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ABSTRACT

Model driven technologies for software development are being considered and used to address issues of size, complexity, adaptability, maintainability, distribution, and validation for large, enterprise-wide software systems. The Object Management Group has been promoting their Model Driven Architecture (MDA) standards, while various academic groups and commercial companies have concurrently been developing model driven techniques, versions of the executable Unified Modeling Language (xUML), and domain specific modeling languages. Over the past few years, large software projects have attempted to employ model based approaches. In this paper we assess the efficacy of MDA during the full development cycle, including: observations on the effectiveness of the model development tools; the practicality of using xUML in a large software development project in terms of managing model complexity, the expressive power of the associated 4th generation language, and the creation of links from xUML to a large conventional code base; and validation, verification, configuration management, runtime performance, and debugging issues that are unique to this approach. Based on our experience with current MDA tools, we conclude with a set of desirable properties for the next generation of tools, especially those needed to support large scale distributed development of network-centric applications.

## 1. Introduction

Increasingly sophisticated software systems are needed to meet complex and evolving DoD requirements. The size of software components, either measured simply in terms of number of lines of code or in terms of more sophisticated complexity metrics, has been steadily increasing. Today, sophisticated software systems, for example operating systems or airplane flight control systems, can consist of tens of millions of lines of code, with the prospect that soon hundreds of millions of lines of code may be required in order to implement certain systems. We may be close to the limit of what human beings can accomplish with current technology. There are pervasive problems with large, monolithic systems, including brittleness (fixing a defect results in additional defects appearing elsewhere), decreasing developer productivity, and increasing maintenance costs. For the DoD this presents a worrisome prospect as costs skyrocket and the quality of the delivered software declines. A succession of software development methodologies, technologies, processes and computer languages has been used to address this problem. Humans are good with abstract concepts, but less talented when dealing with the minute details necessary to communicate with computers at the machine level. To bridge this gap, computer languages have evolved to abstract the machine-level details, starting with assembly language, FORTRAN and C, and continuing with today's object oriented and dynamic languages. Similarly, development tools have progressed from functional programming, to CASE tools and UML. The goal is to bridge the abstraction gap between human and machine by allowing the human to manipulate higher level artifacts that can then be compiled into an executable. These tools frequently over-promised and under-delivered, including for example a variety of CASE tools in the late eighties and early nineties. The core of the problem is that it is difficult to develop a tool that can infer from an abstract representation (a model) the details of a specific instantiation of the model. Therefore, a multi-faceted approach is needed, and tools need to support multiple abstraction levels in their representations. As the capabilities of hardware, networks, and software expand, the problem areas that can be addressed become more complex and more difficult; it is critical to provide tools that will support development of these complex applications throughout their life cycle.

## 2. Model Driven Development and xUML

The Universal Modeling Language (UML) was not designed to be executable, although even early versions included a limited set of actions such as sending a signal, and creating or destroying an object. In 2001 UML was extended with action semantics, a more complete set of abstract actions including for example facilities for manipulating collections of objects. Executable UML (xUML) comprises a subset of the UML standard with sufficiently precise semantics to be capable of being executable over some form of virtual machine. xUML is intended as a generic attempt to support OMG's Model Driven Architecture (MDA). xUML implementations typically include the following:

- support for a well-defined simplified model structure, a subset of full UML
- an implementation of a specific syntax (vendor-specific) for the precise action semantics of the UML standard
- a simulation infrastructure that enables the entire lifecycle of model development (creation, editing, execution/simulation, configuration management, project support)

After discussing an alternative approach to MDA that involves the use of Domain Specific Modeling Languages (DSMLs), and after describing a variety of examples of such languages, we will discuss in detail our experiences with one large scale software project that adopted the xUML approach. Our discussion will include some of the drawbacks of the xUML approach, as well as some concrete suggestions for improving the successor to xUML (currently under standardization by the OMG).

### 2.1. xUML Tools

There is a wide variety of general tools that support model driven development, including many that support some form of executable UML (xUML). We focus here on lessons learned from the extensive use of a particular tool; this is a case study, not a trade study. The tool we have been using is generally compliant with existing xUML descriptions [2][10]. Some of the issues we have found are specific to the tool's interpretation of xUML, but most are related to the way xUML is defined and intended to be used.

## 2.2. Domain Specific Languages

One approach to model driven development involves the use of languages tailored for a specific domain, where "domain" is rather broadly interpreted—our examples include the domain of access to tactical data links, as well as the domain of distributed application development. The use of such languages allows one to build an efficient solution to a particular problem in the domain on a platform designed to make it easier to express those solutions, and that can handle many of the domain's general problems in a consistent manner across a range of applications. It is a step up from a well-defined API to a support library, because one is not restricted to the syntax of a host language (e.g. Java) and program logic can be expressed at a level of abstraction appropriate to the selected domain.

### 2.2.1. XML Defined Gateway (XDG) for Tactical Data Links

The XML-Defined Gateway (XDG) [11] is a router/gateway for tactical data links (TDLs), combining a conventional forwarding/filtering engine with dynamically loadable modules specialized for each supported TDL. It is intended to address a number of problems:

- Specifications for message formats and transmit/receive rules on TDLs are usually only human-readable, making it difficult to verify the correctness of any particular implementation.
- The number of data links in active use is not small (Link-11, Link-16[1], VMF, 6020 for internetworking), and is likely to increase. Support for all of these needs to be built in a way that minimizes the opportunity for programmer error, without sacrificing performance.
- Message forwarding among a variety of TDLs can be an $N^2$ implementation problem: each pair of network types, in a naïve implementation, would require a module to handle translation.

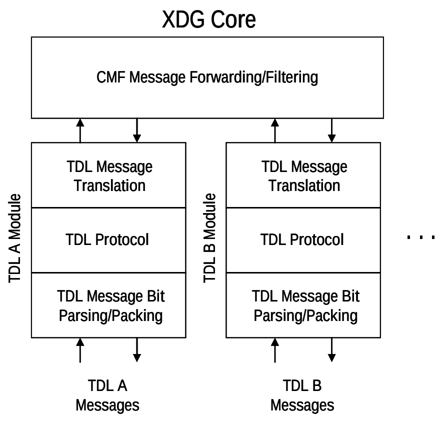


**Figure 1. XDG architecture**

In XDG, the forwarding engine is a standard C++ implementation. It manipulates messages in a Common Message Format (CMF) that is independent of any particular TDL, and that is defined by an XML document that the forwarding engine loads at runtime—further insulating the engine from changes required to support new messages or new TDLs. See Figure 1 for the split between the core and the dynamically-loaded TDL support modules.

Each TDL for which support is required is completely specified by an XML document, the schema for which defines a domain-specific modeling language. The TDL specification describes message formats, transmit/receive rules, and other aspects of the protocol. Rather than being used at runtime, the specification is compiled into a C++ module that can be loaded into a running instance of XDG. A TDL-specific module handles conversion of inbound

[1] For Link-16, the standard is 6016C, but it's recent enough that some systems are still on 6016B.

messages into CMF and of CMF into outbound messages on the link, while providing enough information for the forwarding engine to route messages to the appropriate destination.

The XML document describing a TDL can serve both as the implementation of XDG's support module for it, and as a human-readable specification of the network. Translation of the domain-specific language into C++ provides the module; XSLT (eXtensible Stylesheet Language Transformations) transformations of it can produce a readable document. Thus a correction in a TDL standard can be made in one place, updating both the implementation and the documentation simultaneously.

This is a solution where every aspect is tailored to the specific domain. The language, as defined in the XML schema, is intended only to describe TDL messages and their processing. The runtime implementation is a combination of conventional development with dynamic modules generated from XML documents in the domain-specific language. Although the specific runtime configuration, including the definition of the basic data structures manipulated by the system, is controlled by an XML document, XDG does not otherwise use XML at runtime: messages enter and leave the system in the format native to their specific TDL, and within the system they're represented in the binary CMF. This approach provides high performance, a high degree of flexibility, and dynamic upgrades to a running system, using off-the-shelf tools to edit the models and build the required transformations.

### 2.2.2. eXtensible Distributed Architecture (XDA)

XDA is a model-driven framework whose goal is to address the problem domain of distributed application construction. Its development began in 1998, based on lessons learned from large multi-vendor programs. Typically, these programs require vendors to develop components that address different aspects of the same problem domain and to produce solutions that can be easily integrated into a cohesive distributed system (or system of systems). Frequently, the difficulty involved in accomplishing this integration is not fully appreciated at program startup. In addition to the core system integration issues of managing component complexity, system configuration in a networked environment, and semantic alignment between the components, there are the additional complications of evolving system requirements and a changing definition of the problem domain, in the context of multiple development teams operating remotely. XDA was designed to provide a foundation for addressing some of these issues; specifically, XDA provides the ability to:

- Design a model of the shared domain of interest that forms the foundation for communication between components.
- Automatically generate platform neutral implementations of the domain model in Java and standard C++.
- Generate a transport infrastructure that includes configurable platform-neutral serialization strategies for the domain entities, including XML serialization with an automatically generated XML parser/writer for the domain entities.
- Hide the details of the underlying middleware by utilizing XDA provided libraries with well-defined generic APIs.
- Gracefully evolve the shared domain of interest in a constrained and disciplined way with minimal disruption across multiple development teams.
- Do all of the above consistent with good runtime performance.

One approach that can be used to address many of these issues is to partition the system into well-defined components that expose a well-defined interface using standard communications protocols (such as Web Services). The resulting system is then described as a Service Oriented

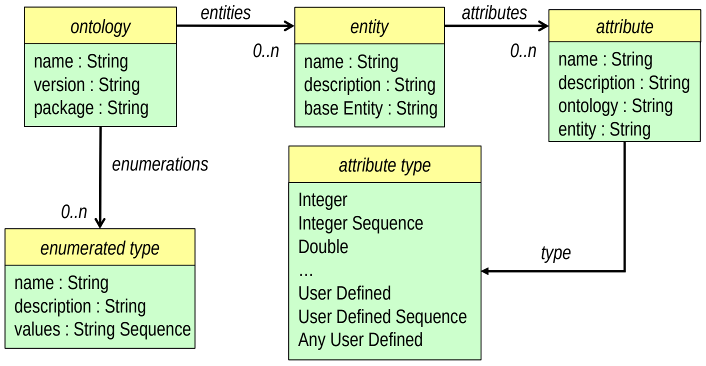


**Figure 2. The XDA meta model captures inheritance and aggregation relationships**

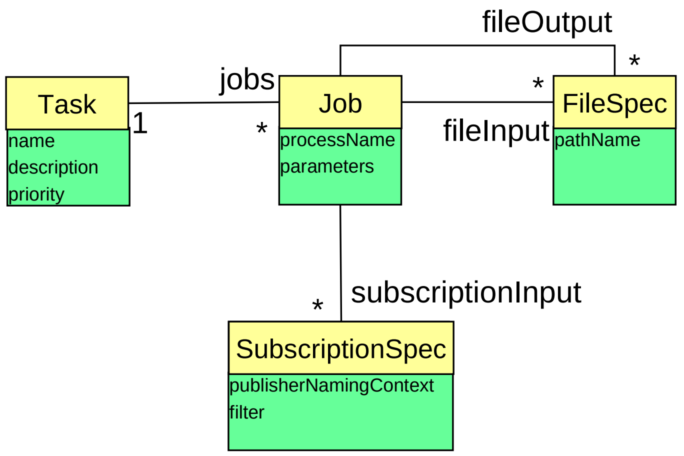


**Figure 3. A partial representation of a distributed processing domain based on the XDA meta model**

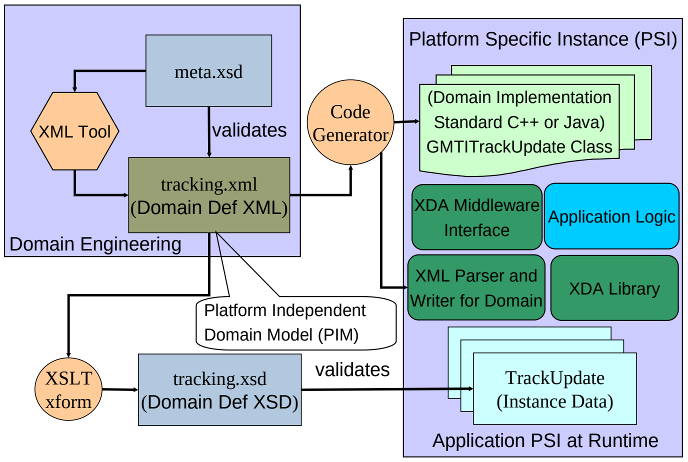
Architecture. The SOA approach minimizes the coupling between components, but does not systematically address the issue of domain architecture and runtime performance. Since XDA was initially designed for the domain of distributed sensor fusion, runtime performance was an important consideration.

XDA uses a meta model that is analogous to OMG's Meta-Object Facility (MOF) and Eclipse's Ecore, but much simpler. The XDA meta model is designed to define classes (domain entities) with single inheritance and aggregation relationships as shown in Figure 2. Code generators can easily traverse the models that are created based on the XDA meta model and can be configured to generate efficient code. A very simple example of such a model, which is part of a distributed processing domain, appears in Figure 3.

Automated (model-driven) code generation for the shared domain structures provides many benefits, especially for projects involving remote collaboration among multiple teams. First, the shared domain model provides strong semantic hints for proper exchange of information. Second, the shared code is less likely to be error-prone and can be fixed by adjusting the generator at a central location. Finally, the generated code supports substitutability [1] of base classes by derived classes, thus permitting domain model evolution as new requirements are uncovered. The model-driven approach allows for easy extensions to the shared domain to support unforeseen requirements. For example, a new requirement might emerge involving the need to identify the processing path as well as a causal trace (antecedent information) that resulted in a certain piece of information appearing as an output of the system. Information Pedigree capability can be modeled using this approach and can be integrated into the shared domain of interest with minimal disruption to the overall system.

XDA is designed to be middleware and computing platform agnostic, enabling the construction of Platform Independent Models (PIMs). It can be bound to a specific platform, for example Linux x86 with CORBA middleware using an XML serialization protocol, thus producing a Platform Specific instance of the Model or a PSM.

As shown in Figure 4, the XDA framework can be used (in this instantiation of it in terms of XML-based transport) at design time for Domain Engineering. The XDA meta ontology of Figure 2 is realized in terms of an XML schema, allowing subject matter experts to use a standard XML tool to develop a definition of the problem domain in XML The XML version of the ontology serves two purposes; it allows the user to operate in conformance with an XSD so as to guarantee the validity of the result, and it is structured with additional information that is helpful to the code generator. An XSLT transform is used to convert the domain XML to a domain XSD that can be used to validate instance data both offline and online. The Code Generator generates the domain implementation in C++ or Java, which, along with the appropriate XDA core and middleware libraries, is used to assemble a platform-specific implementation (PSI) for each component.



meta.xsd
XML Tool
validates
tracking.xml (Domain Def XML)
Domain Engineering
Code Generator
Platform Specific Instance (PSI)
(Domain Implementation Standard C++ or Java) GMTITrackUpdate Class
XDA Middleware Interface
Application Logic
XML Parser and Writer for Domain
XDA Library
Platform Independent Domain Model (PIM)
XSLT xform
tracking.xsd (Domain Def XSD)
validates
TrackUpdate (Instance Data)
Application PSI at Runtime

**Figure 4. XDA enables automated generation of the shared domain definition as a PSM**

### 2.2.3. Other Languages

The MDA approach to software development should make it easier for subject matter experts who are not software engineers to contribute to the design and verification of the software solution. The use of a modeling language permits the domain experts' knowledge to be represented in a way that they can understand, that a software engineer can understand, and that software can understand.

XDG and XDA contain examples of domain-specific modeling languages (DSMLs) defined without using UML. However, there is a considerable amount of effort being devoted to the development of DSMLs using UML. As with XDG, which can take advantage of the considerable toolset that has developed around XML, UML-based languages can use the emerging UML toolset to provide much of the support that developers need.

As France *et al.* [5] discuss, UML 2.0 provides three distinct mechanisms for tailoring: semantic variation points, profiles, and use of the Meta-Object Facility (MOF). These provide increasing flexibility, but at the cost of increasing complexity in the underlying toolset, and increasing difficulty in maintaining a consistent definition of the modeling language being used.

Semantic variation points are locations in the UML standard where a precise semantics is deliberately not specified. These include some of the semantics associated with state machines, aggregation, and so on. The system developer can, by providing a full definition, tailor UML to be better suited for a particular application domain. However, it can be difficult to maintain consistency, both with other parts of the UML specification and with other variation points that the domain may need to have tailored; in addition, the portability of UML specifications between different UML tools may be compromised by different assumptions around semantic variation points.

UML profiles provide another extension mechanism, allowing the creation of new constraints and additional attributes on classes in the meta-model. However, the semantics of these new elements cannot be defined in the model, so once again the tools have to be built or tailored to match the extension, which may inhibit cross-tool portability of models.

Finally, UML provides the Meta-Object Facility, which allows customization of the meta-model. This is essentially unlimited in what it allows; the difficulty, as France *et al*. point out, is that it places the burden of language development on users.

The difficulties associated with these mechanisms for creating DSMLs are not specific to UML. They are part of the cost associated with creating a new programming language. Analyzing the costs and benefits of creating a DSML is particularly difficult. For example, one would expect that the productivity improvements associated with a domain specific language would outweigh the implementation, training, and hiring costs associated with the effort, but it is easy to optimistically ignore many of those costs during the analysis. Will the software engineers be willing to work in a system that is domain-specific? How easy is it to find domain experts with sufficient software engineering background to assist in building the system? How would the costs and benefits of the DSML compare with those of a well-designed class library? And how much will it cost to obtain engineers with the skills needed to build a new language—in our experience, a much more difficult task than the definition and construction of a library.

For many domains and applications, the cost of supporting a domain-specific language will be too great to be practical—but certainly not for all. This is a tool development problem, and as with any tool, even a very large initial cost can be justified for a sufficiently large productivity gain by a sufficiently large number of customers or users, especially if the cost is amortized over a long period of time and across multiple projects. As the tools for developing DSMLs improve, the costs will decrease.

One approach, described by Balsubramanian *et al.* [6], starts with a tool for building and using DSMLs, the Generic Modeling Environment (GME). This supports both the meta-modeling required to define a specific DSML, and modeling using it. It explicitly does not attempt to generate all of the code for either the entire DSML implementation or the entire target application; instead, the system provides a framework that supports the integration of modules written in general-purpose languages. For example, as part of the DSML implementation, GME will provide external model interpreters with access to the model hierarchy it has defined, allowing them to validate the models and generate platform-specific code from them. The same authors' Embedded Control Systems Language (ECSL) [6], which targets embedded automotive applications, handles deployment and integration, including the calling of "application-behavior code," which can be generated by the tool, generated externally, or hand-coded.

This is an important step toward making DSMLs practical. Real systems under development will often have access to a body of pre-existing code that works well enough; if it's easy to integrate this, development costs will be reduced substantially. Similarly, it may be desirable to produce heavily-optimized code by hand for some parts of the system, or to integrate code produced by a subject matter expert who is only comfortable and productive working in MATLAB. These are not exceptional cases; better support of them can reduce costs significantly.

CALM [7] focuses explicitly on system modeling down to the component level, but does not attempt to support the coding of individual components. Thus what is being modeled is the system; obviously the interfaces and connections associated with individual components are part of this, but the components themselves are black boxes. The system also supports the creation of composite components, but beyond that appears to entirely avoid the difficulty of generating efficient code by allowing the code to be written in standard languages. As a system for integrating components using existing middleware, such as CORBA or EJB, it is similar to XDA (see section 2.2.2).

Although these systems are all described as domain specific, the domain is often a platform rather than an application area: integration using CORBA, for example. Each system we have discussed will impose costs in the form of training, documentation, and system maintenance that would not apply equally to general purpose COTS tools. The existence of standards, such as XSLT for XDG, and tools, such as Eclipse for CALM, in some cases has made the cost-benefit ratio quite favorable. XDG uses simple, standard tools to build a specialized line of products; the low cost of the tools matches the relatively small number of engineers using the system. Other systems, such as GME or CALM, are intended to be used in more general ways, so rightly focus much more on user interactions. Of course, in every case the value of the tool is in what it produces—the model, in whatever form, is not useful unless it can be automatically or semi-automatically transformed into an executable version.

## 3. Case Study

### 3.1. The Promise: xUML value proposition for the DoD

The promise of the xUML/MDA approach has significant cost implications for large systems that have largely similar business logic but are deployed on multiple, heterogeneous execution environments.

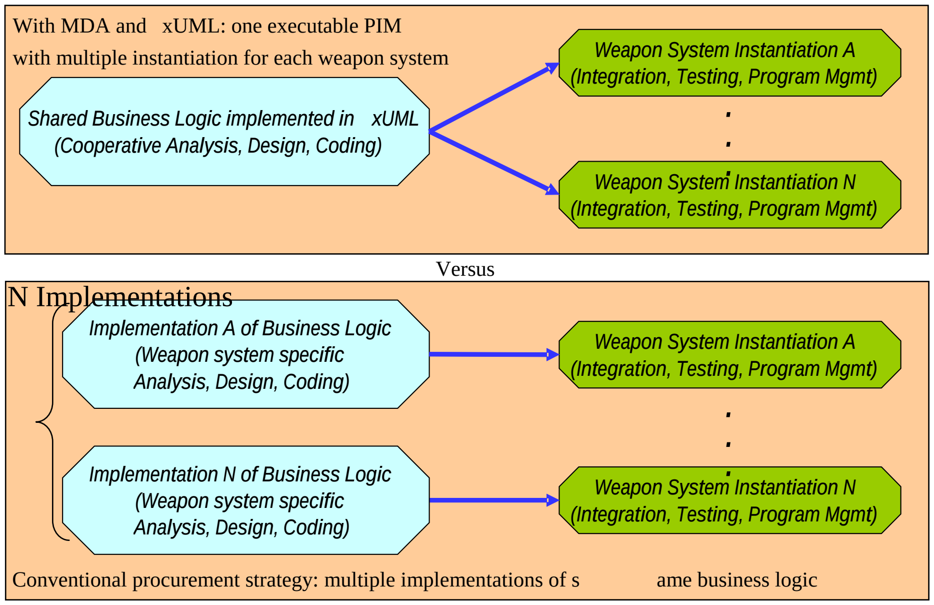

With MDA and xUML: one executable PIM
with multiple instantiation for each weapon system
Shared Business Logic implemented in xUML
(Cooperative Analysis, Design, Coding)
Weapon System Instantiation A
(Integration, Testing, Program Mgmt)
Weapon System Instantiation N
(Integration, Testing, Program Mgmt)
Versus
N Implementations
Implementation A of Business Logic
(Weapon system specific
Analysis, Design, Coding)
Implementation N of Business Logic
(Weapon system specific
Analysis, Design, Coding)
Weapon System Instantiation A
(Integration, Testing, Program Mgmt)
Weapon System Instantiation N
(Integration, Testing, Program Mgmt)
Conventional procurement strategy: multiple implementations of same business logic

**Figure 5. xUML represents a new approach to DoD procurements**

As shown in Figure 5, the conventional approach is to generate a detailed specification for the system in human-readable form. Based on this specification, there is a procurement for analysis, design, implementation, integration, testing, and deployment for each execution platform. This causes significant duplication of effort, as the core logic is implemented multiple times for different execution environments. There is also a significant risk of undesirable variations in the implementation logic because of potentially differing interpretations of the specification, especially in areas where it might be ambiguous. Finally, there are N implementations to debug and maintain. Since software maintenance is said to represent approximately 80% of the cost of software development, this approach to procuring large systems is quite expensive. By contrast, MDA/xUML promises to generate significant cost reductions by pooling resources across all the target execution environments to produce a single, executable platform-independent model. This model can be designed and implemented with the assistance of subject matter experts from all targeted execution environments, and tested and debugged prior to being released to the stakeholders to be transformed into platform specific instantiations.

The shared business logic is developed once. Maintenance is easier, because defects can be fixed once. Costs are dramatically reduced, because each team implementing a PSI can concentrate on what is different about that instance, rather than worry about duplicating the core logic. Figure 6 shows the adaptation of a PIM to a particular execution environment. In addition to the Core Processing Logic, it contains domains that are designed to interact with the external execution environment. These adaptation and interface domains assume the availability of interfaces to the

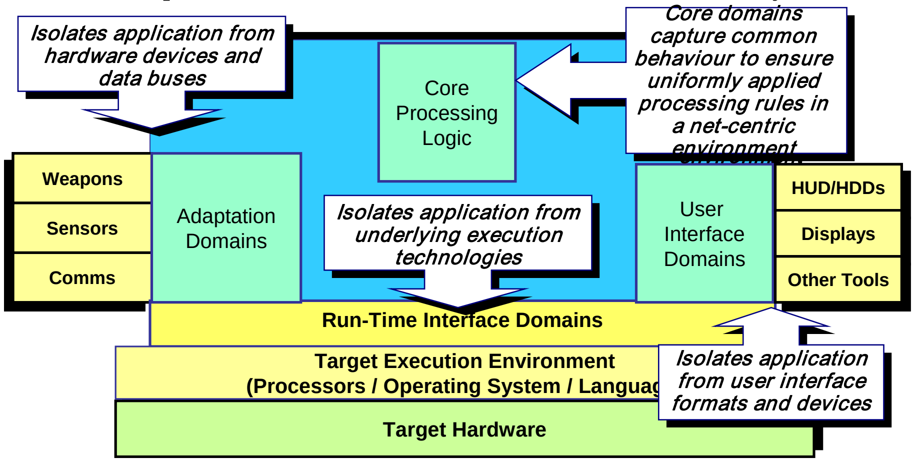

Isolates application from hardware devices and data buses
Core domains capture common behaviour to ensure uniformly applied processing rules in a net-centric environment
Core Processing Logic
Weapons
Sensors
Comms
Adaptation Domains
Isolates application from underlying execution technologies
User Interface Domains
HUD/HDDs
Displays
Other Tools
Run-Time Interface Domains
Target Execution Environment (Processors / Operating System / Languag
Isolates application from user interface formats and devices
Target Hardware

**Figure 6. Adapting a PIM to an execution platform**

execution environment, including operating system facilities, sensors and displays. These interfaces are typically implemented as libraries that are linked into the final PSI.

It is expected that the upfront development costs associated with this program will be larger than they would for an effort of comparable scope developed using more traditional tools and techniques. Any cost savings will be in two areas: the amortization of the development costs for the core processing logic over many platforms, and the reduction of maintenance costs because any bug in the core need only be found and fixed once, and because there is much less chance of differing interpretations of the specification.

## 3.2. Introduction to the Case Study Project

The authors have been associated with a Defense Department project to build a new piece of software using MDA. The product is targeted for a variety of weapons systems, covering the spectrum from large ground-based installations, through surface ships, to E-2 surveillance planes and even fighters. The value of the product is partially in the common implementation of algorithms and standards, and partially in its intended ability to share data among systems: platforms that have access to broadband links can share data with their peers, while using TDLs to share information with legacy systems or with other instances of the product that do not have broadband. Data shared over the TDLs is fully processed; other platforms receive track reports. Data shared over the peer-to-peer network is largely unprocessed; other platforms receive measurements, which they use to execute the core algorithms, so all platforms arrive at the same result by executing common algorithms on shared data.

The product includes a substantial amount of conventional C++ code, both platform-specific and generic, but the core logic is being developed using MDA tools—in this case, Kennedy Carter's iUML product [8]. The modelers on this program do their work on Windows machines, although weapons systems are typically expecting to use Linux, Solaris, or small RTOS environments such as LynxOS. The project poses major challenges in a number of areas: developing software that will allow small systems to keep up with data produced by peers with much higher capacity; ensuring that the software will in fact run on all of the target platforms; providing updates to the core software that can be integrated with adaptations made by the individual platforms; and performing adequate testing, at the unit, system, and system-of-systems levels.

In what follows, we discuss specific issues that we have encountered in extensive testing and integration of the software product, performed in support of various Air Force platforms. Configuration management for MDA is an issue that still needs to be addressed at a theoretical level. Standard tools have yet to be developed. In section 3.3, we discuss our experiences with CM and support for CM in the Kennedy-Carter toolset. In section 3.4, we describe the use and peculiarities of the xUML architecture. In section 3.5, we describe our experiences with model compilation, a process used to generate a platform-specific executable from the model. We will be concentrating on fundamental issues, not shortcomings of a particular modeling tool or artifacts of the implementation of any particular model. From these experiences we extract lessons learned and a set of recommendations detailed in section 4.2.

## 3.3. Configuration Management

### 3.3.1. Description of CM support built into the MDA tool

The program's choice of an MDA tool was driven in part by the desire to implement core processing once, then deploy it essentially unchanged on multiple platforms. However, as we discussed in section 3.1, a deployment typically includes external, platform-specific libraries (developed using conventional methods) or additional iUML domains to adapt the PIM to the requirements of a particular execution platform. For example, such extensions are needed to adapt to specific terminal, sensor and navigation interfaces.

The developers provide to the platforms, or in our case to a service lab set up to evaluate the product, a new release of the PIM every 6-12 weeks. Each release undergoes unit testing and single-system testing in a simulated environment, although it eventually is to be deployed as a system-of-systems. Further, it contains placeholder implementations of some functionality that will almost always have to be customized by the platforms, allowing the PIM to be tested and validated without platform-specific customizations. Our experience has shown, at least in the current rather early stages of development, that it is rarely possible for a platform to adopt a new release without making some patches in the core code, in addition to whatever changes are required for their environment. A typical cause may be a defect in the PIM that affects only a specific platform. Such defects (as well as fixes or workarounds) are reported so that they can be incorporated in future releases of the PIM.

The basic unit of code development and reuse in xUML tools is a "domain," which is a collection of classes similar to a Java package. Domains in this system range from relatively simple ones that provide basic services, such as starting all the components of the system, to complex domains that are built by small teams of developers. An example of such a domain is one that manages the flow of data to and from tactical data links.

A given executable is produced from a "build set," which specifies the set of domain versions to include, as well as the inter-domain bridges that allow domains to interact—they are otherwise treated as black boxes, but bridge code is allowed to make calls inside several domains. In principle, bridge code should contain no business logic, because that compromises the encapsulation of implementation details provided by the domain structure. In addition, bridges are external to domains and cannot easily be treated as units of configuration management.

The tool stores domains and build sets in a proprietary binary format, although there is an API that allows access to the model database. It is easy to export a specific version of a domain, as a binary file, and import it into another database; the export includes all of the UML diagrams as well as the code associated with operations defined in the domain. In fact, the basic release from the developers to the platforms is just a set of domain exports, along with a build set.

On this project, we have geographically distributed teams working on the same product. Frequently, it is necessary for multiple developers to modify a domain simultaneously. This has proved very difficult to manage effectively.

### 3.3.2. Shortcomings of CM support

As noted earlier, configuration management for model-driven development has not yet received adequate theoretical treatment and standard tools have yet to be developed. It is therefore not surprising that the CM support in iUML is rudimentary, rendering the performance of even basic CM tasks difficult, or even impossible. One important shortcoming is the lack of support for differencing between different model versions, and the capability to merge differences. For example, if core model developers identify and fix a major defect it is impossible to issue a patch to the latest release that can be used to automatically apply the fix for the defect. Typically, such updates must be applied manually, or the domains affected must be re-released. Platform developers face the same problem when they fix defects that may be specific to their platform. Folding these improvements into the next release is a manual, error-prone process. Finally, it is difficult to resolve conflicts if two developers have modified the same domain at the same time. With conventional programming languages, this is a simple merge operation, sometimes requiring human guidance to ensure that the conflicts are resolved correctly. There are many tools that support merging conventional source code, but none can be used to merge and deconflict model changes. Further, since domains are both the unit of code reuse and the smallest unit that can be managed separately, conflicts are more likely because a single domain will in general contain many classes and their methods, and multiple developers may be responsible for the implementation of a given domain.

As we discuss in Section 4.2.1, the interactions of domains with each other and with external libraries further complicate configuration management tasks. Bridges break domain encapsulation, since directives can be used to make the internals of multiple domains visible within a single bridge. This induces tight coupling between domains in the bridges, and bridges can only be managed at the build set level. Domain interactions as well as interactions with external libraries are thus hard to localize and manage, forcing the inclusion of the entire code base in each patch release. This is aggravated by the need for each deployment platform to re-apply platform customizations, further increasing integration costs.

## 3.4. Unintended Consequences of xUML Features

Since xUML is not the outcome of a standardization process, it is not surprising that it includes some idiosyncratic features and design decisions. We discuss some features that we have found, in our experience with this large scale project, to adversely affect the quality of the product in a number of dimensions, including runtime performance and maintainability.

### 3.4.1. Relational Runtime Model and Inheritance

By design, xUML enforces a runtime object model that mirrors a relational database system. Each class can be viewed as a table; each class definition must include a unique identifier (or set of identifiers) acting as the primary key. It is possible to define class refinements (analogous to inheritance), along multiple axes; each class so defined in effect represents another table, related to the parent by a foreign key. It is not necessary to hold a reference in order to use an object; the action language has "find" primitives that search the set of all instances of a given class, returning either a single instance or a set. This is the behavior expected of a database, so is consistent with the choice of the relational data model.

Class refinement differs from the traditional OO inheritance model in several respects:

- It makes it possible to reclassify an object without recreating the object.
- It allows multiple refinement hierarchies descending from the same root class, as opposed to the single hierarchy provided by languages such as C++.
- It allows the runtime environment to track all object instances outside any data structure maintained by the model.
- It does not support substitutability.

Figure 7 shows a sample class structure, illustrating multiple refinement hierarchies. An instance of a Track object must refer to either a LocalTrack or a RemoteTrack, and to either a GMTITrack or an AirTrack. Thus, it's possible to reclassify a Track from local to remote without deleting the Track instance itself; instead, the modeler can create a new RemoteTrack instance, and move the link in the Track instance from its old LocalTrack to the new RemoteTrack. This is not behavior that a conventional OO language like C++ supports within its class structure, but of course there are many ways to accomplish something equivalent.

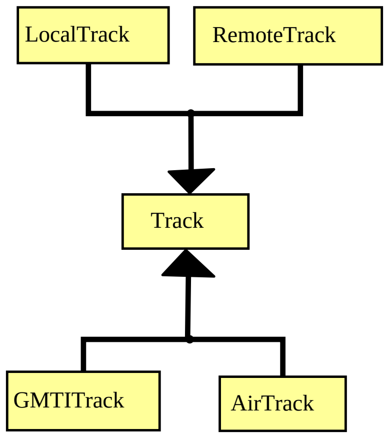


**Figure 7. Specialization hierarchy**

For developers trained in conventional OO languages, thinking in the relational model can be counterintuitive and error prone. The lack of substitutability is especially surprising, even to very experienced engineers. In addition, the system here is a hybrid composed of the model and a variety of external libraries written in C++. Although the model is compiled into C++, the external libraries cannot operate directly on objects managed by the model: doing so requires exact knowledge of the relational object model and how it was translated into C++. This complicates the use of external code, and reduces opportunities for optimizing runtime performance. The complexity of these multiple refinement hierarchies can result in brittle, inefficient code. An instance of the Track class consists of three distinct objects: an instance of Track, an instance of Local or Remote Track, and an instance of GMTI or Air Track. These must be created and manually linked by traversing the refinement hierarchy and using appropriate foreign keys. Leaving aside lower-level performance issues such as memory fragmentation, and the lack of locality of reference for these objects, the construction and destruction of such multiply refined objects requires a significant amount of repetitive code. It will often be written incorrectly, or be corrupted during the life cycle of a large project. Although multiple refinement is touted as a major benefit of xUML, our experience is that in practice any benefits are far outweighed by the cost. In addition, object creation, deletion and reclassification must be atomic procedures guarded by a transaction system, because failure can result in a runtime with compromised relational integrity.

Multiple refinement is particularly inefficient when “deferred” methods, roughly equivalent to C++ virtual methods, are used. In C++, there is a slight memory cost for the virtual function table associated with a class, but the execution time cost is typically negligible. Here, in addition to the memory cost, there is additional overhead for every invocation of a deferred method: the runtime system must search through the refinement objects descending from a parent, possibly several levels down, to determine for each one whether it is an instance of a class that implements the deferred method. As with many other aspects of this object model, this is surprising to developers accustomed to conventional OO languages; the effect is to conceal runtime inefficiencies from even a skilled C++ programmer.

### 3.4.2. Skip Lists: A Cautionary Tale

One of the functions in the core of the system is coarse gating—asking whether two tracks have any likelihood of representing the same object, before performing more detailed and costly analysis to make a final decision. For one such case, the implementation uses a “skip list” data structure to organize tracks along a particular dimension. The skip list permits a relatively rapid search for tracks that are close to the target track in that dimension. The published algorithm [9] uses arrays as part of its data structure. The iUML action language has no notion of arrays, which is a logical consequence of the choice of the relational data model. Modeling a skip list requires modeling arrays, which in turn requires a model that uses  multi-valued associations. Navigating such associations at runtime is expensive, difficult to optimize and ultimately inadequate for this time-critical function. Even with a full description of the algorithm, its implementation is necessarily brittle and inefficient because it is obscured by the semantic weakness (lack of expressivity) of the programming language.

An alternative would be to implement the skip list as an external library using C++. Many complex algorithms in the system, such as Kalman filters, are provided in external libraries, so this might seem like a reasonable alternative. However, there is significant additional cost associated with this; the modeler has to define a set of bridges, and within those bridges provide C++ code to utilize the external library. However, due to the mismatch between the relational runtime model and the external object model it is not feasible for the C++ library to invoke methods on the objects passed to it from the model, resulting in inefficient and overly complex code. Unnecessary complexity in this case could be relocated from the model to external libraries, but it cannot be eliminated.

### 3.4.3. State Machines and Event Queues

xUML [2] provides direct support for state machines. State machines are typically associated with individual objects; it is relatively easy to draw a state machine, define the signals that will cause state transitions, and associate code with each state. A given state machine can be thought of as a thread—it performs some computation when it receives a signal, but its execution is inherently asynchronous with respect to other state machines in the model. Signals are delivered to state machines from an event queue whose processing forms the main loop of the system.

In our experience this concept of state machines has weaknesses that result in hard to diagnose runtime problems. The "state" of an object, in this system, is the ID of the current state of its state machine, rather than the set of values of the object's instance variables. In xUML, all of the instance variables and methods of an object are visible to all classes within its domain, and through bridges to any domain in the system: the state machine therefore cannot have control of the object's true state. This makes it impossible to enforce alignment between the values of the instance variables and the state of the object's state machine; this must be maintained manually, and precariously.

Another issue relating to event processing and memory management involves events referencing objects that get deleted before the event is processed. An event sent to a state machine may include other objects among its parameters; for example, a Track Update event may reference a Track. There is nothing to prevent the Track Update from being queued when the event queue already contains a timer event that will delete the referenced track, leaving the Track Update event on the queue a dangling pointer. These runtime errors are very hard to reproduce, isolate, and diagnose. Typically, complex logic must be inserted to guard against them, increasing code complexity and fragility.

## 3.5. Model Compilation

Model compilers are used to transform xUML models. Typically, Platform Independent Models (PIMs) are transformed into Platform Specific Models (PSMs). As shown in Figure 8 the PIM released by the core development team can be augmented with a Platform-Specific Buildset (PSBS) before being transformed by a Platform Specific Model Compiler into C++ code. Either the union of the PIM and PSBS, or the generated C++ code could be viewed as the Platform Specific Model. A final step involves compilation and linking of the generated code and additional external code or libraries into an executable (PSI).

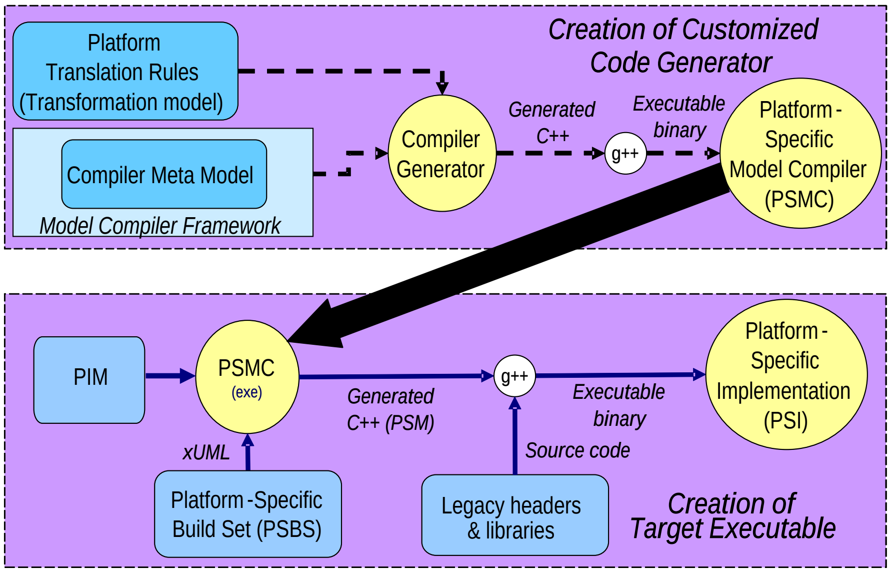

Creation of Customized Code Generator
Platform Translation Rules (Transformation model)
Compiler Meta Model
Model Compiler Framework
Compiler Generator
Generated C++
g++
Executable binary
Platform-Specific Model Compiler (PSMC)
PIM
PSMC (exe)
Generated C++ (PSM)
g++
Executable binary
Platform-Specific Implementation (PSI)
xUML
Source code
Platform-Specific Build Set (PSBS)
Legacy headers & libraries
Creation of Target Executable

**Figure 8. PIM to PSI transform through a Platform Specific Model Compiler**

Generated code is designed to run against a set of architecture libraries that provide access to core operating system services as well as to common functions such as logging—in effect, a superset of the standard C++ libraries.

In theory, model compilers provide an excellent opportunity to address many cross-cutting issues in a uniform manner including infrastructure (for example threading, logging, inter-process communication) and performance optimization. Logging was implemented by extending the xUML action language with logging primitives which the model compiler implements with code utilizing the standard log4cxx [12] package. We could view the logging mechanism as an integral part of the virtual machine on which the executable model runs. We could also imagine an execution platform where a different logging package must be used. In that case the model compiler is modified to generate the appropriate code, while the PIM can remain unchanged.

Model compilers (like conventional optimizing compilers) are also used to optimize runtime performance. For example, the xUML action language includes a primitive “find” that can be used to retrieve instances of a given class. If there is no call to “find” for a particular class, the model compiler could optimize out the code needed to track all class instances. Similarly, if a base class is not used as part of a multiple refinement hierarchy, the highly efficient C++ virtual function mechanism could be used to implement deferred methods.

While the first use of the model compiler as a tool for creating an infrastructure abstraction is highly appropriate, using model compilers to address fundamental performance issues has met with mixed results. First, global optimizations such as the one for the “find” primitive are brittle. For example, a single, accidental introduction of a “find” could lead to performance degradation that would be hard to diagnose. Second, there is very little any compiler can do to generate efficient code from an inefficient implementation of an algorithm. Third, our experience is that it is difficult to modify the model compiler.

Problems associated with compilation are among the most difficult to find; one does not change compiler versions lightly, nor does one generally attempt to enhance the functionality of a working compiler. Although the model compiler produces C++ rather than machine language, the same principles apply: it should be relatively stable, and the platforms should not require, nor should the project accept, modifications of it. The underlying principle of this development effort is that all the platforms will be running the same algorithms, but we can not be confident that processing on different platforms is logically equivalent if the generated platform specific code is significantly different.

It is extremely difficult to write code that reasons about other code and gets it right. There are optimizations that one might be able to make, but identifying them requires a high degree of complexity in the model compiler—but the action language used in xUML lacks the expressive power for building complex algorithms.

## 4. Lessons Learned for Future xUML and MDA Tools

### 4.1. Use xUML only if it is appropriate

This is something that applies both to whole projects and to parts of large projects. One would not use a scripting language like Python to develop a Kalman filter, nor the domain specific language of XDG to develop anything other than the TDL logic for which it was intended. xUML is intended to be a general purpose development environment, but its quirks and limitations, as well as the ways in which it can surprise even very experienced developers, suggest that it is less generally useful than languages like C++ or Java. Transaction processing applications will often map easily into the relational model, since their underlying data store is often a relational data base; controllers will find state machines an extremely valuable facility. Other sorts of applications might find that other approaches produce better results.

## 4.2. Improving xUML

Based on our experience with a tool that follows xUML as described in [2] fairly closely, we believe that the next generation of xUML tools would benefit tremendously if some adjustments were made to the xUML architecture. The OMG is currently in the process of trying to standardize a subset of UML that can be made executable (although it is not called xUML). Our opinion is that in designing new programming paradigms and languages it is beneficial to leverage hard-won experience from previous attempts, and to avoid violating the principle of least surprise where possible. Many successful language introductions were designed as smooth transitions from existing successful languages—witness the introduction of C++ as an extension of C with support for object orientation, and the introduction of Java with a core of syntactic features that were familiar to C and C++ programmers. In this sense, as we have already indicated, the first generation xUML design has fallen short. The new version that becomes standardized by OMG will probably be different and will have its own strengths and weaknesses. In the mean time, we present some suggestions for improving the current xUML design.

### 4.2.1. Change the Domain Interaction Architecture

The current approach to domain interaction, in terms of bridges and inline code, inevitably leads to strong coupling between domains, and breaks domain encapsulation: each bridge can reference an arbitrary set of domains. Consequently, code in bridges tends to rely on implementation details of each domain. This is especially harmful because it hinders domain evolution, including refactoring. When developers make changes to a domain, they must be aware of all bridge code that they might be breaking. Since domains are the smallest unit of reuse, they must be atomic. In particular, there can be no class definition re-use across domains. Classes can be used by other domains, when exposed as services by their home domain, but they cannot be re-used without breaking the atomicity of the domain concept.

Instead, each domain should provide a “domain interface” that can be used by its clients, and it should have a well-defined “required interface” that it assumes is provided for its use in the deployed environment. As long as the “required interface” is made available to a domain, the domain guarantees that it can satisfy the “domain interface”. Part of the OMG standardization effort should include selecting existing features of the UML standard that can be adapted to define domains that are fully encapsulated, with domain and required interfaces that can be precisely specified. An example where OMG has done something similar is the CORBA Interface Definition Language for describing CORBA services.

Existing xUML features that break domain encapsulation, for example counterpart associations, will need to be re-designed so that they rely on domain interfaces only.

### 4.2.2. Modify the Role of the Model Compiler

The model compiler has a complicated role in the xUML framework. First, as shown in Figure 8 a Platform Specific Model Compiler (PSMC) is generated for each execution environment. The PSMC encapsulates the domain specific knowledge that is required to generate a PSI from a PSM. Secondly, a multitude of orthogonal modeling concerns can also be delegated to the PSMC. In particular, the adequacy of runtime performance is supposed to be guaranteed by a suitably optimizing PSMC.

In practice, it is difficult to modify a model compiler, and doing so can result in a maintenance problem. Furthermore, it is simplistic to assume that a model compiler can optimize away all modeling sins. Finally, annotating the PIM to provide hints to the model compiler in support of a variety of concerns such as multi-threading and runtime performance (which are considered not meaningful at the PIM level) only results in a cluttered and bug-prone PIM.

We believe that the model compiler should be modified only when absolutely necessary, and that the PIM should not attempt to capture issues that do not properly belong there. If the recommendations of Section 4.2.1 are adopted, the need for PSMCs disappears. Each domain is completely encapsulated and its method of implementation is completely hidden from its clients. Each domain by its nature will stand somewhere in a spectrum of platform specificity, and each domain will have its own way of converting to PSI. Some domains may be implemented completely in a systems programming language like C, while still providing their services to all domains. For such domains, the model compiler will be responsible for providing the scaffolding that implements the domain interface, while delegating platform specific details like optimization to the C code implementing the domain and an optimizing C compiler. These changes would, when combined with those from Section 4.2.1, eliminate the need for bridge code that violates domain encapsulation and increases the difficulty of configuration management.

### 4.2.3. Redefine Purpose of Precise Action Semantics

The value added by xUML over third generation languages is that visual representation is easier for the developers and more accessible to the subject matter experts (SMEs) who collaborate with the developers. Action Semantics needs to balance two conflicting requirements: it must be abstract, so that it makes sense to the SMEs, but it must be expressive enough to represent the computational logic efficiently. These two goals are hard to reconcile. If complex logic can be faithfully represented in a way that results in efficient runtime performance, the language will appear complex to all except the developers. We must recognize that to be useful the Action Semantic representation can in general only capture the computational logic of a given domain at a certain (probably coarse) granularity. Since domains are fully atomic and encapsulated, in principle they could be implemented in a variety of ways. The purpose of some of these “worker” domains could be to flesh out with precise implementation details the coarser logic captured in other domains, in ways that are consistent with expected runtime quality of service. In fact, multiple such implementations should be possible, given domain encapsulation and atomicity.

### 4.2.4. Address the Runtime Architecture

It is clear that the RDB runtime model is too specialized to be a generic solution to an MDA runtime architecture. In addition to the performance issues, there is a fairly serious violation of the least surprise principle. The same is true of the replacement of inheritance by specialization. In the xUML literature, important issues such as runtime performance are relegated to the platform specific level (to be resolved by an optimized platform-specific model compiler), so one would expect that the runtime models should at least fall in the same category. A similar criticism applies to using a threading model that is tied to the state machine design of xUML. We propose that a standard runtime model (or a reasonable abstraction of one) should be adopted. One of the lessons taken from the Java platform should be that threads and synchronization need to be addressed as first class abstractions at the domain level. If a domain is not designed to be multi-threaded, chances are good that it can not run in multiple threads, no matter how smart the model compiler is. The runtime model should be designed to be compatible with a multi-threaded, event-driven architecture. The future xUML representation should be designed to eliminate memory issues. In the current version it is too easy to reference objects that have already been deleted; for example, the runtime event queue is an external data structure that can hold references to deleted objects. Java has already successfully addressed this problem, and the future xUML standard needs to be at least as effective in this area as Java is today.

### 4.2.5. Change the Buildset Architecture

A buildset is a set of domains that can collaborate to achieve a shared goal. If each domain has a required interface, then we can require that a buildset be closed with respect to that relationship, i.e. each domain must be associated with a set of other domains in the buildset that together satisfy the domain's "required interface." It would be useful if a well-specified mechanism existed for wiring domains together according to their requirements. Automated tools could be built to verify that a buildset is consistent and that each domain's requirements are addressed. A standard buildset architecture would be beneficial because it would allow developers to reuse domains that were built using tools from different vendors. It would also allow vendors to create a market of reusable MDA tools.

### 4.2.6. Create an Abstraction for Distributed Processing

It should be irrelevant how a required interface is provided to a domain. A fully reconciled buildset consisting of domains completely wired with respect to their required interfaces should be deployable in a heterogeneous network-centric environment. It should be as easy to co-locate two domains in the same processor (or process) as it would be to distribute them across different processors. Although this is clearly a PSI issue, it should be addressed with an abstract specification that permits vendors to create standards-compliant deployment tools. For instance: domain A requires domain B, domain A is implemented as a CORBA object, and domain B is deployed as a Java RMI application. A CORBA to RMI bridge could be automatically generated, consistent with the domain interfaces, to link component A to component B.

### 4.2.7. Encourage Interoperability across Vendor Tools

It is important to establish standards that allow users to mix and match "best-of-breed" tools. Version control and model merging is an especially important area, where standardization may be required. If standard solutions arise in this area, the scalability of MDA efforts will be vastly improved. The MDA community needs to take a close look at the Eclipse platform and its strategy of creating an "eco-system" of tool developers and tools

## 5. Conclusion

In the context of ever-increasing size and complexity of software projects, MDA should be considered as a possible software development strategy. MDA seems to be especially effective when it is more narrowly focused to specific domains of interest and when it is used in conjunction with domain-specific modeling languages. We discussed two examples of such use of MDA, and many others can be found in the literature. Tools that support a generic approach to MDA and are applicable to all domains follow a tradition that started in the late eighties with CASE tools and continues today with attempts to standardize some form of "executable" UML. Standardization for such tools is in progress. The tools are not yet mature, and due to the lack of widely accepted standards, not fully interoperable. The tool vendors may have contributed to the confusion in the market place by promising much but not delivering enough, while slowing down the standardization process in order to defend narrow interests. Our case study of a large project that is being developed using the xUML methodology shows some of the promise of the xUML approach, in spite of the immature state of the tools, as well as many of its pitfalls. We believe that MDA in some form will evolve into the next generation of technology and tools for developing demanding software applications. However, this will require several years of standardization efforts as well as practical experience. While generic MDA is being defined and while it is tested in the market place, more modest efforts involving MDA and DSMLs will continue to generate success stories.

## 6. Acknowledgements

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