On the Need for a Formally Complete and Standardized Language Mapping between C++ and UML

Johannes Trageser[1,2,a]
[1] *Willert Software Tools GmbH, Germany*
[2] *TU Clausthal, Germany*

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Abstract: This paper presents a vision of a well-integrated solution for implementing (embedded) software with a model-driven approach by using UML as a semantic and conceptual extension to C++ without losing support for established concepts, tools and libraries of C++. This requires a formally complete and standardized language mapping between relevant and bounded subsets of C++ and UML as the foundation for a bidirectional-translational approach between those two languages, and appropriate tooling that puts this approach into practice. The standardized mapping is prerequisite for a model exchange among different tools.

1 INTRODUCTION

"The UML, a visual modeling language, is not intended to be a visual programming language, in the sense of having all the necessary visual and semantic support to replace programming languages. The UML is a language for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system, but it does draw the line as you move toward code. Some things, like complex branches and joins, are better expressed in a textual programming language. *The UML does have a tight mapping to a family of OO languages so that you can get the best of both worlds.*" (OMG, 1997)

Looking at those lines from the *Outside the Scope of the UML* section of the UML 1.1 specification, it becomes clear that UML initially was neither designed to be executable, nor as an implementation language, but very well with a tight mapping to OO programming-languages and a focus on "artifacts of a software-intensive system" (OMG, 1997). Thus, the intent was not to replace OO programming languages but to extend them by adding new views with more abstraction.

When Grady Booch, one of the architects of UML, was talking about UML at the OOPSLA 1986 (Booch et al., 1996) he pointed out that "the choice of what models/views to create has a profound influence upon how a problem is attacked and a solution is shaped" and "no single model/view is sufficient, but complex systems are best approached through small sets of nearly independent models". He also emphasized it had been a "clear intent with UML to make certain that all of those models are connected to reality" and "mappings to a variety of languages" exist.

Following Booch (1996), when UML was launched, it was challenging to balance the level of abstraction to make UML on one hand extensible and independent from language-specific features but on the other hand still concrete enough that both "forward code generation as well as reverse-engineering" would be supported in a concept they called "round-trip engineering" with the benefit of "getting the best of both worlds" keeping them in a loose synchronization.

A close mapping between UML and selected programming languages has never been permuted as a standard, and up till now remains unresolved.

2 BACKGROUND AND RELATED WORK

In this work, I will take up a pragmatic and implementation-oriented position towards modeling, driven by real-world problems from industry projects, using a model-driven approach with UML and code generation to C++ for implementing embedded systems for different domains.

[a] https://orcid.org/0000-0002-6027-8501

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2.1 Embedded Programming Languages

Regarding *Embedded Markets Studies* from 2005 till 2019 (EETimes, 2005)-(EETimes, 2019) it can be outlined that

- about 80% of the respondents use C or C++ as programming language and
- current embedded projects often consist of upgrades or improvements from earlier projects with a new/upgrade ratio of 44%/56%.

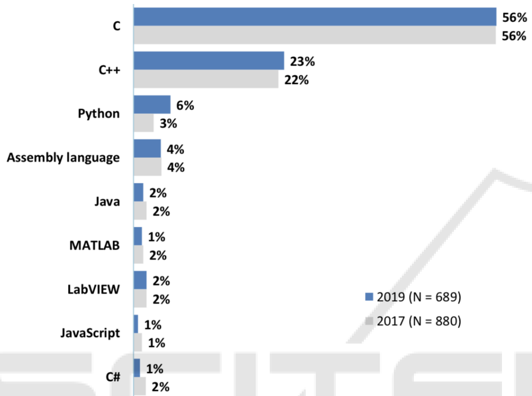

Figure 1: My current embedded project is programmed mostly in: (EETimes, 2019).

Figures 1 and 2 are showing an extraction from (EETimes, 2019). The percentage of C and C++ has widely been constant over the last 15 years. This substantiates the relevance of C and C++ being the most important programming languages in embedded software. C and C++ are probably not going to disappear soon and there is a large legacy code base existing in industrial projects.

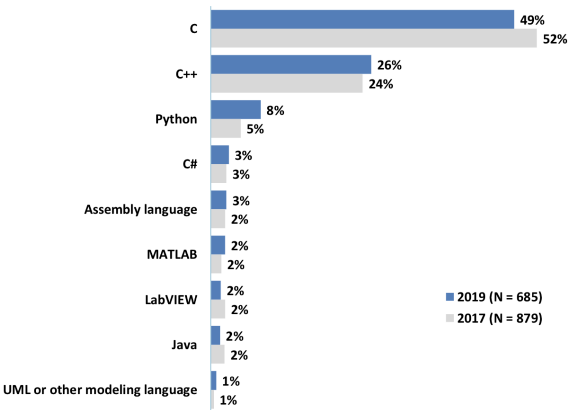

Figure 2: My next embedded project will likely be programmed mostly in: (EETimes, 2019).

Other languages like Java, C# and Python only play a subordinate role as embedded programming languages, because they only make up a small percentage and would most likely not be found in small embedded targets.

Figure 2, showing intended programming languages for the next embedded project, also introduces a new category *UML or other modeling language*, confirming modeling is gaining in importance.

With a Model-Driven-Development (MDD) solution that builds upon C++, 70 - 80% of current and future embedded projects could be covered. Legacy C code could easily be integrated with C++ models and C would not have to be considered separately, because "C++ is a direct descendant of C that retains almost all of C as a subset." (Stroustrup, 2020) Integration of legacy code would probably be realised *as external* by only round-tripping interfaces to the model and leaving the code as it is.

2.2 The Pragmatics of Model-Driven Development

Bran Selic, author of the ROOM methodology and co-chair of UML 2.0, published "The Pragmatics of Model-Driven Development" (Selic, 2008). Although this paper was released 12 years ago, it is still up to date and relevant.

Following Selic (2008), in software engineering, model-driven approaches still have to deal with acceptance problems and rejection.

As challenges, Selic (2008) names "a conservative mindset in both individuals and corporations" that relies on the fact that often a large base of legacy code has to be maintained and upgraded and building up competency in new (model-driven) programming technologies would require "a significant investment in time and effort".

"Model-driven development holds promise of being the first true generational leap in software development since the introduction of the compiler. *The key lies in resolving pragmatic issues related to the artifacts and culture of previous generations of software technologies.*" (Selic, 2008)

The Quality of Models. Selic identifies five key characteristics for the quality of models - *abstraction, understandability, accuracy, predictiveness and being inexpensive* - and declares:

"Probably the main reason why software modeling techniques had limited success in the past is that the models often failed to meet one or more of the criteria just listed. In particular, the techniques tended to be weak in terms of accuracy (which also meant that the models weren't very useful for prediction). In part, this is because it *wasn't always clear how the concepts used to express the models mapped to the underlying implementation technologies such as programming language constructs*, operating system functions, and so forth. This semantic gap was exacerbated if the modeling language was not precisely defined, leaving room for misinterpretation. Also, *because the* ***models weren't formally connected to the actual software****, there was no way of ensuring that the programmers followed the design decisions captured in a model during implementation*. They would often change design intent during implementation — thereby invalidating the model. Unfortunately, because the mapping between models and code is imprecise and the code is difficult to comprehend, such digressions would remain undetected and could easily lead to downstream integration and maintenance problems. (Changing design intent isn't necessarily a bad thing, but it is bad if the change goes unobserved.) Given these difficulties, many software practitioners felt that software models were untrustworthy, merely adding useless overhead to their already difficult task." (Selic, 2008)

The Pragmatics. Selic (2008) highlights several pragmatic issues that need to be resolved to make MDD successful in industrial environments:

Model-level Observability. A Model needs to obtain a level of observability that programmers are used to. This includes model-level-debugging and diff/merge-capabilities. (Selic, 2008)

Model Executability. A most useful model would be executable both in "a simulation environment (for example, on a development workstation)" and "on the actual target platform." (Selic, 2008)

Efficiency of Generated Code. "Current model-to-code generation technologies can generate code with both performance and memory efficiency factors that are, on average, within 5 to 15 percent (better or worse) of equivalent manually crafted systems", so "for the vast majority of applications, efficiency is not an issue." (Selic, 2008)

"Still, there might be occasional critical cases, where manually crafted code might be necessary in specific parts of the model. Such hot spots are often used as an excuse to reject MDD altogether, even when it involves a very small portion of the complete system — the proverbial 'baby and bathwater' scenario. A useful MDD system will allow for seamless and overhead-free embedding of such critical elements." (Selic, 2008)

Integration with Legacy Environments and Systems. "A prudent and practical way to introduce new technology and techniques into an existing production environment is to apply them to a smaller-scale project such as a relatively low-profile extension to some legacy system. This implies not only that the new software must work within legacy software but also that the development process and development environment used to produce it must be integrated into the legacy process and legacy development environment. [...] For example, a useful MDD tool should be able to exploit a range of different compilers, build utilities, debuggers, code analyzers, and software versioning control systems rather than requiring the purchase of new ones. Furthermore, this type of integration should work 'out of the box' and should generally not require custom 'glue' code and tool expertise. [...] Last but not least, an MDD project must be able to take advantage of legacy code libraries and other legacy software." (Selic, 2008)

2.3 Execution of UML Models

Referring to Selic (2008) model executability is an essential aspect of MDD. Model executability can be achieved with an interpretive or translational approach (Figure 3).

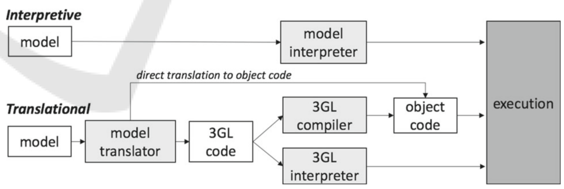

Figure 3: Model execution strategies (Ciccozzi et al., 2018).

In a systematic review of research and practice on the execution of UML models, Federico Ciccozzi ascertained: "The number of translational solutions (70/82) clearly outnumbers the number of interpretive (14/82) solutions" (Ciccozzi et al., 2018). Further, out of the interpretative solutions, "none seems to provide a solution for the execution of UML models on the actual target platform. Instead, they focus on higher-level execution for simulation and model-based analysis." (Ciccozzi et al., 2018)

Following those findings, it seems expedient to choose a translational approach for modeling actual production-quality software.

2.4 The UML/C++ Interrelationship

As UML models, besides the graphical notation also require textual action language for the implementation of actions, there are 2 possible ways to look at the interrelationship between UML and C++ from a UML viewpoint:

- C++ as the target language for code generation, without constituting the action language, e.g. Chess Project (Ciccozzi et al., 2012)
- C++ as both the target language for code generation as well as the action language

Both approaches have their reason for being. If the action language is independent of the target language, this adds more abstraction and can be useful for heterogeneous systems with different target languages, but also has disadvantages as it requires additional learning effort and possibly adds restrictions in expressiveness, compared to the use of the target language as action language. Regarding "integration with legacy environments and systems" (Selic, 2008) and the percentage of C and C++ as the programming language in embedded projects (EETimes, 2019), using C++ as target and action language with a language mapping as close to C++ as possible is therefore seen as the preferred practice.

Another way to look at the UML/C++ interrelationship is a bottom-up approach. From this viewpoint, UML diagrams are a graphical representation of written C++ code and UML tools can use reverse-engineering to import C++ code as a model and visualize it in diagrams.

Listing 1 exposes a simple example written in C++. The final keyword used in line 6 and line 8 was introduced with C++11.

```
1 class Base {
2   public:
3     virtual void foo() = 0;
4 };
5
6 class A final : public Base {
7   public:
8     virtual inline void foo() final { };
9 };
```

Listing 1: Final keyword sample.

Trying to create a model from this code through reverse-engineering with the three most used UML tools Rhapsody, Enterprise Architect and Magic Draw, it could be detected that none of those tools was able to execute the reverse-engineering of this code out of the box. Without the final keywords, the code is C++98 compliant and reverse-engineering was straightforward with all three tools. This indicates that UML tools have problems dealing with up-to-date C++ standards. As this experiment only scratches the surface, further investigations have to be done to get a better-founded data base on the limits of current UML modeling solutions regarding C++ code generation capabilities.

Figure 4 shows an extract of the C++ mapping to UML for an operation that is used by Magic Draw. This mapping is proprietary for Magic Draw and also incomplete regarding keywords like *final*, *override* or *constexpr* that are available since C++11.

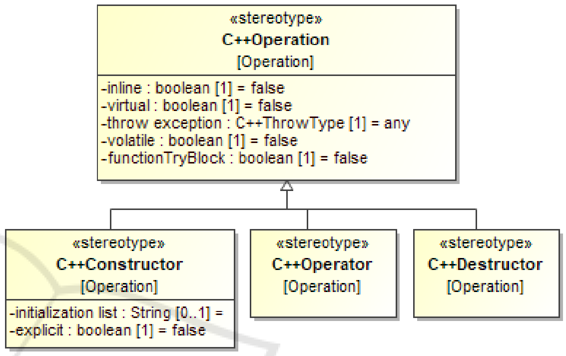

Figure 4: Magic Draw C++ Mapping to UML for Operation (NoMagic, 2020).

Also, other tools like Rhapsody and Enterprise Architect have such proprietary mappings, but more implicitly integrated within the tool.

This experiment substantiates the need for a standardized UML/C++ language mapping that refers to up-to-date C++ standards.

2.5 Research Gaps

There are several research gaps concerning the interrelationship between UML and C++.

First of all, there is no standardized language mapping between UML and C++ at all. UML, even with the fUML (OMG, 2018) and Precise Semantic Standards PSCS (OMG, 2019a) and PSSM (OMG, 2019b), still is not precise and formal enough to be translated to C++ without a risk of misinterpretation, acknowledging that this was never in scope of neither pure UML nor fUML.

Furthermore, existing proposals and solutions for model transformation or execution are often limited in the coverage of the UML language, and "only a few research studies provide evidence of industrial use." (Ciccozzi et al., 2018)

Even though publications exist for UML code generation to C++, e.g. (Jäger et al., 2016), the gaps

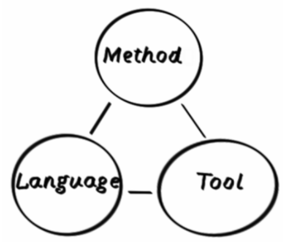

Figure 5: The Three Concerns of Modeling (Weilkiens, 2016).

regarding the UML/C++ interrelationship identified in this paper are still unresolved. There is no existing solution that covers all three concerns of modeling - method, language and tooling (Figure 5). Due to the missing standardized language mapping between UML and C++ - or in other words, a missing modeling language for C++ software, modeling tool vendors introduce proprietary, non-portable solutions, making it impossible to define a tool- and language-independent method.

3 THE VISION - CppML

In the following sections, I will present my vision of a well-integrated solution for implementing (embedded) software with a model-driven approach by using UML as a semantic and conceptual extension to C++ without losing support for established concepts, tools and libraries of C++. This requires a formally complete and standardized language mapping between relevant and bounded subsets of C++ and UML as the foundation for a bidirectional-translational approach between those two languages. C++ code will be regarded as a textual representation of the model in analogy to diagrams being regarded as a graphical representation. The fusion of those two languages will be introduced as CppML (C++ Modeling Language). This vision includes aspects of all three concerns (Figure 5): The CppML-Profile and the transformation rules represent the language aspect. Furthermore, also appropriate tooling has to be available, guiding the developer through a well-defined method with documented best practices and restrictions.

Figure 6 displays the way to look at the UML/C++ interrelationship this work will be based on. The CppML levels will be introduced in detail in (3.1). The overlap between C++ and UML represents the concepts that exist in both languages (e.g. classes, objects, relations). Level 2 and 3, including the overlap between UML and C++, correspond to the scope of fUML, the executable subset of UML (e.g.

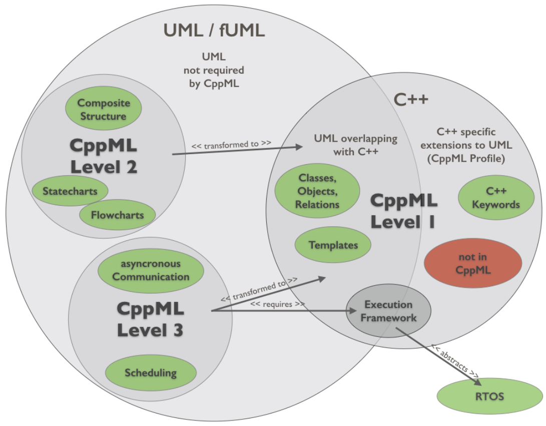

Figure 6: Overview of UML/C++ Interrelationship.

activities, state machines, signals, active classes). The part of C++, not being available in UML, will have to be specified as an extension for UML in a CppML-Profile and will primarily contain modifiers, e.g. for classes or operations like virtual, final and constexpr that are important as an implementation detail in C++, but are not available in UML at the moment, neither without nor with a standardized profile. Certainly, it will not be possible to cover every aspect of C++ in this CppML-Profile. The red oval in the right represents C++ features that are not part of CppML. For example, it will be out of scope to map every possible C++ preprocessor magic to UML because even in C++, it would not be best practice to use it. Also, it has to be investigated how functional programming aspects of C++ can be mapped to UML. CppML therefore will probably be limited to a subset of UML and a subset of C++. Nevertheless, those subsets have to be identified and specified and mapped to each other as formal and as complete as possible.

3.1 CppML Abstraction-levels

There is a large number of UML tools out there, being able to generate code from UML models, but there are large differences in the supported subset of UML used for code generation and therefore the provided level of abstraction, starting from only generating code frames from class diagrams and ending with a completely model-based approach including code generation from activity diagrams, state machine diagrams, modeling of scheduling and concurrent behavior and generation of test code from sequence diagrams. In this section, I will introduce a proposal for categorizing models and tools in the completeness of code generation to C++, regarding a meaningful subset of UML. I will explain the different levels and identify software developers' needs and their benefits on the certain levels.

The levels 1-3 refer to the CppML Levels in Figure 6.

Level 0 - Using the Implicit Model

This level does not appear in Figure 6 because there is no explicit model involved. But in fact, working with a modern IDE is already kind of model-based. The IDE builds up an internal model on top of the source code and allows navigating, code completion, auto-formatting and refactoring. The source code is the primary artifact and a model representation is only used internally. This is common practice in software development and probably a large number of projects work on this level.
At this level, alternate views like diagrams are only used for specification and documentation but not in sync with the code.

Level 1 - Basic Structural / Language Modeling

At this level, source code is not only text anymore. Existing source code can be reverse engineered to a model, or code frames can be generated from architecture models. Ideally, model and source code stay in sync after the first transformation and support a round-trip workflow. Otherwise, they will diverge. The source code is just a textual representation of the model with the ability to be regenerated at every time. This level enables additional graphical, textual or tabular views and the possibility to link artifacts to other engineering domains.

On this level, the broadest possible subset of the meta-model of the programming language should be reflected in the meta-model of the modeling language. Otherwise, a model would be incomplete, regarding the level of detail needed in the programming language.

The behavior is encapsulated in operations that are implemented as opaque behavior. On this level, there is not yet abstraction for scheduling, nor support for any RTOS concepts like asynchronous communication. The scheduling is all hidden in opaque behavior. RTOS features can only be used in source code without abstraction.

This level adds the benefit of enabling additional views on existing concepts but does not yet introduce new concepts. Class diagrams are the most commonly used diagrams at this level.

On Level 1 the gap is that UML neither represents the complete C++ meta-model, nor a **standardized** C++ profile exists for UML. So up to now, even on this level, models become proprietary, using either a custom C++ profile or a tool specific built-in language extension. A standardized mapping is required here. Creating a proposal for such a mapping will be part of future work. As mentioned before, it will not be possible to cover C++ completely with this profile. It will be in focus to identify, specify and map a meaningful subset of C++ to UML to make it more useful for code generation.

Level 2 - Extending the Language

At this level, for the first time, new concepts and new views are added. Concepts that are not directly mappable to programming language features, but can be transformed using patterns. Behavioral models like state behavior, with the graphical representation of state machine diagrams, are a good example. State behavior is hard to program textually in a 3GL without the support of a DSL like Boost SML or a graphical semantic. UML provides a graphical semantic for state machines, being inspired by David Harel (Harel, 1987). Many publications have been written on *how to generate code from state machines*, and also, many tools already support generating code from state machines. But in a systematic review from 2012, the authors found out that "papers published in recent years show that the problem is still unresolved." (Dominguez et al., 2012)

Questions that arise when adding more complex behavior like state behavior are: How does it integrate with existing concepts? How is it scheduled? There are tools out there that generate execution code for a state machine as transition function, either as step-function or event-based, but leave it to the user to invoke it.

On this level, there is no abstraction for scheduling. The scheduling stays hidden in opaque-behavior. Model elements like signals and other asynchronous communication concepts are not yet supported. This level only contains concepts that can be transformed into code without using any libraries or frameworks.

Level 3 - Entirely Model based

On this level, the whole executable subset of UML can be transformed and synced to code. The concepts of behavior and how behavior is invoked (synchronous or asynchronous) are entirely supported. This requires an execution framework for abstracting scheduling and RTOS concepts and managing asynchronous communication. A part of the code will be generated from model elements by using patterns. Those parts should normally not be changed in the source code. Other parts, e.g. bodies of operations, can be edited in source code and be round-tripped to the model. It would also be helpful to have clear interfaces - on both model and code level - to integrate other model-generated code, e.g. from Matlab or from GUI tools. Additionally, also test code can be generated from structure and sequence diagrams.

Future work for Level 2 and 3 will be an evaluation and specification of appropriate patterns for transforming Level 2 and 3 concepts to prior specified Level 1.

3.2 Model Transformation

The idea for the transformation from model to source code is a two-step-bidirectional-translational approach shown in Figure 7.

To be able to execute those transformations, the language mapping between subsets of UML and C++ has to be formalized completely.

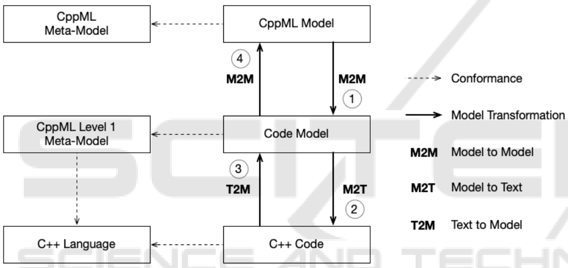

Figure 7: From Model to Code.

Starting from the UML Model, in step ①, a Model-to-Model (M2M) Transformation to an intermediate Code Model is executed.

For CppML Level 1, the Code Model would be identical with the UML model, both only containing elements from the CppML Level 1 meta-model.

For CppML Level 2 and 3, the UML Model will contain new concepts with new views, that have pattern-based counterparts in the Code Model.

The use of intermediate models in the code generation process is common practice (Ciccozzi et al., 2018). In this proposal, the intermediate Code Model will be a CppML Level 1 model that conforms to the C++ meta-model, only remaining to be serialized to text through a Model-to-Text (M2T) Transformation in step ②.

Ideally, it would even be possible to write CppML Level 2 or 3 patterns in code, e.g. for state machines, and have them round-tripped in the UML model through step ③ and ④. Then the restriction, not to modify this generated code, would be void. Looking at C++ code from a projectional editing viewpoint (Fowler, 2008) could be helpful to restrict the usage of C++ to a scope that is supported by CppML.

Rhapsody Code Generation

A similar code generation concept is already realized in the code generator of IBM Rational Rhapsody (Figure 8). The code model is called *Simplified Model* and the transformation plugin, that is responsible for the first transformation ① is called *Simplifier*. What is missing here is the conformance to standardized meta-models, which is reasoned by suitable standardized meta-models being unavailable.

Rhapsody also offers execution frameworks for different purposes. For small embedded targets, Willert Embedded UML Studio (Willert, 2020) with the RXF as Realtime eXecution Framework is available. Many ideas of this paper arose developing the RXF. Rhapsody, in combination with this framework, already enables a scope of modeling that gets close to CppML Level 3, but again as a proprietary solution, not connected to standardized meta-models and transformation rules.

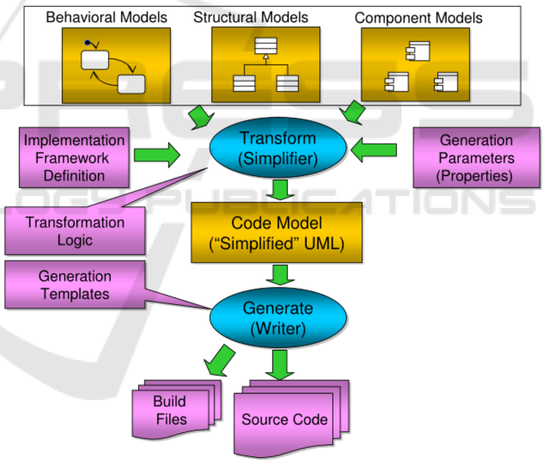

Figure 8: Rhapsody Code Generation (IBM, 2014).

4 CONCLUSION

This paper outlined some research and specification gaps concerning the UML/C++ interrelationship and the language mapping between those two languages. Additionally, the negative impact of those gaps on tooling and portability of models is addressed. The stocktaking of existing solutions has been started but needs to be continued to gain a better understanding of what is needed to really improve the situation. Also, a vision for a solution approach is presented. This vision needs to be elaborated in future work.

5 FUTURE WORK

In a first step, the stocktaking of existing solutions has to continue, and it has to be discovered more detailed, which level of CppML current UML tools support - regarding the conceptual coverage - and if there are best practices in the way how code is generated.

In a second step, based on the data collected in the first step, a proposal for a standardized CppML Level 1 has to be prepared to get a foundation for the intermediate model. Also, aspects of projectional editing (Fowler, 2008) will be taken into account to find the best solution. The stereotypes, that will extend the existing UML meta-model to the CppML Level 1 meta-model will look similar to the stereotypes from the Magic Draw C++ Mapping (NoMagic, 2020) in figure 4.

In further steps, research has to be done, on how to transform CppML Level 2 and Level 3 artifacts to Level 1. Therefore both existing solutions in tools (e.g. the simplifier in Rhapsody) and academic work (e.g. (Dominguez et al., 2012)) will be taken into account.

In parallel to the conceptual work, appropriate tooling will be developed. A prototype tooling will be developed based on Rhapsody and the Willert Embedded UML Studio (Willert, 2020). This tooling will also be evaluated in real-world industry projects.

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