COLLEGE DOCTORAL BRETAGNE | MATHS, TELECOMS INFORMATIQUE, SIGNAL SYSTEMES, ELECTRONIQUE

Université de Rennes

Thèse de doctorat de

L'Université de Rennes

École Doctorale N° 601
Mathématiques, Télécommunications, Informatique, Signal, Systèmes, Électronique
Spécialité : *« voir README et le site de votre école doctorale »*

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ACKNOWLEDGEMENT

Je tiens à remercier
I would like to thank. my parents..
J'adresse également toute ma reconnaissance à ....
....

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Chapter 1

Introduction

1.1 Context and Motivation

Software systems are increasingly growing in complexity, which leads to a substantial burden in terms of maintenance, often resulting in a high cost that may surpass the cost of software development itself [1]. Since Object Management Group (OMG) has introduced Model Driven Engineering in 2001 [2], MDE has been prominent in developing and maintaining large-scale and embedded systems while increasing the developers' productivity. By adopting MDE, industry can reduce time (development time and time-to-market), costs (development, integration, and reconfiguration), and improve sustainability and international competitiveness. In MDE, metamodel is a central artifact for building software languages [3]. It specifies the domain concepts, their properties, and the relationship between them. A metamodel is the cornerstone to generate model instances, constraints, transformations, and code when building the necessary language tooling, e.g. editor, checker, compiler, data access layers, etc. In particular, metamodels are used as inputs for complex code generators that leverage the abstract concepts defined in metamodels. The generated code API is used for creating, loading and manipulating the model instances, adapters, serialization facilities, and an editor, all from the metamodel elements. This generated code is further enriched by developers to offer additional functionalities and tooling, such as validation, transformation, simulation, or debugging. For instance, UML [1] and BPMN [2] Eclipse implementations rely on the UML and BPMN metamodels to generate their corresponding code API before building around it all their tooling and services in the additional code.

1. `https://www.eclipse.org/modeling/mdt/downloads/?project=uml2`
2. `https://www.eclipse.org/bpmn2-modeler/`

1.2 Challenges

C1: Resolve the impact of the metamodel evolution on the code automatically

One of the foremost challenges to deal with in MDE is the impact of the evolution of metamodels on its dependent artifacts. We focus on the impact of metamodels' evolution on the code. Indeed, when a metamodel evolves and the code API is regenerated again, the additional code implemented by developers can be impacted. As a consequence, this additional code must be co-evolved accordingly.

However, manual co-evolution can be tedious, error-prone, and time-consuming. Therefore, experts tried through last decades to find more sophistic solutions to tackle the problem of co-evolution when metamodels evolve. This interest covered almost all the artifacts in MDE ecosystem not only the code, and many solutions were proposed, inter alia, raising the automation degree of the co-evolution. Note that other aspects treated in co-evolution problem like optimization and evolution resilience. The co-evolution challenge has been extensively addressed in *MDE*. In particular, [4]–[9] focused on consistency checking between models and code, but not its co-evolution. Other works [10], [11] proposed to co-evolve the code. However, the former handles only the generated code API, it does not handle additional code and aims to maintain bidirectional traceability between the model and the code API. The latter supports a semi-automatic co-evolution requiring developers' intervention. Moreover, it does not use any validation process to check the correctness of the co-evolution and with no comparison to a baseline. In this thesis, we tackle the challenge of resolving the impact of the metamodel evolution on the code automatically followed by checking the correctness of the co-evolution.

C2: Behavioral correctness of the metamodel and code co-evolution

In literature, when the problem of metamodel and code co-evolution is addressed, the challenge of checking that the co-evolution impacted or not the behavioral correctness of the code is not handled. In any Model-Driven Engineered system, the elements of the metamodel are used in the code. The evolution of the metamodel will be propagated in the code that is co-evolved and its behavior may be altered. Hence, the importance of checking the correctness of the co-evolution. In a larger scope, only few works were dedicated to check the correctness of a code evolution in general. Ge et al. [12] propose to verify the correctness of refactoring. Out of the scope of testing code evolution, we find the incremental test selection approaches Infinitest [3], EKSTAZI [13], and Moose [14]. All of Infinitest, EKSTAZI and Moose aim to analyze code changes incrementally to select impacted tests in the evolved version of the code only.

C3: How to draw benefit from LLMs for the metamodel and code co-evolution

In the MDE ecosystem, we can consider that metamodel and code co-evolution is one of many other MDE tasks. For example Model generation and code generation. Since their appearance, LLMs have been applied in different domains of scientific research, such as Software Engineering and Model-Driven Engineering (MDE), however, to the best of our knowledge, the challenge of exploring LLMs in the task of metamodel and code co-evolution has not yet been addressed. In Software Engineering side, Fu et al. [15] evaluated ChatGPT ability to detect, classify, and repair vulnerable code. Kabir et al. [16] evaluated ability of ChatGPT to generate code and to maintain it by improving it based on a new feature description to add in the code. Zhang et al. [17] proposed Codeditor, an LLM based tool for code co-evolution between different programming languages. It learns code evolutions as edit sequences and then uses LLMs for multilingual translation. Moreover, other studies focused on evaluating LLMs in MDE activities. Chen et al. [18] and Camara et al. [19] used ChatGPT to generate models. Chaaben et al. [20] showed how using few-shot learning with GTP3 model can be effective in model completion and in other modeling activities.

1.3 Contributions

To tackle these three challenges, we propose three contributions:

- ➔ First, we propose a fully automatic code co-evolution approach due to metamodel evolution based on pattern matching. Our approach handles both atomic and complex changes of the metamodel. This approach is evaluated, on nine Eclipse projects from OCL, Modisco, and Papyrus, based on four actions: 1) Measuring the co-evolution correctness using automatically generated unit tests. 2) Verifying the behavioral correctness using unit tests running before and after automatic code

3. `https://infinitest.github.io/doc/eclipse`

co-evolution. 3) Comparison with the state-of-the art semi-automatic co-evolution approach [11]. 4) Comparison with Quick Fixes popular tool. The prototype implementation of an Eclipse plugin is available online (link). Results show that our approach reached an average of 82% of precision and 81% of recall, varying from 48% to 100% for precision and recall respectively.

➔ Second, we propose an approach that assist developers to check the behavioral correctness of the co-evolution. This approach leverages unit tests before and after the co-evolution and gives visual report about passing, failing, and erroneous tests before and after the co-evolution. This visual report allow to have more insights about the co-evolution ans its impact on the code. We then evaluated our approach on 18 Eclipse projects from OCL, Modisco, Papyrus, and EMF using both automatically generated and manually written tests. When we studied the usefulness of our approach quantitatively, we found 88% of reduction in the number of tests and 84% in execution time.The prototype implementation of an Eclipse plugin is available online (link). The other part of the evaluation consisted of an user study experiment to gain evidence on the difficulty of the manual task of tracing impacted tests after metamodel evolution and co-evolution.

➔ Third, we investigate the ability of LLMs in giving correct co-evolutions in the context of metamodel and code co-evolution. The prototype of implementation of an Eclipse plugin is available online (link). We evaluated our study approach with ChatGPT version 3.5 on seven Eclipse projects from OCL and Modisco evolved metamodels. the evaluation included temperature variation, prompt structure variation, and comparison with IDE Quick Fixes as baseline. Results show that ChatGPT can co-evolve correctly 88.7% of the errors, varying from 75% to 100% of correctness rate. When varying the prompts, we observed increased correctness in two variants and decreased correctness in another variant. We also observed that varying the temperature hyperparameter yields better results with lower temperatures. Finally, we found that the generated prompts co-evolutions completely outperform the quick fixes.

1.4 Outline of the thesis

This manuscript is organised as follows:

- Chapter 2 provides a short background about our MDE context and main concepts that will be employed throughout the thesis.
- Chapter 3 focuses on a review of relevant studies carried out within Metamodel change detection, co-evolution in MDE ecosystem, API-client evolution, language evolution, and evolution in low-code platforms. This chapter ends with a discussion about limitations and research gap.
- Chapter 4 is devoted to our first contribution about the automatic code co-evolution approach du to metamodel evolution. It presents the algorithm of pattern matching process that selects the appropriate resolution for each error. It presents also its evaluation and results.
- Chapter 5 presents our second contribution about leveraging unit tests to check metamodel and code co-evolution behavioral correctness with its evaluation including the user experience that we conducted and results.
- Chapter 6 details the empirical study that we conducted as last contribution about exploring LLMs in metamodel and code co-evolution context, with its evaluation and results.
- Chapter 7 summarises the contributions of this work and discusses its limitations and potential avenues for future work, thereby concluding this thesis.

Chapter 2

Background

In this chapter, we introduce the field of Model-Driven Engineering. In Section 2.2, we present the activity of metamodeling and the involved artifacts. Section 2.3 discusses the automation task related to the artifacts presented in Section 2.2. We finish this chapter with a presentation of the evolution concept in the context of model driven engineering.

2.1 Model-Driven Engineering

To develop a software, a list of specifications is given to the developers, to code the final product. This approach can work in the case of small projects. When the complexity of the software increases, more efficient approaches must be adopted. Model-Driven Engineering has proven its efficiency comparing to other engineering disciplines in developing hyper-complex systems [21].

Model-Driven Engineering(MDE) is the systematic use of models as primary artifacts during a software engineering process. MDE includes various Model-Driven approaches to software development, including Model-Driven Architecture, Domain-Specific Modeling and Model-Integrated Computing [22]. The first appearance of MDE-like approaches started in the 80's [23]. MDE is still adopted and a lot of work is being done in academia and industry [8], [24]–[26].

The goal of MDE is to improve productivity, quality, and maintainability by leveraging high level abstractions throughout the development process. The metamodeling phase implied the experts of the domain who focus on the major key aspects of the problem rather than being concerned about the underlying programming language and the implementation. Moreover, it aims to improve communication between multi-disciplinary collaborators [26].

The metamodel represents the main artifact in MDE. There are many definitions of the concept "metamodel" that can be found in literature [27]:

Definition 01: *A metamodel* describes concepts that can be used for modeling the model (i.e. in the instances of the metamodel).

Definition 02: *Metamodels* are models that make statements about modeling. More precisely, a metamodel describes the possible structure of models in an abstract way, it defines the constructs of a modeling language and their relationships, as well as constraints and modeling rules, but not the concrete syntax of the language.

Definition 03: *A metamodel* defines the abstract syntax and the static semantics of a modeling language ,Vice versa, each formal language, such as Java or UML, possesses a metamodel.

Seidewitz [28] gives another commonly used definition of *metamodels* in MDE:

Definition 04: *A metamodel* is a specification model for a class of systems under study where each system under study in the class is itself a valid model expressed in a certain modeling language.

2.2 Metamodeling

Metamodeling is the process of metamodel creation. Metamodeling is done thanks to metamodeling languages (that is in turn described by a meta-metamodel).

Metamodeling must gather the whole knowledge that is required to define, precise, and deal with MDE challenges in its different tasks [26], related to other artifacts shown in Figure 2.2:

— The construction of metamodel describes the abstract syntax of target (software languages, solution system).

— Model validation: models are validated against the constraints defined in the metamodel.

— Model-to-model transformations: such transformations are defined as mapping rules between two metamodels.

— Code generation: the generation templates refer to the metamodel of the "system".

— Tool integration: based on the metamodel, modeling tools can be adapted to the respective domain.

In the context of Domain-Specific Languages, DSMLs can be tailored via metamodeling to precisely match the domain's semantics and syntax. The concrete syntax that is, the concrete form of the textual or graphical constructs with which the modeling is done must represent the metamodel in an unambiguous way. Having graphic elements that linked directly to a familiar domain makes it easier to learn and allows domain experts to contribute, such as system engineers and experienced software architects, ensure that software systems meet user needs [29]. The metamodel is the basis for the automated, tool-supported processing of Metamodeling models. On the other hand, a suitable concrete syntax is the interface to the modeler and its quality decides what degree of readability the models have [27].

Metamodeling languages are classified into two categories linguistic and ontological [30]. Linguistic metamodeling represents way for defining modeling languages and their primitives (e.g., Object, Class, MetaClass) on the layer of a metamodel. Ontological metamodeling aims to represent domain knowledge accurately, it is concerned with semantics and meaning, e.g., OWL [1]. Linguistic metamodeling aims to define a language for creating models. it is concerned with syntax and structure. We can use a different classification by purpose: General Purpose Modeling Langugaes and Domain-Specific Modeling Languages [31]. General purpose modeling languages as for example : UML and its variants, generic metamodeling frameworks, such as MOF [2], and Ecore [3]. As examples of DSLs, we cite sysML and EXPRESS DSL.

In MDE, there are language workbenches that are used for language creation, such as Xtext, MetaEdit+ [26].

In the language modeling ecosystem, other artifacts are created by the mean of the metamodel. By definition, the model is an instance of a metamodel, which means that the metamodel defines the concepts with which a model can be created. The created models can be validated through a set of constraints to check the models' correctness. Constraints are written in Object Constraint Language. They precise specifications on the model that cannot be expressed by diagrammatic notation. In order to save effort and avoid errors, models transformation is one of the common automated tasks in Model-driven engineering. Model transformation are expressed in Transformation Languages for example, ATL). A transformation consists of a set of rules that map the source metamodel elements to the metamodel target's elements. All of these artifacts have its specific tools and represent an important topic of research in MDE.

1. https://www.w3.org/TR/owl-features/
2. https://www.omg.org/mof/
3. https://eclipse.dev/modeling/emft/search/concepts/subtopic.html

2.3 Automation in the MDE ecosystem

Brief description about automated tasks in MDE.

2.3.1 Code Generation

One of the most important advantages of MDE, is the automation in many of its activities. The code generation activity is recurrent, and its automation enhances the productivity and the cost. For example, Eclipse Modeling Framework built-in code generator allows to generated a java API from an Ecore metamodel. The generated code API structure and technical choices are done to fit Java programming language and model driven engineering abstraction standards/principles (e.g., each metaclass is used to generate an interface and concrete implementation class that extends the generated interface, pattern observer), to have an efficient as possible. *@generated* annotation is used to mark generated interfaces, classes, methods, and fields. This annotation can be used to differentiate the generated code from the manually written one.

In Eclipse Modeling Framework, two model resources (files) are manipulated: the .ecore file that contains xmli serialization of the Ecore model and the .genmodel for the serialized generator model. The Ecore file is the document that contains the metamodeled main concepts that are used in code generation process.

2.3.2 Evolution in the MDE context

During the software development process, software artifacts are meant to be changed, due to many reasons: client requirements and domain specifications, software maintenance, or bug correction. Like any other software system, modeling languages are the subject of an inevitable evolution, during their process of building, multiple versions are developed, tested, and adapted until a stable version is reached.

Different types of evolution are categorized depending on the impact and purpose of the applied modifications [32], [33]:

- Corrective: aims to correct discovered problems and inconsistencies such as processing failures, performance failures, or implementation failures by applying a set of reactive modifications of a software product.
- Adaptive: in case of changing environment, such as changes in data environment or processing environment, this evolution aims to keep a software product usable.

— Perfective: this evolution aims to improve functionalities, enhance the performance, reliability, or to increase the maintainability of a software.

It is unavoidable to change, whether to answer to requirement modifications, and/or technological progress. The term *Evolution* can be refined as the literature presents various related terms like: Maintenance, Refactoring, and **Co-evolution**, which are different types of modifications that could be applied on a software.

Evolution: when users and developers get by learning new requirements that lead to adapt the software to new changes.

Maintenance: It is modifying a software product after delivery to correct faults, to improve performance, or to adapt the product to a changing environment.

Refactoring: It is an oriented object term, that means modifications of software to make it easier to understand and to change or to make it less susceptible to errors when future changes are introduced.

Co-evolution: It consists of the process of adapting and correcting a set of artifacts A_1, A_2, ...A_N in response to the evolution of an artifact B on which A_1, A_2, ...A_N strongly depend, for example the co-evolution of models with the evolving metamodel.

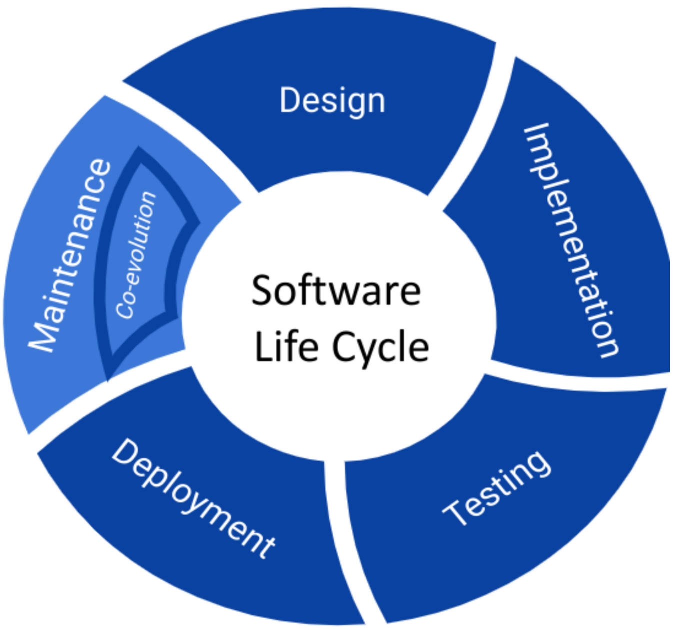

Figure 2.1 – Software Life Cycle (not sure to include)

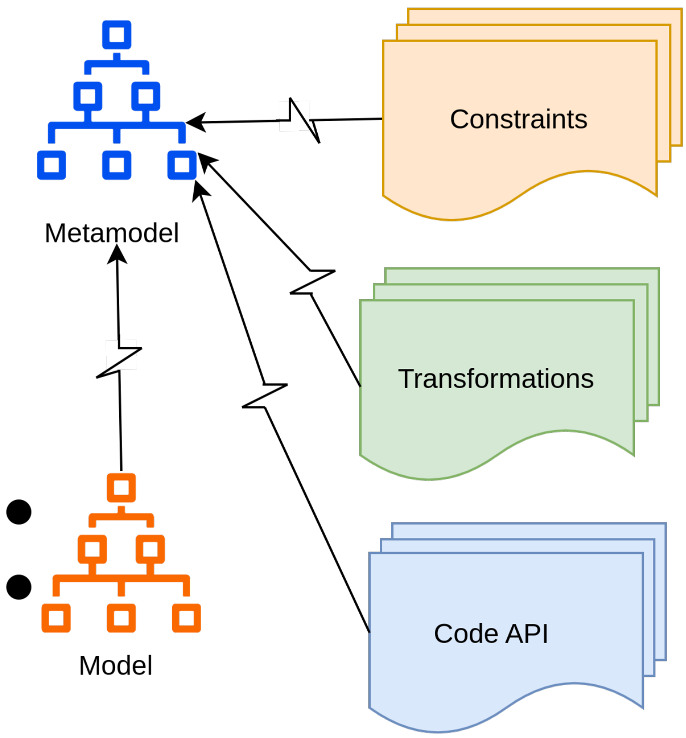

Figure 2.2 – MDE Ecosystem (not sure to include)

Chapter 3

State Of The Art

In this chapter, we present an overview of what has been done in the field of code co-evolution in the context of Model-Driven Engineering. We split this overview into four parts. In section 3.1, we present the metamodel change detection approaches. Section 3.2 presents the co-evolution of model, transformations, constraints with evolving metamodel. In section 3.3, we discuss code co-evolution and relevant literature about API-client evolution, and language evolution. In Section 3.4, we browse related work to checking the behavioral correctness of code co-evolution. Section 3.5, presents an overview of the use of LLMs in related MDE and SLE tasks. We finish this chapter with a discussion focused on limitations and research gap.

3.1 Metamodel change detection

One of the intrinsic properties of software artifacts is its continuous evolution [34]. Like any software artifact, metamodels are meant to evolve to meet the represented domain. In this thesis, our context is triggered by the metamodel evolution, that's why we find essential to understand this evolution in detail. A lot of work has been done on metamodel diffing. Detection approaches can be classified into two main categories; online [1] detection approaches, and offline [2] detection approaches. This classification can be refined using some factors: automation degree, types of detected changes, considered issues (overlap, indefinite length, hidden changes, order of changes, and undo operations)[35].

In another hand, many of them classified the detected changes based on their impact on the treated artifact (models, constraint, transformation, and code). Here we put the largest set of changes types, later, we will specify treated types with their possible impact on the code.

Two types of evolution changes are considered when evolving a metamodel: *atomic*

1. Offline approaches perform detection after the metamodel has been evolved.
2. Online approaches perform instant detection for each change during the metamodel evolution

Table 3.1 – Catalog of changes that occur during the metamodel evolution. (To fill)

Type	Change name
Atomic changes	Delete class
	Delete property
	Add class
	Add property
	Rename class
	Rename property
	Generalize property
Complex changes	Move property
	Push property
	Pull property
	Inline class
	Change property type

and *complex* changes [35], [36]. Atomic changes are additions, removals, and updates of a metamodel element. Complex changes consist of a sequence of atomic changes combined together [37], [38]. For example, move property is a complex change where a property is moved from a source class to a target class. This is composed of two atomic changes: delete property and add property [36]. Many approaches in the literature [37], [39]–[44] exist to detect metamodel changes between two versions.

In Model-Dricen Engineering area, metamodel changes can be divided into three categories[45]:

— Non-breaking changes can be resolved automatically.

— Breaking and resolvable changes break the conformance of existing data, although they can be automatically adapted.

— Breaking and unresolvable changes break the conformance of existing data, that cannot be automatically adapted, and require user intervention

In API evolution context, API changes can be classified as Non-breaking API Changes or Breaking API Changes. A breaking change is not backwards compatible. In this case, client code calling the evolved API by a Breaking Change fails to compile or may behave differently at runtime. A non-breaking change is backwards compatible. This kind of changes aims to extend the functionalities or fix errors [46].

3.2 Co-evolution of models, constraints, and transformation

In MDE ecosystem, the metamodel is the starting point to have other artifacts that we defined in section ?. in this section, we will present an overview of the existing work about these artifacts co-evolution. Note that if the solution is applied during the evolution of the metamodel, we call it an online solution, otherwise it is offline. The comparison, advantages, and drawbacks of the presented approaches is out of the scope of this dissertation.

3.2.1 Metamodel and model co-evolution

Due to metamodel evolution, the model becomes "no conform". A set of resolutions are applied to co-evolve the model to gain again its conformity to the metamodel. The co-evolution between metamodel and models can be processed manually but it requires a huge expertise, and when the number of models to co-evolve increases, manual co-evolution becomes hard task. Most of automatic and semi-automatic Co-evolution approaches use automatic or manual diffing metamodel approaches in their solutions. Model co-evolution approaches that we found can be categorized into five categories [47]. The first category is Resolution Strategy Languages that specifies in a transformation language how to update the model given the list of metamodel changes [48]–[54]. The category Resolution Strategy Generation groups approaches that generate full or partial resolution for each metamodel change [55]–[59].

The third group of "Predefined Resolution Strategies" contains approaches that provide automation, when it is possible, by applying predefined resolution strategies [60]–[68].

Some of these approaches requires the user intervention to make decision on the selected operation to adapt the model. The fourth category of Resolution strategy leaning that adopt machine learning algorithm to select the resolution strategy for metamodel changes.[69].

The fifth and last category is called Constrained Model Search. It groups approaches that do not use the metamodel change, but uses the original model and the new metamodel to apply a constrained-based search of valid model variants [70]–[72]. Other approaches consider the model co-evolution problem as an optimization one that does not need the list of changes of the metamodel [73]–[75].

3.2.2 Metamodel and constraints co-evolution

Another artifact that depends on the metamodel and needs to be adapted to the evolution of its metamodel is Constraints. Constraints co-evolutions that we can find in literature may be online [3] or offline [4]. Every approach has its own co-evolution mechanism that treats specific types of metamodel changes and has its automation degree. Demuth et al. [76] proposed a template-based, hat cannot cover all changes types, of the predefined structure of the updated constraint. Markovich et al. [77] proposed refactoring rules that depends on the impact of UML class diagram evolution on the constraints. Hassam et al. [78] propose METAEVOL, based on a transformation language.Kusel et al [79] propose a solution for the co-evolution of the constrain body and do not include its context that may need co-evolution also. Cabot et al [80] treats OCL constraints co-evolution due to metamodel deletion change. Khelladi et al [81] proposed an approach that record the metamodel atomic and complex changes in a chronological order then apply one or many resolutions to co-evolve the constraints. Batot et al. [82] tackles the constraint co-evolution problem as an multi-objective optimization problem and apply heuristic-based recommendation approach that does not require/use a predefined set of transformation rules/resolutions to co-evolve the constraints. Demuth, markovitch, cabot [76], [77], [80] their approaches ar fully automatic while Hassam, kusel and Khelladi, and Batot [78], [79], [81], [82] propose semi-automatic approaches since the user must select from the recommended output constraints.

3.2.3 Metamodel and transformations co-evolution

Almost all the existing transformation approaches that we find in literature start by analyzing the impact of the metamodel on the model transformations. Mendez et al. [83], Ruscio et al. [84], Garces et al.[85], Kusel, et al.[86], and khelladi et al. [87] proposed to co-evolve impacted transformations with a set of resolutions. The approach of khelladi et al. [87] covers the largest set of possible resolutions where Ruscio et al. [84], estimate the cost of the co-evolution to decide about the co-evolution,they further explored the variability of the co-evolution due to the possible alternative resolution. Garcia et al.[88] proposed a ATL transformation-based approach which means that their resolutions are ATL transformations. All the approaches propose unique resolution to

3. Online approaches perform instant co-evolution for each change during the metamodel evolution
4. Offline approaches perform co-evolution after the metamodel has been evolved.

co-evolve each transformation. Ruscio et al. [84] approach allows developers to manually replace or refine a resolution. Khelladi et al. [87] allow to compose existing resolutions into a new one. Kessentini et al. [89] used a different approach that do not use the changes of the metamodel as input and do not process by an impact analysis, but it uses a search-based approach that relied on multi objective heuristic algorithm NSGA-II.

3.3 Code co-evolution

We divided the related work to code co-evolution into four (4) main categories : 1) Metamodel and code co-evolution, 2) API and client code co-evolution, 3) Automatic Program repair, and 4) Consistency checking.

3.3.1 Metamodel and code co-evolution

Co-evolution of code is distinguished from the co-evolution of other artifacts by the fact that *one* change in a metamodel element will affect n different code elements, in contrast to a *one* to *one* impact relationship between metamodel elements and models, constraints and transformation elements [57], [63], [74], [81], [85]–[87], [89]–[96].

Yu et al. [10] proposed to co-evolve the metamodels and the generated API in both directions. However, they do not co-evolve the code on top of it.Khelladi et al. [11] proposed an approach that propagates metamodel changes in the code as a co-evolution mechanism. However, it is based on static analysis to detect the impacts and not on the actual errors that appear from the compilation of the code after the metamodel evolution. It further applies a semi-automatic co-evolution requiring developers' intervention, and without checking behavioral correctness with tests with no comparison to a baseline.

3.3.2 API and client code co-evolution

Existing approaches for code migration are related to our work.Henkel et al. [97] proposed an approach that captures refactoring actions and replays them on the code to migrate. However, they support only the changes renames, moves, and type changes.

Nguyen et al. [98] also proposed an approach that guides developers in adapting code by learning adaptation patterns from previously migrated code. Similarly, Dagenais et al. [99]–[101] also use a recommendation mechanism of code changes by mining them from previously migrated code. Anderson et al. [102] proposed to migrate drivers in response to evolutions in Linux internal libraries. It identifies common changes made in a set of files to extract a generic patch that can be reused on other code parts. Gerasimou et al. [103] extract a set of mapping rules and apply code-based transformations to update its clients.

// Survey about Library evolution [104]

ref :Automatically Generating Refactorings to Support API Evolution ref :Experience Paper: A Study on Behavioral Backward Incompatibilities of Java Software Libraries

Other migration approaches [105]–[107] rely on pre-collected examples to learn how to evolve the additional client code. Xu et al. [108] instead of learning from code examples, it constructs a database of edits to use during clients' migration.

Zhong et al. [109] proposes "LibCatch", a tool to co-evolve client code to APIs evolution by reducing the compilation errors. They do not consider the API changes to correctly propagate them to the code, which may lead to only eliminating the code errors while they could be incorrect resolutions, as shown in our RQ3. They further do not use any mechanism to check the behavioral correctness of the code co-evolution and with not comparison to a ground-truth.

3.3.3 Automatic Program Repair

[110] : evaluation metrics of APR systems could be biased.

In addition to migration approaches, extensive state of the art exists on program repair [111]–[114]. However, they do not repair code errors, but rather bugs that are found due to failing tests (e.g., Meng at al. [115]). They could be used as a next step after o co-evolution.

//To refresh new references

3.3.4 Consistency checking

Close to code co-evolution, Riedl et al. [4] proposed an approach to detect inconsistencies between UML models and code. Kanakis et al. [5] showed that inconsistency information of model change and code error can help to resolve them in the code, which is equivalent to our matched pattern usages. Pham et al. [6] proposed an approach to synchronize architectural models and code with bidirectional mappings. Jongeling et al. [7] proposed an early approach for the consistency checking between system models and their implementations by focusing on recovering the traceability links between the models and the code. Jongeling et al. [8] later rely on the recovered traces to perform the consistency checking task. Zaheri et al. [9] also proposed to support the checking of the consistency-breaking updates between models and generated artifacts, including the code. However, [6]–[9] do not focus on co-evolving the code to repair the inconsistencies with the models.

3.3.5 Language evolution

Language evolution is related to various technological spaces [116]. Metamodels evolve [117] (Section 3.2), APIs evolve [46] (Section 3.3.2), grammars evolve in [118], schemas evolve [119], [120], and ontologies evolve [121], too.

There are two types of languages: General Purpose Languages (GPL) and Domain-Specific Languages(DSL).

DSL is strictly coupled to the domain and its requirements/capabilities at the time in which the DSL is written. If the domain requirements and/or capabilities change, then the DSL could become inadequate to deal with the changed domain. [122] incrementally changed the language ()a five year old DSL) supporting multiple hardware configurations. initially prefixed later defined by the user. Domain experts no longer need DSL experts to define new configuration with new movements, states and zones. DSLs evolve [123], [124], that presence of inter-DSL dependencies in an MDSE ecosystem causes a ripple effect and increases costs of manual maintenance. Hence, an automatic approach is required to facilitate co-evolution of artifacts in MDSE ecosystems. Regarding Domain-Specific evolution, works treated this topic from many aspects, and from different ecosystems and case studies [125]. Opensource ecosystems like GMF [5] The Graphical Modeling Framework (GMF) is a widely used open source framework for the model-driven development of diagram editors implemented on top of the Eclipse Modeling Framework (EMF).

Herrmannsdoerfer et al. present a method to investigate the evolution of modeling languages hint at the possible effects on the related language development artifacts [126].

Industrial ecosystems like CARM (Control Architecture Reference Model) is an industrial ecosystem for ASML [6] is the world's leading provider of complex lithography systems for the semiconductor industry [125].

In another hand, we have Programming Languages which are General purpose one. Their evolution consist mainly of feature additions that allows at some extent the stability

5. https://eclipse.dev/modeling/gmp/?project=gmf-runtime
6. https://www.asml.com/en

of the code and do not break it. This evolution is due to two types of causes : 1) External, for example for hardware changes, the control of business needs, or the progress of scientific research. 2) Internal for bug fixing, or improving the verbosity of the language. Every change to a programming language API has the potential to affect programs written in this language. For example, Python 2 and 3 have major incompatibilities that leads to maintenance costs. A recent study shows that developers lack awareness of the subs-generated tests often present limitations and possible incompatibilities which make code maintenance a hard task [127].

Regarding programming languages evolution, many works were centered around change-impact analysis before proposing an adaptation approach [128]–[130]

Urma et al.[131] propose PytypemonitorInfer, a dynamic light-weight type inference tool for Python to automatically provide insights useful for migration about a Python program. few works were done for specific languages evolution, for example, Expansion and evolution of the R programming language regarding linguistic understanding of human language [131]. Another programming language, Pharo [132] in their empirical study, analyzed the the most important changes in Pharo API and their impact on different systems in Pharo ecosystem. Ochoa et al. [133] propose Breakbot, a tool to analyze the impact of the breaking changes of java libraries on their client code.

3.4 Behavioral correctness of the co-evolution

To ensure the behavioral correctness of a given version of the code, we can follow different methods. The first one is manual and exhaustive debugging to ensure that the code acts as expected. This method can be tedious and error prone for relatively complex code. Another method which is widely exploited is Testing. Testing in software engineering is a large research area with different approaches and tools. To check the behavioral correctness of a program, we can use Unit Testing through good quality unit tests that pass. In the case of more critical systems (Medical devices systems, autopilot systems, avionics engineering..etc), it is primordial to use formal methods like model checking or theorem proving [134] (costly).

In the context of code evolution, we need to verify that this evolution operations did not alter the behavior of the code. In more large perspective, we would like to check the impact of this evolution on the code, did it improve, kept, or alter the behavior of the code. From this point of view, we investigated the literature to explore the different approaches that are used for this purpose : checking the impact of a code different type of evolution on the behavioral correctness of the code.

In Automatic program repair, after fault localization, the goal is to remove bugs. The correctness of this bug removal is often checked using test suit that passes. [135] propose an extension of EVOSUITE, that generates repairs patches of better quality plus the tests proves the veracity of the patches. Roziere et al. [136] leverage generated unit tests to filter out invalid translations and reduce the noise in the generated translations to have better candidates.

In the literature, correctness is generally assessed manually by comparing the APR-generated patch against the developer-provided patch available in the benchmark. This paper proposes metrics that limit the biases when assessing APR tools.- :Upper bound Repair Performance metric aims to clearly provide an indication of the patch generation limitations when focusing on this part of the APR system (i.e., APR systems are given with the exact bug-fixing positions obtained from the ground of truth developers' patches). The list of the used metrics:
• Fault Localization Sensitiveness metric aims to assess the impact of the used fault localization on the repair performance of the APR system. • Patch Generation Efficiency metrics aim to clarify the APR efficiency, the effort to yield a plausible/correct patch.
• Bug Diversity metrics aim at evaluating APR system performance from intrinsic attributes of bugs.
• Benchmark Overfitting metrics aim to clarify the difference of APR systems performance between in-the-lab and in-the-wild assessment settings.

Qi et al. [137] also divide exsting approaches for APR assessment into two main approaches on assessing patched program correctness: formal specifications and APR assessment metrics with test suits.

Liu et al. [110] exploit the number of bugs for which a correct patch is generated appeared to be a more reasonable metric and is now widely accepted in the literature for evaluating APR tools. metric: number of successfully fixed bugs with patches can pass all the given test cases (both previously-passing and previously failing test cases on the buggy version). validated patch might break a necessary behavior or introduce other faults.

In code refactoring, one of the followed approaches is to minimize the number of code smells, and a test suite that passes or both. Soares et al. [138] deal with semantic errors (non behavior-preserving transformations). The current practice to avoid refactoring errors relies on compilation and tests to assure semantics preservation, their approach starts by identifying common methods between source and target source code (before and after refactoring). Then generates tests on the common methods, run them on source then the target if no test fail, developer will have more confidence the correctness of the refactorings. Wahler et al. [139] use static analysis and software metrics as objective evaluation combined with Software Engineers judgment as subjective evaluation to validate refactorings and to improve the maintainability of their case study.

Da Silva et al. [140] leverage generated unit tests to detect semantic conflicts in different merging scenarios, and differential generated unit tests generated and run on both commit the changed commit pairs. Their results show the efficiency of the generated unit tests and no conflict was wrongly detected.

Assumption:

Unit test can be used to check the behavioral correctness of the code at some state. If a transformation occurs in the code from a state to another, We can use unit tests (manually written or generated) to check if the code evolution has improved, kept, or altered the behavior of the code.

Talk about limitations?

3.5 LLMs for co-evolution

Since their appearance in 2022 [7], Large Language Models revolutionized the computer science industry and the industry of the world since computer science is concretely used everywhere. In this thesis, that started a little bit before this revolution, we found that it is important to investigate the path of LLMs and its intersection with the scope of our work. Thousands of scientific papers are produced in many domains to treat thousands of topics. In this section, we present the most related work to code co-evolution.

White et al. [141] propose a set of prompt patterns for different tasks that can be used in different phases in the life cycle of a software development, for example: API generation prompt pattern, DSL creation prompt pattern, code quality, and refactoring prompt patterns.

Sridhara et al. [142] explore how ChatGPT can be used in ambiguity resolution in Method Name Suggestion Log Summarization, Anaphora resolution, Python Type Inference, Commit Message Generation, Code Review, Duplicate Bug Report Detection,

7. texthttps://www.dataversity.net/a-brief-history-of-large-language-models/

Natural Language Code Search, Vulnerability Detection, Code Clone Detection, Test Oracle Generation, Code Generation from natural language, Merge Conflict Resolution, and Code Refactoring. Some of Extract Method refactorings meet developers' refactorings where other results that do not meet developers' refactorings are syntactically correct and semantically correct.

Besides code generation and code documentation, the paper of Sadik et al. [143] investigates the potential application ChatGPT as an LLM for bug detection and refactoring particular code bad smell detection. Hemberg et al. [144] explain their approach on how an algorithm, with the general algorithmic structure of an EA and evolutionary operators, can use an LLM to evolve code, how the operators are designed to formulate LLM prompts, task the LLM via the prompts, and process LLM responses, while code is represented as a sequence of text in code syntax. Its goal is to get the best solution code that fits the best the beforehand mentioned operators as hyper parameters of the genetic algorithm.

Chapter 4

Titre du premier chapitre

4.1 Première section du chapitre

4.1.1 Première sous-section

4.2 Approach

This section presents the overall approach of our automated co-evolution of code with evolving metamodels, instantiating on the Ecore technological space. First, we give an overview of the approach and specify the metamodel evolution changes we consider. Then, we present how we retrieve the resulting errors due to metamodel evolution, followed by the regeneration of the code API. After that, we present the pattern matching process, which is an important part of our fully automatic co-evolution approach, before discussing the resolutions of the code errors.

4.2.1 Overview

Figure 4.1 depicts the overall steps for the automatic co-evolution of the metamodel and code, with horizontally separated parts defining chronological order from the top to the bottom. After the generation step (the upper part of Figure 4.1), the evolution of the Ecore metamodel will cause errors in the additional Java code that depends on the API of the newly generated code (the middle part of Figure 4.1). We take as input the evolution changes of the metamodel between the two versions of this metamodel $\boxed{1}$. Then, we parse the additional code $\boxed{2}$ to retrieve the list of errors. After that, we get to the bottom part of Figure 4.1, both the list of metamodel changes and the list of errors are used as inputs for the pattern matching step $\boxed{3}$. It analyzes the structure of the error to match it with its impacting metamodel change and decides which resolution to apply for the error co-evolution $\boxed{4}$. The metamodel changes provide the ingredients and necessary

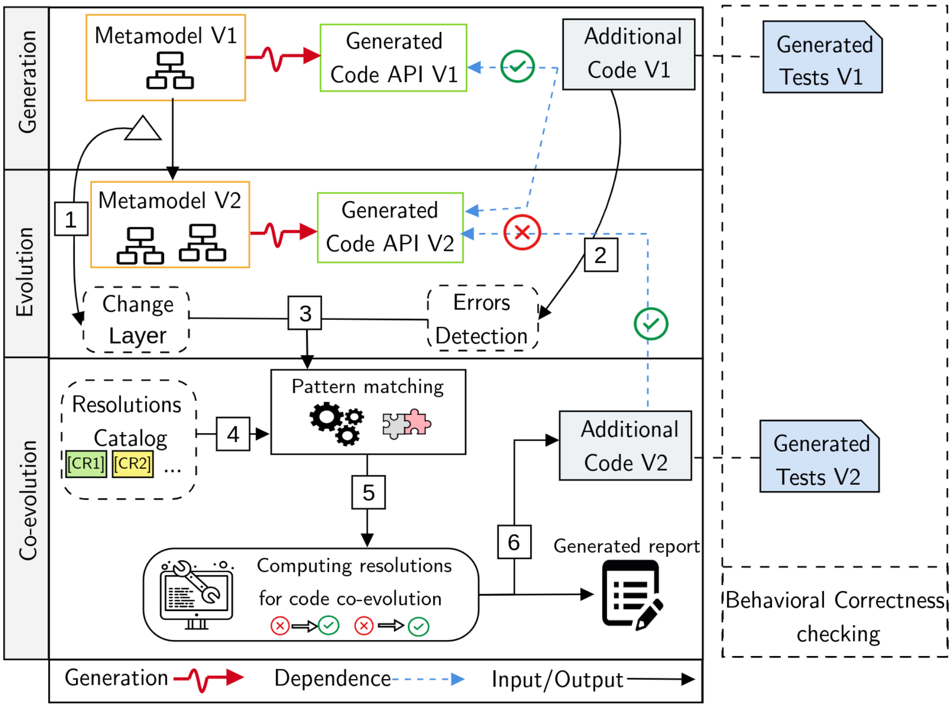

Figure 4.1 – Overall approach for metamodel and code co-evolution

information that are used for the co-evolution. At the end of the automatic co-evolution, we obtain a new co-evolved additional code $\boxed{5}$. In addition to the automatic co-evolution, we generate test cases before and after co-evolution to highlight its possible effect. In fact, many research papers rely on the use of tests to check the behavior of the code during its evolution. For example, Godefroid et al. [145] uses tests to find regressions in different versions of REST APIs. In particular, Lamothe et al. [107],test [106] use tests to validate the evolution of the client code after Android API migration. We apply a similar method to check the effect of the co-evolution. [115] Finally, during the co-evolution process, we generate a report linking the applied resolutions for each code error with its impacting metamodel change. If needed, this can help developers in understanding the performed co-evolution, since we fully automate it.

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COLLEGE DOCTORAL BRETAGNE | MATHS, TELECOMS INFORMATIQUE, SIGNAL SYSTEMES, ELECTRONIQUE

Université de Rennes

Titre : titre (en français)..............

Mot clés : de 3 à 6 mots clefs

Résumé : Eius populus ab incunabulis primis ad usque pueritiae tempus extremum, quod annis circumcluditur fere trecentis, circummurana pertulit bella, deinde aetatem ingressus adultam post multiplices bellorum aerumnas Alpes transcendit et fretum, in iuvenem erectus et virum ex omni plaga quam orbis ambit inmensus, reportavit laureas et triumphos, iamque vergens in senium et nomine solo aliquotiens vincens ad tranquilliora vitae discessit. Hoc inmaturo interitu ipse quoque sui pertaesus excessit e vita aetatis nono anno atque vicensimo cum quadriennio imperasset. natus apud Tuscos in Massa Veternensi, patre Constantio Constantini fratre imperatoris, matreque Galla. Thalassius vero ea tempestate praefectus praetorio praesens ipse quoque adrogantis ingenii, considerans incitationem eius ad multorum augeri discrimina, non maturitate vel consiliis mitigabat, ut aliquotiens celsae potestates iras principum molliverunt, sed adversando iurgandoque cum parum congrueret, eum ad rabiem potius evibrabat, Augustum actus eius exaggerando creberrime docens, idque, incertum qua mente, ne lateret adfectans. quibus mox Caesar acrius efferatus, velut contumaciae quoddam vexillum altius erigens, sine respectu salutis alienae vel suae ad vertenda opposita instar rapidi fluminis irrevocabili impetu ferebatur. Hae duae provinciae bello quondam piratico catervis mixtae praedonum.

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