However, this
does not decrease the total amount of work that has to be done, and adds additional work for the creation of an intermediate DSL version (which is often tedious). Thus, the need arose for an approach with an increased level of automation.

V. Evaluation of the Operator-based Approach

Next we evaluate the operator-based approaches for application in industry. As far as we know, operator-based approaches have been evaluated in industry on at most four meta-models. We investigate to what extent the operator based approach is usable for the evolution of large-scale industrial MDSE ecosystems (i.e., twenty-two meta-models).

A. Operator Based Approach

In an operator-based approach, the user specifies the evolution of the meta-model using a set of pre-defined operators. Each of these operators can have a coupled operator if the meta-model evolution breaks conformance to the models. Such a coupled operator can be performed on model instances in order to mitigate the conformance-breaking effects of the evolution operator. For example, changing the type of an attribute in the meta-model from EInt to EDouble requires all values of this attribute in models to be changed to doubles. Edapt (previously COPE) is a tool that implements an operator-based approach.

Because evolution is primarily specified using a pre-defined set of operators, the practical applicability of an operator-based approach depends heavily on the available library of operators. The set of operators available (both in literature and in tooling) has been constructed in a demand-driven fashion: as the need for more operators arose through use cases, they were constructed. Herrmannsdörfer et al. provide a library of 61 coupled operators, summarizing a number of these case studies. To the best of our knowledge, this is the most complete library available in literature.

To the extent of our knowledge, the operator-based approach has never been evaluated on an industrial case study of the size and complexity of CARM. An earlier study has shown that an operator-based approach is suitable for the evolution of up to four DSLs. We wish to investigate whether an operator-based approach is still feasible for specification of evolution on a large scale as indicated in Section III.

B. Experimental setup

To evaluate the usability of the operator-based approach in industry, we investigate which operators are required for the specification of the CARM use case and evaluate whether these operators are offered by the catalog of Herrmannsdörfer et al., and the library of Edapt. Although both these sources originate from the same research group, the catalog represents the academic view, whereas the library of Edapt is more practice oriented.

For now, we limit ourselves to atomic operators (also known as primitives), i.e., operators with effects that cannot be decomposed into smaller operators on the meta-model. For example, the compound operator CreateOppositeReference can be decomposed into an application of CreateReference and an application of SetOppositeReference, where the two latter operators cannot be decomposed further.

We restrict ourselves to atomic operators for two reasons. Firstly, an atomic operator encodes an atomic change on the meta-model. To be able to support every change on the meta-model, a complete set of atomic operators is required. Secondly, every compound operator can be expressed in terms of atomic operators. We aim to first make a complete library of atomic operators, and use this library to define compound operators later on.

To perform our evaluation, two distinct sets of data are required: the set of operators required for the the CARM use case, and the set of operators offered by the available libraries.

We first investigate which operators are required to specify the evolution of CARM. The tool EMFCompare was used to compare subsequent pairs of revisions of the twenty-two DSLs stored in the ASML MDE repository. We have chosen to use EMFCompare for its ability to fine-tune comparisons in order to gain accuracy improvements. Comparing all the subsequent revisions of all twenty-two DSLs yields a total of 3551 atomic changes represented in the EMFCompare difference model. In the remainder of the paper we refer to this set of changes as the change history.

Next, we wish to understand to what extent the available operator libraries cover the change history. We do so by automatically mapping every atomic operator offered by the libraries to a change in the EMFCompare difference model. This yields a set of changes in CARM that are covered by operators in literature, and a set of changes that are not.

C. Results

Of the twenty-two DSLs in CARM, only 19 in Table I have a history of changes. Languages in the Analysis, Application, Deployment, Mapping and Platform clusters are presented in Figure 3 for remaining languages in CARM having a history of changes we have made a Misc group.

1) Holistic analysis: From the analysis of our results, we observe that CARM requires support for 75 distinct atomic operations on meta-models in order to specify its evolution history. The catalog by Herrmannsdörfer et al. supports 40 atomic operators, 32 of which are a subset of the 75 required
by CARM. These 32 operators together cover 85% of the change history. Edapt implements a slightly smaller subset of these operators, namely 28 operators, covering 81% of the change history.

An example of an atomic operator required for the specification of the change history, that is not supported by Herrmannsdörfer et al. and Edapt is the addition of an EEnumLiteral Alto an EEnum. Where operations for adding empty enumerations, moving enumeration literals between enumerations, and merging enumeration literals are supported, no operator exists for simply adding an enumeration literal. A more complex example is related to the eKeys of an EReference. An EReference may require all concepts referenced to be unique with respect to one or more attributes of those concepts, the so-called eKeys of a reference. The eKeys works similar to keys in the context of databases [35]. We see that eKeys are used throughout CARM DSLs (e.g., to enforce each component in a machine to have a unique name). However, an operator for this is neither present in literature [18], nor in Edapt [51].

2) Differences between groups of DSLs: Having observed that at most 85% of our change history is supported by existing operator libraries, we also observe large differences between the coverage for different languages: for instance, the best covered language by the operators of Herrmannsdörfer et al. such as PlatformMap, AppMap, and Deployment-Application all exceed 95% of changes being covered, while for the worst covered languages L3 and Deployment-Mapping the coverage values are 42% and 28%.

To obtain further insights in differences in coverage by the operator libraries we investigate whether any differences can be observed between different groups of DSLs. Indeed, DSLs have been grouped according to stacks and layers of the CARM ecosystem and can be seen therefore as representing the domain of the DSL. To this end we derive two contingency tables from Table I: the first contingency table (Table II) has language groups as rows, and changes covered (or not) by Herrmannsdörfer et al. [18] as columns. The second contingency table for changes covered (or not) by Edapt can be constructed in a similar way.

Next we apply the χ²-test of independence to each one of the contingency tables [18]. We use R, a free software environment for statistical computing, to perform statistical calculations [36].

The null hypotheses are therefore, $H_0^E$, the coverage of the operators by Herrmannsdörfer et al. [18] is independent of the DSL group; and $H_0^E$, the coverage of the operators by Edapt is independent of the DSL group.

Both $H_0^H$ and $H_0^E$ can be rejected (the p-value was too small to be computed exactly). Hence, operator coverage, both for the library of Herrmannsdörfer et al. and of Edapt, is not independent of the DSL group. Closer inspection of the residuals reveals that for both operator libraries, coverage of the Application and Misc groups is lower than expected and Platform is higher than expected, whereas the Platform layer has a more traditional architecture, and is less complex. We conjecture that the lower coverage in the Application is related to the use of the ontological instantiation pattern [37].

3) Operator libraries: We observed that overall 85% of the change history is covered by existing operator libraries, and important parts of the CARM ecosystem, such as the application layer, are being covered worse than expected. Hence, we conclude that the libraries of atomic operators currently available are insufficiently rich to specify the evolution of DSLs in a large-scale industrial MDE ecosystem. To mitigate the shortcomings in existing libraries, we propose to compute a complete set of atomic operators, rather than extend the available libraries in a demand-driven way.

VI. COMPLETING THE OPERATOR-BASED APPROACH

As stated before, we aim to derive a complete set of possible atomic operators for the evolution of Ecore-based metamodels. We do so by computing possible differences from the meta-meta-model and mapping these to atomic operators.

### TABLE I: Coverage of languages in the CARM ecosystem

<table>
<thead>
<tr>
<th>Group</th>
<th>DSL</th>
<th>#Changes</th>
<th>Covered by [18]</th>
<th>Covered by [51]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis</td>
<td>DAG</td>
<td>129</td>
<td>108</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>Resource</td>
<td>39</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Schedule</td>
<td>226</td>
<td>206</td>
<td>203</td>
</tr>
<tr>
<td>Application</td>
<td>Application</td>
<td>183</td>
<td>158</td>
<td>154</td>
</tr>
<tr>
<td></td>
<td>Basics</td>
<td>112</td>
<td>105</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>ControlBlocks</td>
<td>1115</td>
<td>925</td>
<td>871</td>
</tr>
<tr>
<td></td>
<td>ServoGroups</td>
<td>129</td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>TransducerGroups</td>
<td>88</td>
<td>77</td>
<td>77</td>
</tr>
<tr>
<td>Deployment</td>
<td>Deployment-Application</td>
<td>74</td>
<td>71</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Deployment-Mapping</td>
<td>25</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Deployment-Platform</td>
<td>107</td>
<td>105</td>
<td>99</td>
</tr>
<tr>
<td>Mapping</td>
<td>AppMap</td>
<td>178</td>
<td>170</td>
<td>141</td>
</tr>
<tr>
<td>Platform</td>
<td>LogicalPlatform</td>
<td>118</td>
<td>109</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>PlatformMap</td>
<td>266</td>
<td>261</td>
<td>261</td>
</tr>
<tr>
<td></td>
<td>PhysicalPlatform</td>
<td>507</td>
<td>482</td>
<td>462</td>
</tr>
<tr>
<td>Misc</td>
<td>L1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>37</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>L3</td>
<td>182</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>L4</td>
<td>35</td>
<td>35</td>
<td>34</td>
</tr>
</tbody>
</table>

|           | Misc           | 144      | 112             | 112             |

The numbers shown are the absolute amount of the change history covered.
A. Computation of Operators

First we determine all possible changes that can be made to a meta-model. For this, we use the fact that a meta-model is an instance of a meta-meta-model [16]. The number of features (i.e., attributes and references) in a meta-meta-model that can be instantiated to create an actual meta-model is limited. We call the features of the meta-meta-model that can be instantiated to create meta-models instantiation points.

For example, the name attribute of an EAttribute, or the isAbstract attribute of an EClass.

Subsequently, we again use the EMFCompare difference model to encode possible changes on instantiation points of the meta-meta-model. This yields every possible way in which the instantiation of a meta-meta-model can be modified (i.e., every way in which a meta-model can be altered). This set of changes to meta-meta-model instantiation points then has a one-to-one correspondence to the complete set of atomic operators. For example, an ADD EClass change on the instantiation point EPackage.eClassifiers corresponds to the “Add class to package” operator.

The algorithm for calculating the complete set of atomic operations is presented in Algorithm 1. The workings of this algorithm rely on the fact that Ecore meta-meta-model conforms to the “Add class to package” operator.

We then iterate over all structural features (i.e., attributes and references), including inherited ones, of non-abstract classes in the Ecore meta-meta-model to find all possible instantiation points. More specifically, we wish to avoid structural features of abstract classes, as these do not occur in practice. We can easily iterate over all structural features of a class by using the eAllStructuralFeatures reference on every non-abstract class of the meta-meta-model.

When we have computed all instantiation points, we distinguish between a number of different operations that can be performed on the instantiation points, as prescribed by the EMFCompare difference model [33]:

1) If the feature consists of multiple elements (isMany), and the ordering of these elements is important (isOrdered), we support internal re-ordering of these elements via a MOVE operation.

2) If the feature is a containment reference, additive operations on these references actually introduce new elements into the model (as opposed to cross-references). We thus allow ADD and DELETE operations.

3) If the feature is a reference with an upper-bound of more than one, we are dealing with a collection. Values from collections can be added and deleted. We thus allow ADD and DELETE operations.

4) If the feature is a reference, and the upper-bound is one, we only allow the CHANGE operation, using the same reasoning that is applicable to attributes.

5) If the feature is an attribute, its value can be changed (CHANGE). In the Ecore meta-meta-model, there are no occurrences of attributes with multiple values, (i.e., isMany is always false), hence we need not support ADD and DELETE. Note that this might be the case for other meta-meta-models.

The algorithm generates a four-tuple for every atomic operator that can be performed on an Ecore-based meta-model. For example: a “rename class” change would be encoded as (EAttribute(name), EClass, EString, CHANGE), and an “add attribute” change would be encoded as: (EReference(eStructuralFeatures), EClass, EAttribute, ADD).

One thing to note is that the implementation of Ecore in Eclipse imposes additional constraints that are not captured in the meta-meta-model. For example, the eType of an attribute can theoretically have any EClassifier. In the graphical editor of Eclipse, it can only have an EDataType as its eType. However, the EMF API does allow for all the changes specified by our four-tuples to be performed, hence we consider \( R \) to be the set of all atomic operations that can be performed on the Ecore meta-meta-model.

Algorithm 1: Algorithm for computing possible changes in a meta-model

```plaintext
Data:.ecore : The root package of the Ecore meta-meta-model
Result: R : A set of atomic changes that can be performed on Ecore-based meta-models

1 R = \{\}

2 foreach o ∈ ecore.eAllContents() do

3 if o instanceof EClass ∧ ¬ o.isAbstract() then

4 foreach f ∈ o.eAllStructuralFeatures() do

5 if f.isChangeable() then

6 t ← f.eType()

7 if f.isMany() ∧ f.isOrdered() then

8 R ← R ∪ (f, o, t, MOVE)

9 end

10 if f instanceof EReference then

11 if f.isContainer() ∧ f.upperBound = 1 then

12 R ← R ∪ (f, o, t, ADD)

13 R ← R ∪ (f, o, t, DELETE)

14 else if f instanceof EAttribute then

15 R ← R ∪ (f, o, t, CHANGE)

16 end

17 end

18 end

19 end

20 end

21 Algorithm 1: Algorithm for computing possible changes in a meta-model
```
be performed on an Ecore-based meta-model.

Running the presented algorithm on the Ecore meta-meta-model yields a set of 213 atomic operators. The calculation of these operators is a one-time effort, only taking several seconds. In Section VI-B we will compare this set of operators to the operators offered in literature [18] and by Edapt [31].

B. Discussion

Using our methodology, we have generated 213 atomic operators, 75 of which are applicable to the CARM use case. A total of 3551 applications of these 75 operators are required for the complete specification of the evolution history. The comparison resulting from our study has been illustrated in Figure 7.

Of the 40 atomic operators supported by the catalog of Herrmannsdörfer et al. [18], 32 are applicable to the CARM use case. Together, they are able to specify 85% of the change history. Edapt [31] covers slightly less of the CARM use case. Edapt implements 32 of the operators by Herrmannsdörfer et al. that are useful for CARM, resulting in a specification coverage of 81% of the change history.

Additionally, we have identified 43 operators, that are neither available in the catalog of Herrmannsdörfer et al., nor in the library offered by Edapt. Together these 43 operators cover 15% of the CARM change history. Among these 43 is the eKeys example mentioned in Section V-C.

Lastly, 138 operators are not used in specification of the CARM evolution. Of these 138, 127 are not available the library offered by Herrmannsdörfer et al. or in Edapt. We observe that among these 138 operators, 94 relate to annotations and operations in the meta-model. These modeling concepts are very scarce in the CARM use case, and the use cases in literature [3], [4].

Summarizing our results: Of the 213 operators theoretically possible, 75 are required for the specification of our change history, and only 32 are available. This leaves 43 operators left to be implemented before current operator libraries are sufficiently rich for specification of large-scale evolution specification. The remaining 138 operators, mainly concern EOperations and EAnnotations. We conjecture that these concepts are relevant for specification DSLs, and are thus of less importance for specification of evolution in large-scale MDSE ecosystems.

VII. RELATED WORK

In literature, a number of approaches have been proposed towards solving the co-evolution problem. These approaches can be divided into a number of different categories:

- **Co-evolution oriented** (cf. manual specification [17]) approaches consider the co-evolution specification to be the primary source of specification, and do not concern themselves with the evolution of meta-models. An example of such an approach is Epsilon Flock [38], which offers a DSL tailored towards co-evolution of models. Developers can use this DSL to specify co-evolution strategies for their models.

- **Evolution-oriented approaches** aim to capture the essence of an evolution, and automatically derive a co-evolution specification from it. A number of different approaches to this have been described in literature:

  1. **State-based approaches** [17] attempt to calculate the evolution between two versions of a meta-model supplied by the user (e.g., MMA and MMA’ in Figure 1). An example of such an approach is the EMFMigrate tool [39] developed at the university of L’Aquila.

  2. **Operator-based approaches** [17] allow the user to specify the evolution of a meta-model using pre-defined operators. Each of these operators specifies part of a
TABLE IV: Fragment of comparison results

<table>
<thead>
<tr>
<th>Operation</th>
<th>Value type</th>
<th>occurrences in CARM</th>
<th>18</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHANGE reference type</td>
<td>EClass</td>
<td>571 (16%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>CHANGE attribute type</td>
<td>EDataType</td>
<td>367 (10%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ADD reference to class</td>
<td>EReference</td>
<td>312 (9%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ADD attribute to class</td>
<td>EAttribute</td>
<td>245 (7%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ADD supertype</td>
<td>EClass</td>
<td>239 (7%)</td>
<td>Yes</td>
<td>Partial</td>
</tr>
<tr>
<td>ADD class to package</td>
<td>EClass</td>
<td>215 (6%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DELETE reference from class</td>
<td>EReference</td>
<td>201 (6%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DELETE attribute from class</td>
<td>EAttribute</td>
<td>141 (4%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DELETE supertype</td>
<td>EClass</td>
<td>132 (4%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DELETE class from package</td>
<td>EClass</td>
<td>119 (3%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ADD a literal to an enumeration</td>
<td>EEnumLiteral</td>
<td>107 (3%)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>ADD attribute to eKeys</td>
<td>EAttribute</td>
<td>32 (1%)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CHANGE namespace of a language</td>
<td>EString</td>
<td>18 (0.5%)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>76.5%</td>
<td></td>
</tr>
</tbody>
</table>

meta-model evolution. Additionally, each of these operators can have a coupled operator that aims to mitigate conformance breaking effects the operator on the meta-model may have had. [7], [10]

3) **By-example approaches** have the user input a number of evolution examples. That is, for a number of models (i.e., alpha.MMA in Figure 1) users present their evolved counterpart (i.e., alpha’.MMA’ in Figure 1). Subsequently they attempt to re-construct an evolution and co-evolution specification that meets the constraints imposed by the examples presented. [40]

4) **Generation approaches** aim at completely regenerating artifacts, rather than evolving them. An approach to this is using semantics from ontologies to migrate artifacts with respect to altered DSLs. [41]

Among these approaches, a number of tools implement a variety of them. A feasibility study was preformed at ASML to evaluate applicability on the CARM use case. The tools under review are those reviewed by Herrmannsdörfer et al. [42]. Like Herrmannsdörfer et al., we selected two tools as top candidates: Edapt (previously COPE) [31], [32], and Epsilon Flock [38]. These tools were selected based on maturity, stability, and application to the ASML use-case.

VIII. CONCLUSIONS & FUTURE WORK

In this paper, we have described a large industrial MDSE ecosystem, and identified (co-)evolutionary challenges arising from its size and complexity. We have found that co-evolution effort incurred by the evolutionary changes can put at risk the advantages and promises of the application of MDSE in industry.

To address this challenge, we have investigated to what extent an operator-based approach is feasible for solving the co-evolution problem. We have observed that the existing approaches [18], [31] cover up to 85% of the changes in the ecosystem history, and that 43 additional atomic operators need to be implemented to achieve 100% coverage.

Rather than extending an operator library in an *ad hoc* way, we have designed a top-down approach generating all possible atomic operators. On top of the existing operators and 43 operators that need to be implemented, the top-down approach revealed 127 additional operators. We conjecture that these operators express modification of meta-model elements that are less relevant for DSL specification. For example, in our ecosystem EOperations and EAnnotations elements have been used to improve performance of the source code generated from the models.

As future work, we aim to investigate more case-studies to establish to what extent this research generalizes. Furthermore, we will consider compound operators and extend the set of compound operators found in the literature [18] to support more co-evolution scenarios. Furthermore, we wish to extend the operator-based approach to support co-evolution of further artifacts types, e.g., model-to-model transformations. With respect to models, our goal is to support meta-model refactoring [12]. That is, when we only refactor the metamodel, *i.e.*, no expressivity is added or deleted, model co-evolution should be fully automatic.

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