Practical Large-scale Model-Driven Development of Business Applications with an Executable UML[1]

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Abstract: Despite intensive work in academy and industry around it in the last two decades, the discipline of model-driven development with UML apparently has not become the industrial mainstream for building large-scale information systems. In this paper, we present our attitude toward two probably mostly debated topics: 1) the lackluster adoption of MDD with UML in this field; we try to identify and explain what we believe are the main reasons for it, and 2) the controversial debate about general-purpose modeling languages, UML in particular, versus domain-specific modeling languages (DSLs). We present our approach to building large-scale business applications based on an executable profile of UML, named OOIS UML, and implemented as a framework named SOLoist. We also briefly report on our experiences and lessons learnt from successfully using the approach and the framework in industrial projects of different size and domains over the last fifteen years.

1 INTRODUCTION

Model-driven development (MDD), as a general software engineering discipline, along with the accompanying technologies and standards such as OMG's Model-Driven Architecture (MDA) and the second generation of the Unified Modeling Language (UML 2.x) have been around for about fifteen years, but apparently have not become the industrial mainstream in large-scale development of information systems, i.e., of business (database) applications. Although there has been intensive work in academy and industry around this paradigm, and model-driven engineering in general is found to be widespread in industry in general (Whittle et al., 2014), reports from recent research attempts indicate, among others, two interesting and to some extent controversial findings:

1) UML is very poorly adopted in industrial practice (Petre, 2013; Petre, 2014): out of 50 software practitioners interviewed in the stud (Petre, 2013), 35 did not use UML at all, 11 used it selectively (in a personal and informal way, for as long as it was considered useful, after which it was discarded), 1 used to retrofit UML in order to satisfy management or comply with customer requirements, while only 3 used it for automated code generation (which could be treated as kind of MDD) and 0 used it "wholehearted", meaning an "organizational, top-down introduction of UML, with investment in champions, tools and culture change, so that UML use is deeply embedded". We must say that we were not at all surprised with these findings, as their fully coincide with our experience: apart from the few environments (except from our team) where we have successfully deployed MDD with UML, we have not come across any company or team that used MDD with UML "wholeheartedly", although some of the teams used it occasionally and informally, mostly to comply with customer demands or for documenting requirements (use cases or business processes) or sketches of (usually partial) design. It also seems that the optimistic bubble around UML on its emergence in late 1990s have burst as many people got disappointed with using UML in its early stages (the reports in (Petre, 2013; Petre, 2014) indicate a

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large potion of those being disappointed with UML).

2) The majority of those who exploit some kind of model-driven engineering use DSLs, usually small ad-hoc languages for narrow, well-understood domains (Whittle et al., 2014). Although these DSLs are indeed sometimes UML profiles, it can be concluded that DSLs prevail over UML as a general purpose language.

In Section 2 of this paper, we explain the reasons that we deem to be most relevant for the lackluster adoption of MDD with UML, while in Section 3 we briefly comment on the debate on DSLs versus UML. Then, in Section 4, we present our approach to effective MDD of large-scale information systems. The approach is based on an executable profile of UML, named OOIS UML, and is implemented as an open-source framework named SOLoist (SOLoist, 2016). Since the OOIS UML profile has been described in detail elsewhere (Milićev, 2009), we only outline some of its main elements and illustrate how it cures the problems identified in Section 2. In Section 5, we briefly report on our experiences and lessons learnt in using the approach and the framework in medium to large industrial projects over the last fifteen years. In Section 6 we also comment on some of the other findings from reports given in (Whittle et al., 2014) and (Petre, 2013) from our empirical viewpoint. It should be underlined that we focus on the development of information systems, i.e., of business, database (data-centric) applications of various application domains, especially those with complex Web-based UIs, which is the domain of our industrial practice.

2 PITFALLS OF MODEL-DRIVEN DEVELOPMENT WITH UML

What we deem the most critical pitfalls of modeling in general were identified and described long ago in the seminal book by Selic et al. (Selic et al., 1994), and were revisited in the context of UML modeling in a more recent book (Milićev, 2009). (Although the argumentation given long ago in (Selic et al., 1994) was sound and reasonable, and are in our opinion the most relevant reasons for the lackluster adoption of MDD with UML, it is strange how little attention and recognition it gains nowadays, even though the problems described there still persist in practice in virtually the same form.)

The first generation of UML (UML 1.x) was almost completely free of formal, executable semantics. This is because UML, in its initial conception inherited from some of its predecessors, was primarily designed as a descriptive language for specifying, visualizing, and documenting the construction and design decisions of programs developed in traditional object-oriented programming languages (OOPLs). Its scope of applicability was intended to be very wide: UML was designed to be used for specifying programs implemented in a variety of programming languages and for very different application domains, partly because UML was a synthesis of many other modeling predecessor methods. While UML provided some rough hints about the intended meaning of its concepts (mostly derived as generalizations of the concepts found in different OOPLs), the precise interpretation of the semantics of UML models was almost completely left to the way the models were mapped to the target implementation language. Obviously, such interpretation was highly dependent on the semantics of the target language, as well as of the mapping. Consequently, UML models were semantically ambiguous. It was completely up to the creativity and discipline of a development team to impose a certain unambiguous semantic interpretation of UML models in the domain of their interest.

When information systems are concerned in particular, such usage assumes the following. Most UML tools can easily generate the relational database schema (DDL) as well as the class definition code in a target OOPL from a UML class model. However, the coupling between the space of objects of the OOPL and the data in the relational DBMS (RDBMS) is typically left to a separate object-to-relational mapping (ORM) framework, such as Hibernate or similar. Such ORM frameworks, on the other hand, do not have anything to do with UML and its semantics, especially with action semantics, but provide the semantic coupling between the OOPL and the RDBMS. In addition, such coupling often assumes that the database schema is developed separately and independently from the OOPL class structure.[2] This means that the database schema is designed from the conceptual

2 In the extreme, some methods advocate the so called *code-first* or *DB schema-first* approaches, where high-level models, such as Entity-Relationship or UML class models are obtained by reverse-engineering of already designed programs or database schemas.

(data) model of the problem domain and optimized for particular data access patterns according to the traditional practices of relational database normalization and optimization, while the OOPL code is designed according to the practices of object design. The task of an ORM is then to couple these two. In addition, ORMs often make it explicit to the developer that an OOPL object that resides in (volatile) operating memory and its (persistent) database representation are two distinct entities that have to be linked (typically over an object ID) and kept in sync by the ORM's mechanisms. These mechanisms typically burden the developer with having to be aware of the "lifecycle" of the memory object and taking care of issuing the proper calls to the ORM, such as to "save," "load," or "discard" the memory object. This is one drastic example of unnecessary accidental complexity imposed by the imperfect technology of coupling two semantically different spaces (OOPL and RDBMS).

A very similar situation is when the OOPL semantic space is coupled with the application's presentation layer. Most user interface (UI) frameworks and libraries couple the presentation semantic space (e.g., HTML for Web-based UIs) with the OOPL space; this simply means that the UI components are constructed to work with memory objects that have the semantics of the OOPL. With more or less success of that coupling, virtually all of the popular approaches do not have any connection or provide any semantic coupling with UML and the application's model. Yet again, the developer has very often to be aware of the purely technological implementation details, such as the separation between the Web page vs. the backing bean/controller object, the client code vs. the server code, the business layer vs. the entity (data) object, etc.

With all this linguistic and semantic heterogeneity imposed by the mainstream development technologies, the OOPL code typically appears to be the central artifact, "the semantic master" to the semantics of which all other artifacts are adapted. This holds for the UML model too. In such circumstances, the model becomes just an additional and unnecessary burden: it is rather pointless to draw UML diagrams just to obtain skeletons of classes in OOPL code. In fact, UML is used just to "sketch and draw the code." Apart from somewhat better clarity of the relationships between classes, due to diagrammatic visualization, this brings little or no additional value; quite the contrary. The very semantic heterogeneity, on the other hand, is a big problem for itself even without using UML models (Groenewegen et al., 2010), and is a typical example of undesired accidental complexity.

As an effect, developers typically exhibit the "rush-to-code syndrome": "a pervasive unease during the early development phases, a prevailing attitude among the developers that requirements definition and design models are 'just documentation,' and a conviction that the 'real work' has not begun until code is being written" (Selic et al., 1994). Although they would claim that requirements and design models provide useful insights into the nature of the system being developed, the more time is invested in building such models, the more uncertainties multiply. This is caused by the lack of objective evidence that the developed model is correct and complete.

As a result, once the development passes to the implementation phase, the requirements and design models remain as documentation artifacts only, without executable semantics or any effect on the ultimate executable system. When the development process is iterative and incremental, it often calls for modifications. Such modifications on the initial design model are not enough to upgrade the running system and therefore, the developers are not forced to update it properly. Instead, they update what they merely have to – the implementation, i.e., the relational data definition code and the OOPL code, which directly affect their running system. This ultimately leads up to inconsistencies between the design model and implementation, which turns the design model into incorrect and thus harmful or at least useless documentation. To illustrate this, we cite a comment reported in (Petre, 2014): "Other [UML modeling] tools I've used... always end up being dropped after the initial thought stage simply because they end up being too painful to keep tweaking in order to sync the diagrams with code changes." This often forces the development teams to discard the models and stick only to the implementation in later iterations. The reports in (Petre, 2013; Petre, 2014) indicate a large potion of those using UML this way; for example, one rather common opinion is quoted in (Petre, 2014): "For large, complex software projects, with continuous delivery, UML would slow down practice continually... The fastest software development teams don' t use UML."

The essence of the described problem is called the *semantic discontinuity* and is well described in (Selic et al., 1994), (Milićev, 2009): it is the lack of formal coupling between the representations of different kinds of related detail, as we have described. The central artifact that imposes the unambiguous semantic interpretation is the code, while the model is not the central, authoritative specification of the software and its semantics is interpreted via the semantics of the obtained code. This is certainly not the idea of MDD, where models are considered to be central artifacts of development from which all other artifacts are derived or subordinate.

The problem of the lack of formal, executable semantics was recognized and tackled by the emergence of the second generation of UML 2.x (UML 2.5, 2015) and especially by the Foundational Subset for Executable UML Models (FUML) initiative of OMG (FUML 1.2.1, 2016). The latter initiative has the objective to identify a subset of the UML 2 metamodel that provides a shared foundation for higher-level UML modeling concepts, as well as to define a precise definition of the execution semantics of that subset. It is expected to cure the described essential problem of the lack of executable semantics of the core UML concepts.

Unfortunately, nothing has changed in the mainstream yet. The FUML initiative seems to be still new and not yet widely supported by tools and frameworks. It is even less recognized in the wide development community. In addition, FUML provides a general-purpose programming platform that should be carefully profiled for various problem domains. For example, some UML concepts are not so important or necessary in building information systems, while the development of UI is of major importance and typically consumes most of the development resources. This has been also recognized and addressed by a most recent OMG's standard named Interaction Flow Modeling Language (IFML) (IFML 1.0, 2015). Being very new, it has very modest recognition yet. However, building large-scale information systems requires much stronger concept and tool support, covering all typical and important needs of this domain, such as querying of very large object spaces, massive and scalable concurrent and distributed processing, concurrency control (isolation) and transactions, etc.

As a result, developers still use UML as before, selectively and informally, or do not use it at all (Whittle et al., 2014; Petre, 2013; Petre, 2014). MDD as a discipline, especially with UML, with its accompanying tool support, still seems to be immature at least for the information system domain.

3 UML VS. DSL

On the other hand, the report (Whittle et al., 2014) indicates that MDD is more widely applied with DSLs instead of UML. This claim contributes to the recent very intensive debate on UML (as a general-purpose language) vs. DSLs. Without any ambition to resolve this dilemma, we would like to put forward some arguments based on our experience with the approach we successfully apply in the given domain (some of these being in accordance with the reports in (Petre, 2013)).

Our main conjecture is that the reason for the apparent prevalence of DSLs over UML (Whittle et al., 2014) may not necessarily be inherent in the very nature of these languages (domain-specific vs. general), but is due to several other facts.

First, and maybe most important, is the presence of the proper semantic coupling, coherence, and formality of the language that is necessary for success, as already discussed. In the first instance, as described, UML lacks them in many parts. However, this can be solved with proper profiling of UML and with adequate tooling, as in our example. Making a small, semantically coupled and well defined DSL is presumably much easier than profiling UML in that way.

Second, it is about the context: DSLs usually put their concepts in a very specific context of a particular domain, while UML does not by default, but this can also be done by profiling though. The need for context is also mentioned in (Petre, 2013; Petre, 2014), the lack of context being one of the main reasons for disappointment with UML.

Third, it is about the size and complexity of the language: UML is often accused of its extreme volume, complexity, and heterogeneity, which is indeed true. In order to make it practical, one has to narrow its scope by selecting only a subset of concepts and features that are useful for a particular usage (domain, team, or project). This is again what profiles are meant for: UML is intended for selective use, as opposed to a common misconception that its selective use is wrong or against its spirit (Petre, 2014). A DSL is, on the other hand, usually by its design confined to the selected (typically small) set of necessary concepts.

UML is very broad, and although its size and complexity may really be treated as its drawbacks, they can also be taken as its potential, because it can be profiled for many different purposes. Its concepts are so diverse that one can very likely find a concept that fits into particular needs in the given context. Indeed, the report in (Whittle et al., 2014) confirms that some DSLs used in practice can be defined as UML profiles; IFML (IFML 1.0, 2015) and our DSL for user interfaces (Milićev and Mijailović, 2013) are additional good examples of rather exotic DSLs that can be expressed as UML profiles.

However, shaping a DSL into a correctly defined UML profile is not an easy task. In order to recognize the UML concepts that the conceived domain concepts fit into, one has to be an expert in UML and know its metamodel and semantics, including semantic variation points, and to understand the mechanisms of extending and profiling UML. It is thus often the case that defining a DSL from scratch with a powerful tool like (Tolvanen and Kelly, 2015) can be much easier.

One should not totally give up profiling UML in favor of developing a DSL from scratch though, because staying within the boundaries of a standard language has many advantages: modeling tool support and model portability (interchange); modeling is more likely to be understood and adopted by newcomers and people external to the team, because they are more likely to be educated and trained with a standard language than with an in-house DSL; better potential for reuse of profiles for different projects, products, or even domains, etc.

4 MDD WITH SOLoist

We now briefly describe how MDD looks like in a semantically homogeneous and coherent environment of SOLoist.

Coupling of Structure and Behavior

Once the UML class model of a problem domain, like the sample one shown in Figure 1, is developed using an ordinary UML modeling tool, SOLoist generates all necessary artifacts for the application automatically. This includes the relational database schema, as well as the code in the target OOPL used for implementation (Java in this case). The generated code is linked with the SOLoist runtime

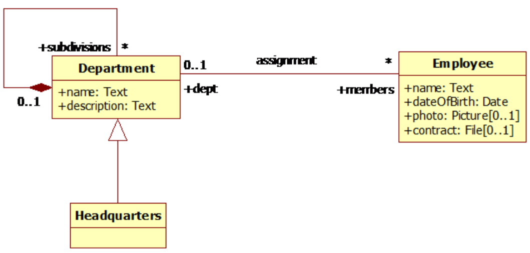


Figure 1: A sample UML model.

environment, which provides the necessary UML action semantics and ORM, in a manner of a UML virtual machine.

Objects that are instances of the modeled classes, as well as their attributes and links as instances of the modeled associations, comply with the UML semantics and are inherently persistent. An object is a single and coherent entity, and there is no any semantic distinction between its memory and database representations, nor is the latter visible or accessible to the application by any means.3 This is manifested by the way the object space is managed with actions. Actions are written in the notation of the hosting OOPL (Java in this case). For example, an object of Employee is created with a *create object* action that is simply written as:

```
Employee anEmpl = new Employee();
```

Although the notation is (intentionally) exactly the same as the one in Java, this is not the case with the semantics. The created object is inherently persistent and lives until it is explicitly destroyed by a *destroy object* action; this can happen much later, independently of the execution of the program that created the object:

```
anEmpl.destroy();
```

There is no need to *save* or *load* an object, or to deal with any kind of "persistence managers," "entity objects," "sessions," object IDs, or other kinds of elements as in other ORM approaches.

Values of objects' attributes are accessed via *read* and *write attribute value* actions. For example:

```
anEmpl.name.set(new Text("John Doe"));
...
if
(anEmpl.dateOfBirth.val().isEqualTo(Date.tod
ay())) ... // Happy birthday!
```

As it can be seen, reading or writing attribute values are explicit actions invoked through operations from the SOLoist API of the runtime environment (`val()` and `set()` in this example). The API offers a full set of operations on attribute values, supporting the semantics of multivalued attributes from UML, with optional ordering. This is somewhat different from the concealed actions in an OOPL, where read and write actions are implied from the position of a term within an expression (e.g., an assignment implies a write action to the left-hand side operand).

The similar holds for managing links of associations. For example:

3 This is why we use the term *object space* instead of *database*.

```
anEmpl.dept.set(aDept);
```

creates a link between the objects referred to by `anEmpl` and `aDept`. After that, the object referred to by `anEmpl` will be a member of the collection returned by the action that reads the slot `aDept.members`.

The behavior is specified within methods of operations. The methods are written in Java code, which may include all available Java control flow structures (conditions, loops), expressions, and statements. The access to the object space is linguistically embedded by means of the API for the actions, as already described. In addition, methods can call operations of objects with the usual operation call semantics in Java, including argument passing and polymorphism. References to objects are ordinary Java references and comply with the usual Java typing rules (e.g., conversion). The only trick is that those references refer to proxies that provide the described action semantics and access to the data values that are stored in the database and cached in memory outside these proxies. However, this is a matter of the implementation and is completely hidden from the developer.

The developer does not need to make any intervention or configuration in order to achieve the described semantics. As in Ruby on Rails (Viswanathan, 2008), we prefer convention over configuration. The relational database schema is obtained by a default set of ORM rules. For the purpose of performance tuning for large-scale information systems and huge object spaces, we provide a set of configuration options that can adjust the ORM if necessary. However, this fine tuning can be done completely independently from the application development, as it does not affect the model and the action code within methods. The entire ORM, the synchronization between the cached objects in memory and their database representations, as well as the semantics of UML actions, including concurrency control (isolation on the object level, not on the record level) and transactions, is provided by the SOLoist runtime.

We also support hierarchical UML state machines for modeling life cycles of objects. As a special feature, our state machines allow triggerless transitions, making state machines cover the semantics of classical flowcharts (because the control flow can leave the state as soon as its action ends and branch over decision vertices). Hierarchical state machines are not interpreted by the runtime, but Java code is generated from them, making the implementation efficient. We also support submachines with entry and exit points, as a very powerful concept for abstraction, decomposition, and high-level behavioral polymorphism. This way, we do not have to support UML activities, as most of the practical needs for modeling complex behaviors and business logic can be handled by state machines.

To support large-scale processing of huge object spaces and especially lifetimes of objects modeled with state machines, our framework provides the notion of so-called *agents*. Agents are (profiled) active classes, whose instances are concurrent threads that process parts of object space. Each agent (as a class) can be configured with a query that selects a number of objects (e.g., objects residing in a certain state). The class can be automatically instantiated in a configurable number of concurrent instances that partition the selection of objects for concurrent processing. Each of the instances, in each of its processing iterations, takes a chunk of its own partition of objects (by executing the query) and performs the polymorphic operation upon each object; this can, but need not be, result in a call of an operation of the target object, or triggering its state machine. If the partition is empty, the agent instance goes to sleep for a while and then re-executes the query to fetch a new chunk of objects.

The combination of these two notions, hierarchical state machines (as a general UML concept) and agents (as a profiled, domain-specific notion) provide a very powerful vehicle for abstract modeling and efficient and scalable concurrent processing, again thanks to proper semantic coupling and domain-specific profiling.

Querying

An important feature of a technology for building information systems is the possibility to pose complex queries in order to perform searches or make reports. For that purpose, we provide a variant of the ODMG's Object Query Language (OQL). OQL inherits the syntax flavor of SQL, but supports the object data model. Our variant of OQL is adapted to UML. Its syntax and semantics is fully described in (Milićev, 2009) and briefly demonstrated here.

For the sample model previously shown in Figure 1, in order to retrieve the names and dates of birth of all employees of the 'R&D' department, one can write in our OQL:

```
SELECT empl.name, empl.dateOfBirth
FROM Department d, d.members empl
WHERE d.name='R&D'
```

It can be seen that an OQL `SELECT` query, in its `FROM` clause, uses navigation terms (e.g., `d.members`) over objects and links, instead of joining relations as in the relational algebra. The difference is especially noticeable when the navigation has to be done over a many-to-many association. The OQL query looks the same as shown above, while the equivalent SQL query has to join three tables (two for the entities on the ends and one for the many-to-many relationship). The more complex the navigation in the query, the bigger the difference between the OQL and SQL counterparts.

OQL supports inheritance and polymorphism. For example, the following query includes the access to the inherited properties `name` and `members` of the class `Headquarters`:

```
SELECT hq, hq.name, empl, empl.name
FROM Headquarter hq, hq.members empl
```

The following query will return the set of all departments that have members having 'John' in their names; the set will include headquarter(s) too:

```
SELECT dept
FROM Employee empl, empl.dept dept
WHERE empl.name LIKE '%John%'
```

Our OQL supports specialization, too. If we want to retrieve only headquarters that have members having 'John' in their names, we can write:

```
SELECT hq
FROM Employee empl, empl.dept:Headquarter hq
WHERE empl.name LIKE '%John%'
```

The result of a query is a collection of tuples that can be iterated in the Java code or directly rendered by UI controls. The references to objects and values returned in the components of tuples can be used as already described.

Our OQL supports many other features, like aggregate functions in the `SELECT` clause, equivalence for outer joins, `GROUP BY`, `ORDER BY`, and `HAVING` modifiers, unions and subqueries, and parameters of queries.

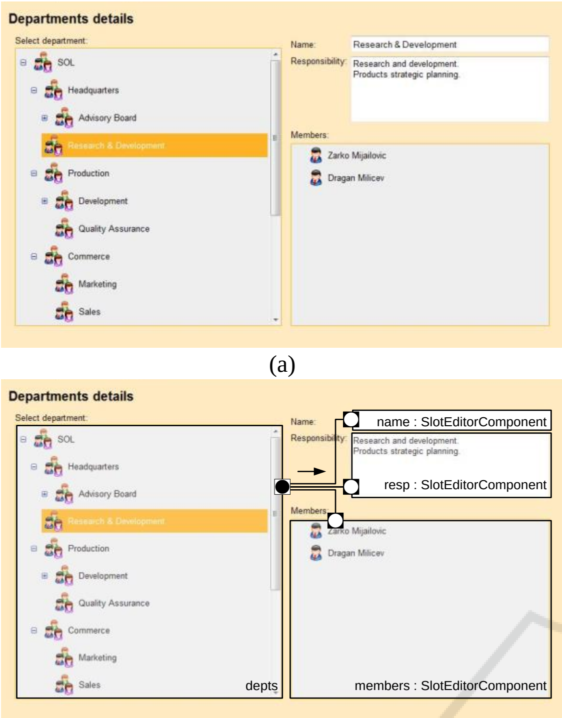
Another particularly important and useful querying feature is the *query builder*, an API that allows declarative definition of (an internal representation of) queries that may have dynamic form, based on the presence or absence of certain query parameters. This is necessary to support complex searches required in typical applications. For example, a typical search for employees in our running example would allow an optional criterion to select only those employees that are assigned to a certain department, and satisfy some other optional criteria (in terms of attribute values of employees or departments). If the search includes the criteria related to the department of the employee, then the underlying query should have a navigation term in the `FROM` clause that joins the employee with the department (`Employee e, e.dept d`), and another term in the `WHERE` clause that filters only the requested department(s); if the search does not include criteria related to the department, the `FROM` and `WHERE` clauses should not include these terms. This dynamics of the query form is not easy to achieve via usual programming approaches, especially not by direct manipulation of a textual representation of the query. On the other hand, the declarative approach with the query builder makes definition of very complex and dynamic forms of queries rather straightforward, as it hides the complexity of the dynamics from the developer.

Coupling with UI

Typically, the most resource-consuming part of information system development is development of UIs. In order to reduce accidental complexity and ensure a proper impedance matching, our framework provides a full semantic coupling between the object space and the UI by using a novel paradigm for building UIs. It is briefly presented here, and described in details elsewhere (Milićev, 2009), (Milićev and Mijailović, 2013).

The motivation behind our paradigm is illustrated in Figure 2. A simple UI form from the sample application whose model was previously shown in Figure 1 works as follows. The tree view on the left in Figure 2a is configured to render the hierarchy of departments. The three UI controls on the right display the properties of the department currently selected in the tree view. The first two controls are editable text boxes that render and edit the `name` and `description` attributes of the class `Department`. The third control is a list box that displays all employees who are members of the selected department.

The behavior of the UI controls can be abstractly described like this. Whenever an object of `Department` is selected in the left-hand tree view, each of the three right-hand controls has to display the value of the corresponding slot of that object (`name`, `description`, or `members` – the collection of linked objects of `Employee`). Obviously, the object of `Department` selected in the tree view has to be dynamically provided as the input parameter of each right-hand control. Thus, the property (attribute or association end) of the class `Department` whose value will be displayed by each of these three right-



(a)

(b)

Figure 2: (a) An example of a form with coupled UI components. (b) The message passing perspective to the functional coupling of UI components.

hand controls can be configured at design time, when the UI is being constructed. On the other hand, what changes dynamically, by user's actions, is only (a reference to) the object of `Department` whose slot (as an instance of the configured property) has to be displayed.

By such observation we come to the perspective depicted in Figure 2b. The UI controls can be logically regarded as components with *pins* that form their interfaces. A *pin* is a connection point through which a UI component can send or receive signals or data to or from other components. For example, the tree view has one *output pin* through which it sends a reference to the object selected in the tree view each time the selection is changed; of course, this selection is changed dynamically, by user's actions. Each of the three right-hand components has one *input pin* that accepts a reference to the object whose configured slot the component will display and edit. The internal behavior of the control ensures that each time a new value occurs on its input pin, the control accesses the underlying object space by reading the corresponding object's slot and reflects its current value on the screen.

In order to ensure the proper functional coupling of these components, the developer simply has to connect the output pin of the tree view component to the three input pins by *wires*. Wires specify the connections through which data will flow from an output pin to one or more input pins, whenever a new value is provided on the output pin, as shown in Figure 2b. The components are created as objects and wired through the SOLoist Java API or through models as described in a DSL that is defined as a UML profile (Milićev and Mijailović, 2013).

SOLoist provides a rich library of built-in UI components for Web-based applications. These components, on one hand, wrap around usual UI widgets, such as textboxes, checkboxes, combo boxes, lists, tree views, pictures, grids, and many more, providing a usual appearance and behavior to the user, as well as interface pins to other components. On the other hand, these components raise the level of abstraction and directly match with the underlying object space with the UML semantics (Milićev, 2009).

As another illustrative example, we present the UI component shown in Figure 3. The component shown in Figure 3 is an editor of a slot of an object provided on its `elem` input pin. In the presented example, the object is an instance of the class `Employee`. Let us refer to it as the host object. The slot is an instance of an association end from the UML model. The association end is configured as a construction parameter (and stored in an attribute) of the component. In this example, this is the association end `dept` that maps an employee to its department. The component shows a collection of objects of a certain class that are candidates for creating links with the host object over the configured association end (`dept`). The component can be configured to show this collection of objects as a list, obtained from a collection given on another pin, or as a tree, with the object given on another pin as its root and the tree spanned over the links on the given association end (`subdivisions` in this case). Whenever a new `Employee` host object arrives on the `elem` input pin, the component fetches the link (or multiple links in a general case) of the host object on its `dept` slot from the underlying object space and updates the checkboxes to reflect this link (or multiple links in a general case). Whenever the user changes the state of the checkboxes, the component updates the underlying object space by creating or deleting the links. As a result, in order to provide this typical behavior, the developer has nothing to code in a traditional way, i.e., in imperative code of components' event handlers;

everything is done declaratively, by configuring the (construction parameters of) the component and connecting its pins with pins of other components in its environment.

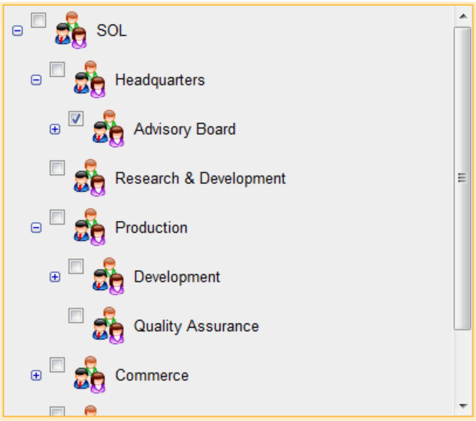


Figure 3: A sample UI component for editing an association end instance.

Our library is full of sophisticated components that follow the same paradigm. Their implementation is Web-based. The Web client tier implements the entire UI layer, while the object space layer resides on the Web server. The client tier uses Google Web Toolkit (GWT) as its implementation platform. In particular, the off-the-shelf components from our component library wrap up GWT widgets. The client tier accesses the object space via AJAX calls: whenever a component has to fetch or modify a piece of the object space, it issues an AJAX call, concurrently and independently of other components. Obviously, the reflectivity of the underlying UML object space plays a significant role in this paradigm, since the domain object space is accessed through UML reflection.

5 EXPERIENCE

We conceived the described MDD approach in early 2000. Since then, we have developed four generations of the framework in different languages (Visual Basic, C++, and Java), and on different UI platforms and architectures (Desktop: Visual Basic, MFC, Qt; Web: GWT). These four generations had different sets of features, levels of semantic integration, and internal architectures and design. Using these four technology generations, we have implemented a few dozens of commercial, industrial projects of different size and from very different application domains, some of them resulting governmental systems of national scale.[4] We will here briefly report on our experiences collected and lessons learnt from this practice.

The main conclusion from our experience is that MDD really works and scales quite well for all sizes of projects, provided that it is applied properly and in a framework that ensures the proper semantic coupling as in our approach.

We have also confirmed many other claimed benefits of applying MDD and using a semantically coherent environment. The accidental complexity is much reduced as compared to other mainstream approaches that are linguistically or semantically heterogeneous. This leads to more concise, but also more expressive development artifacts (model and code) due to the use of more abstract modeling concepts.

As a result, the development cycle becomes shorter. This claim is difficult to quantify and prove, and we do not tend to do that here. Although we have not conducted experiments of independent development of the same systems by different approaches, because we focused on real-life, industrial projects that had very tight deadlines, we can say that our clients, as well as partners who were professionals experienced and trained in many other popular mainstream frameworks, were pleased with the complexity of the developed systems compared to the achieved performance and delivery time.

Our experience also fully corroborates the statements given in a paper on the pragmatics of MDD (Selic, 2003), especially about the benefits and importance of automation, standards, model executability, and integration with external and legacy systems.

We also agree with the conclusions on the importance of education and training (Selic, 2012), as well as of the skills for abstract thinking (Kramer, 2007). From our experience of training in general and for our MDD in particular, we have found that the existence of runtime semantics is the key to successful adoption of new abstract concepts by engineers. If a concept has precisely defined, clear, and observable effects at runtime, so that one can immediately experiment with it, then it is more likely to be quickly adopted, even without too detailed and formal explanations. It is the same case as with learning any other classical programming language or environment, where new concepts are typically introduced with examples that

4 A selection of these projects can be seen in the Case Study section at www.sol.rs.

programmers can immediately experiment with ("hello world" is the classical ultimate and trivial example of this approach). Explaining runtime effects of a concept can be treated as a kind of operational approach to teaching and understanding semantics. One simple example can be the explanation of the concept of a pointer: taken abstractly and in an operational way, one can explain it by defining the meaning of the operations with the pointer (linking it with an object, dereferencing it). Another example from our domain is the notion of a link between objects, as an instance of association, described in terms of actions on links and linked objects.

On the other hand, when a clear description of runtime semantics is missing, the concept becomes difficult to comprehend or remains unclear. In such cases, the alternative way people usually take to understand the concept is to map it to already known concepts (usually in a different semantic domain, that is, different language), i.e. to something the semantics of which they are already familiar with. This is a kind of denotational approach to capturing semantics. Although this can also be a viable and correct approach that can help with understanding, if treated carefully and in the right way, it can also be misleading, as already explained, as the semantic domain it is usually mapped to is the implementation (OOPL, relational, etc.). To take the previous examples, a denotational approach for teaching the semantics of pointers could explain its implementation in terms of an operating memory cell containing the address of another memory cell where the pointed object is located, while a link can be explained with how it can be implemented in an OOPL via pointers (references) between linked objects.

One important characteristic of our method and framework is its adherence to the basic principle of software design – localization of design decisions. Namely, it has turned out in practice that the number of ways in which a certain requirement can be implemented or retrofitted to an existing application is limited to only few or one in most cases. This is good, because the implementation becomes straightforward and independent of the developer who makes it, while the applications are easier to understand and maintain.

As a special case of this principle, one piece of design can be maintained at only one place, either code or model in most cases. For example, although theoretically possible, the approach makes it extremely difficult to make any change to the class structure of the system, such as to introduce a new (persistent) class or change any detail of an attribute of a class, in the generated code, because it will not guarantee the full consistence of all artifacts (the UML reflection, the database schema) and ensure proper functioning of the system. In fact, such a change is almost as difficult and unreliable as changing a piece of binary code produced by a compiler. For that reason, it is much easier and secure for the developer to follow the strict procedure of changing the relevant piece of model only and regenerate all other implementation artifacts automatically. The similar holds for state machines. Consequently, we do not exploit reverse engineering and round-trip engineering (generate the code from the model, tweak the code when a small change is necessary in the running system, and then reverse engineer the code to update the model in order to keep it in sync): we find round-trip engineering inappropriate, and reverse engineering useful only for the purpose of extracting information from legacy systems to understand their design, and not as a tool for round-trip engineering in developing new systems.

As a proof of our claims, we give the only exception to this rule that represents a weak point of our framework: operations of classes can be specified in model as well as in sections of code preserved by the code generator. And as soon as it is possible to do one thing in different places, different people *will* really do it in different places: some define operations in the model, while the others take the much easier and quicker approach and define operations in the code, resulting in not fully complete models (but without any impact on the executable software). Although this weakness does not represent a big problem in practice, we plan to tighten it up by better coupling of the modeling and coding environments in the future.

Not surprisingly, we have often been faced, especially in the early period of our practice, with "one of the first questions asked about MDD: how the automatically generated code's efficiency compares to handcrafted code" (Selic, 2003). This is definitely one of the fears of pitfalls of MDD most frequently expressed by customers and partners, especially managers, having no experience with MDD. MDD or any other highly abstract and reflective approach is often accused of introducing additional and unacceptable overhead, especially in terms of execution time or space consumption, as compared to more traditional approaches.

Our reply is also classical: "This is nothing new; the same question was asked when compilers were first introduced. The concern is the same as before:

humans are creative and can often optimize their code through clever tricks in ways that machines cannot. Yet, it is now common knowledge that modern optimizing compilers can outperform most practitioners when it comes to code efficiency. Furthermore, they do it much more reliably (which is another benefit of automation)" (Selic, 2003). We would add that the same situation was with Java in its early stages, when it was suspected of "being much slower because it is interpreted by a virtual machine;" nowadays, real-time and embedded software runs on JVM.

Our practice has shown that efficiency problems may arise, but that the automation and abstraction can also provide the right means and place to solve a problem in a generic way, without affecting the application, because the problem and its solution can be localized in the runtime or the code generators and thus isolated from the application. One such problem arose in one of our large governmental projects, which had to handle an object space with hundreds of millions of objects and with temporal dimension (i.e., keeping all versions of modified objects and links). At the beginning, some large-scale queries in the system suffered from performance problems. This forced us to dig deeply into the problem, and as a result, we conceived some advanced optimizations, such as placing redundant values in the database or avoiding unnecessary joins in queries. Once we have implemented the optimizations in our query translator and ORM, the achieved performance was often even better than what could have been achieved with manual coding or with a purely relational approach (and orders of magnitude better than initially). Namely, the redundancy is handled in a generic way, by the ORM only, and is completely transparent to the application; if it had been done manually, it would have been very difficult to design the schema consistently and then maintain the redundant data copy on every write action, or to optimize each critical query. On the other hand, unnecessary joins are very difficult to identify manually (while the algorithm behind is not so complex), and is not automatically feasible on the relational database level, because this level of abstraction lacks the necessary information about the semantics of relationships that are known to the more abstract, UML model level. This experience has also opened a completely new field of our ongoing research that investigates even more sophisticated and aggressive optimizations that are completely impossible to implement manually and on the level of a relational model.

Our second example is related to state machines and massive processing of objects by agents. Initially, we used to store the current state of an object in its textual attribute, encoding the fully qualified name of the state (note that it can be nested within other states or submachines). Such encoding is very convenient, because it allows for flexible searching of objects residing in different composite states (making composite states a kind of abstraction, union, or generalization of nested states), by simple substring expressions in queries (searching for state names having a certain prefix). However, when agents select their chunks for processing, such queries can be very inefficient in case of huge object spaces. We have thus found another approach that benefits from both sides: objects can still be searched for states using path prefixes (composite states), but the queries are orders of magnitude more efficient, because they rely on integer search.

In order to be successful, an MDD approach for a particular domain has to be full-fledged and cover all typical situations and support practical needs that may occur in practice (Selic, 2003), (Selic, 2012). In our case, one typical situation is the following. During development, until production, it is easy to regenerate the entire database schema each time the source UML model evolves. However, once in production, the database contains valuable user's data that have to be preserved and the database cannot be simply regenerated from scratch, but has to be carefully updated to ensure data preservation. Although manual maintenance is possible, it is tedious and error-prone, especially in case of complex models/schemas. For that purpose, we have designed a tool to solve this database schema evolution problem (Milovanović and Milićev, 2015), which is invaluable in our practice. A second example is a complex UI component designed to render results of complex queries, typically used for already described searches. It is, of course, coupled with the query builder. Our framework is full of such examples, and even more will come in the future.

Finally, it is of utmost importance to preserve pragmatism in real-life situations. Although we advocate an "orthodox" approach to MDD, as briefly described here and in (Milićev, 2009), this does not mean that it has to be dogmatic or restraining in any way. An MDD approach or framework, especially while it is not yet full-fledged and mature to cover all possible situations and needs, has to be flexible and open to enable pragmatic escape from obstacles in real development. Our practice is also full of such examples: although we we are planning to capture some of these in a more abstract and controlled way, we still use the traditional techniques and tools to: communicate with external systems via very different interfaces (e.g., Web services, REST, sockets, or even files), exchange data via different formats (XML or even spreadsheets), integrate other technologies in our applications (e.g. custom-made or third-party widgets, biometric capturing software, Google Maps, etc.), design reports (using external report generators), access legacy relational databases (though JDBC), or simply make certain ad-hoc tweaks in the system. Founding our implementation on mainstream platforms and Java code with sections for manual coding of methods that are preserved by the generator, keeps our door open to such important flexibility. In that sense, we have been challenged many times when presenting our approach, by being asked the same type of questions: “How is this or that done in your approach?” The concrete answers can be generalized to the following: *we either offer an advanced, more abstract/automated/efficient concept/feature/technique for what is asked, or we do it as usual (traditionally, as anybody else)*. Doing such things, however, does not mean that we escape from or give up the MDD and UML models: these are just pragmatic actions to cope with real-world problems in a traditional manner, in cases where there is no adequate support in the MDD framework. As long as manifestations of such actions are localized and properly placed, encapsulated, and coupled with the rest of the system, everything is under control and makes no harm to the overall approach; on the contrary, it makes it pragmatic, adaptive, and effective.

6 REFLECTIONS ON OTHER REPORTS

We now briefly comment on several other findings from the reports (Whittle et al., 2014; Petre, 2013; Petre, 2014), from the perspective of our experience.

“It is common to develop small domain-specific languages (DSLs) for narrow, well-understood domains... Keep domains tight and narrow: In agreement with other sources, we have found that MDE works best when used to automate software engineering tasks in very narrow, tight domains. That is, rather than attempting to formalize a wide-ranging domain (such as financial applications), practitioners should write small, easy-to-maintain DSLs and code generators.” (Whittle et al., 2014) Although our UML profile is dedicated to a particular kind of applications, its domain is not narrow at all. Instead of an application 'domain', its dedicated to a certain *kind* of systems with certain characteristics, as described before. They cover very different business domains. Although it might be much easier to apply MDD in a very narrow domain, we do not believe this is a necessary prerequisite for success.

“There is widespread use of mini-DSLs, often textual, and there may be many such mini-DSLs used within a single project. A clear challenge is how to integrate multiple DSLs. Our participants tended to use DSLs in combination with UML; in some cases, the DSL was a UML profile.” (Whittle et al., 2014) Indeed, our approach combines profiling of UML with 'mini-DSLs', such as our OQL or DSL for UI. The key to integration is, in our opinion, proper semantic coupling and adequate tooling.

“Most successful MDE practice is driven from the ground up. MDE efforts that are imposed by high-level management typically struggle... Top-down management mandates fail if they do not have the buy-in of developers first.” (Whittle et al., 2014) *“Investment is made in tools and education, and 'champions' or visible early adopters are influential, because they provide authentic examples of relevance to the company, they help to develop and promote conventions (e.g., naming conventions) that assist communication, and because they are available for advice.”* (Petre, 2013; Petre, 2014) This resonates with our experience too. Although we have had only very few cases where we introduced our MDD approach into external teams, and although in all of them it was strongly supported by the management, the key to the successful implementation was the presence of 'buy-in developers'.

“Successful MDE practitioners use MDE as and when it is appropriate and combine it with other methods in a very flexible way.” (Whittle et al., 2014) We have already emphasized the importance of flexibility and pragmatism too.

“*Code generation is not the key driver for adopting MDE... [There are] other benefits to MDE which are much more important than these relatively minor productivity gains... The real benefits of MDE are holistic.*” (Whittle et al., 2014) Although not measured, our productivity gains are obvious and (subjectively) fall into a range from 30% to several times. However, we agree that other known benefits are much more important (better and clearer architecture, improved expressiveness, improved comprehensiveness, easier maintenance, etc.).

"*MDE makes it easier to define explicit architectures, especially when MDE is a ground-up effort.*" (Whittle et al., 2014) In a certain sense, many of the features of our approach were conceived ground-up, and it is still an ongoing process.

"Success requires a business driver. MDE... marketed as a technology that can do the same things faster and cheaper... is not usually enough motivation for companies to risk adopting MDE; rather, companies that adopt MDE do so because it can enable business that otherwise would not be possible." (Whittle et al., 2014) In all cases where our customers were interested in our technology (and not only in the final software product of it), there was a clear business driver. Sometimes it was related to a particular situation of a project (e.g., project got stuck) or particular domain (motivation similar to that described in (Whittle et al., 2014)). As an illustration of something that "otherwise could not be possible", we can put it this way in the context of our approach: although the same basic functionality in the systems developed with our technology could have theoretically been implemented with traditional approaches (ultimately, everything could be, at least theoretically, implemented in assembly), the *complexity* that was covered by these systems was completely impracticable, if not impossible to develop with traditional approaches in the given timeframe and with the given resources. For example, a very complex searching feature that is rather easily implemented with our approach and is standard in our solutions, is very difficult to implement otherwise and thus often does not exist in other systems; a complex business logic that is rather easily captured by hierarchical state machines would never be so complex, flexible, and reliable if implemented without them.

Certain types of individuals can be very resistant to MDE, such as 'code gurus', 'hobbyist developers', or 'middle managers' (Whittle et al., 2014). We have encountered such situations in our practice, too, and agree with the explanations in (Whittle et al., 2014).

"Since most MDE efforts are highly domain-specific, domain knowledge is crucial" (Whittle et al., 2014). With this claim we only partially agree. For designing proper systems, with or without using an MBE approach, domain knowledge is really crucial, as it is for designing DSLs. But we challenge this claim for the success of MDE in general. Our successful projects from very different domains were all implemented with the same (generic) MDD approach.

"Companies that target a particular domain... are more likely to use MDE than companies that develop generic software." (Whittle et al., 2014) This observation coincides with our experience with other teams who adopted our approach: they produced domain-specific software solutions with our 'generic' solution. However, our team develops 'generic' software and systems in very different domains. In our opinion, this has more to do with the *kind* of applications, not with a business domain, and to the already discussed business drive. For example, MDE has been very widely and successfully used in a broad field of embedded and real-time software (of different domains).

"Developers are hired based on what technologies they are familiar with rather than what domains they have knowledge of." (Whittle et al., 2014) We agree with this criticism, but we would like to add the importance of other skills (other than domain knowledge), such as general programming skills and the already discussed capability of abstract thinking.

"Put MDE on the critical path... Avoid the temptation to try out MDE on side-projects which will not have sufficient resources or the best staff. MDE should still be introduced incrementally but each increment needs to add real value to the organization for it to succeed." (Whittle et al., 2014) We fully agree.

"Companies that do succeed invariably do so by driving MDE adoption from the grassroots: that is, small teams of developers try out aspects of MDE, which in turn lead them to recognize reusable assets, and eventually MDE propagates to the organization as a whole." (Whittle et al., 2014) This is exactly the way we took in the situations where we trained the other teams for our MDD.

"*Selective (and often informal) use is the majority use – and is consistent with the intentions of the UML community.*" (Petre, 2014) As already discussed, selective use (profiling being one controlled and disciplined way of doing it) is *not* against the spirit of UML – on the contrary, it is the key to its successful use, as in our example. The same holds for informal use: using UML diagrams to sketch a piece of design or convey an idea is certainly a valuable thing and is not against our philosophy: indeed, we also do it often. However, trying to persist with the same way of use for developing systems with MDD and UML leads to all the described problems and hazards. This is why this kind of use is limited, and what we have shown opens a much bigger potential of MDD with UML.

7 CONCLUSIONS

We have presented a semantically homogeneous and coherent environment for model-driven development of information systems based on an executable profile of UML. We have also briefly reported on our experience in using the environment in large-scale industrial projects. Our experience has undoubtedly shown that MDD can work efficiently and as a powerful tool for tackling large essential complexity of information systems, provided that it is applied the right way. That right way, in our opinion, assumes using models as central and executable artifacts, just as code is in traditional approaches. As an effect, the models are not just sketches any more, but become accurate documentation of design decisions, as well as authoritative specifications of software. Because of that, the rush-to-code syndrome can be cured, while all benefits of using a language of higher level of abstraction can be gained. To cite one of the opinions quoted in (Petre, 2014), “The overhead [of using UML] usually outweighs the benefits unless it is very selectively used... Modeling a complete application in UML is just plain awkward.” This is indeed true, as we have explained, when a UML (or any other) model does not bring any additional value, but just represents a redundant and possibly unreliable information about the system. However, when one can get *much more outcome and value* from a piece of a UML model, as in our approach, than by traditional coding, then it is much easier to make a model than to write the code. Modeling should not be taken in a dogmatic way: one should select the most efficient way to express a design detail, be it a piece of model or code; for example, an algebraic expression, object query, or if-then-else construct will be most effectively expressed in the adequate (textual and possibly domain-specific) languages, while insisting on the use of activity diagrams to specify an implementation of 15 lines of structured code for a class method could bring us back to the times of flowcharts and spaghetti programming; on the other hand, a complex class structure or object life cycle will be much better expressed with a high-level UML model.

The fear of pitfalls is one of the main impediments for adopting a new method such as MDD by a wider community (although MDD is not new at all, it still may appear so to the mainstream industry). Of course, as other new approaches or frameworks, our framework also suffered from some weaknesses, especially in its earlier versions. Although we fully understand this reluctance, we think it should never prevent a progress, provided that a real potential can be recognized (the proverbial “baby and the bathwater” scenario). Patience and effort should be invested in a technology so that it can get mature enough, provided it is inherently healthy. Our experience shows that a real problem should always be tackled with a pragmatic approach, technical sense, and care, and if the software is designed with all principles of software engineering obeyed (proper abstraction, localization of design decisions, encapsulation, clear and coherent architecture, etc.), most technical problems or risks can be overcome without jeopardizing the overall idea.

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