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FV-RAD
A Practical Framework for Rapid Application Development

Luís Filipe Ferreira

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Project Report
Master in Informatics and Computer Engineering

Supervisor: Prof. Ademar Aguiar

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Abstract

The way conceptual models are used today within application development depends heavily on the level of detachment between model and implementation. This model-implementation gap has an impact on model detail and its maintenance effort. In an environment where new requirements tend to be added while a project is evolving it is often very difficult to manage this gap.

Typical roundtrip based approaches were able to tighten this gap at the cost of merging implementation detail in the model structure. They also imposed an additional effort on keeping those changes synchronized with implementation changes. Recent generative methodologies like Model-Driven Software Development (MDSD) overcome this problem by a forward only generative process directed by highly abstract Domain Specific Languages (DSLs), but they also have its drawbacks. They impose a delay between model changes and application execution that could inhibit model experimentation.

Other approaches like Adaptive Object Modelling (AOM) focus on reducing the model-implementation gap by embedding the model within the implementation that is responsible for its run-time interpretation. Changes occurring in the model are immediately perceived by the application and have a direct impact on its behaviour.

This dissertation is about building an AOM based framework for model embedded applications and applying it to specific domains. This framework (FV-RAD), based on a subset of UML class models, should provide instant model based prototyping of application requirements and its progressive refinement throughout the development process. It should also allow additional code attachments, extending its global functionality and "filling the holes" where the framework lacks in grasp.

Two practical examples, one of them in the field of public transportation, are also provided as a demonstration of the framework's capabilities.

Resumo

Actualmente, a forma como os modelos conceptuais são utilizados para o desenvolvimento de aplicações depende largamente da ligação entre o modelo e a implementação. Esta lacuna entre modelo e implementação tem um impacto sobre o nível de detalhe e esforço de manutenção do modelo. Num ambiente de constante mudança onde novos requisitos tendem a ser adicionados à medida que um projecto evolui, torna-se muitas vezes difícil gerir esta lacuna.

Abordagens típicas como a engenharia *roundtrip* mostraram-se capazes de reduzir esta lacuna mas ao custo da imposição de detalhes de implementação na estrutura do modelo. Revelaram igualmente um esforço adicional na manutenção do sincronismo entre as alterações no modelo e aquelas resultantes da implementação. As metodologias generativas mais recentes como o Software Dirigido por Modelo (*Model-Driven Software Development*) são capazes de ultrapassar estes problemas através de um processo de geração de sentido único (*forward only*) dirigido por linguagens de modelação orientadas ao domínio (*Domain Specific Languages*) de um grande grau de abstracção, mas também têm as suas desvantagens. Elas impõem uma demora entre as alterações no modelo e a execução da aplicação que pode ser inibidora relativamente à modelação experimental.

Outras abordagens como a Modelação por Objectos Adaptativa (AOM – Adaptive Object Modelling) incidem na redução da lacuna modelo-implementação pela incorporação do modelo na implementação que é responsável pela sua interpretação em tempo de execução. As alterações no modelo são imediatamente percebidas pela aplicação onde exercem impacto comportamental directo.

Esta dissertação aposta na construção de um *framework* prático baseado em técnicas adaptativas, para aplicações de modelo embebido, e na sua aplicação em domínios específicos. Este *framework*, baseado num subconjunto dos modelos de classes do UML, deverá permitir a prototipagem automática dos requisitos da aplicação e o seu refinamento progressivo através do processo de desenvolvimento. Deverá igualmente permitir a anexação de código à implementação, estendendo a sua funcionalidade global e "tapando os buracos" onde o framework se revela mais limitado.

Dois exemplos práticos, um deles no domínio dos transportes públicos, são também fornecidos como forma de demonstrar o potencial deste framework.

Acknowledgements

The implementation of this framework is a result of a deep interest in model oriented development and its practical application and integration in software development processes.

First I would like to thank OPT for giving me the opportunity to complete and apply this framework to real projects of relevant importance to the company. Special thanks to Sara Silva who has played an important contribute for the implementation of the user interface layer and the persistence mechanism. My thanks also go to Prof. Teresa Galvão who has been a source of encouragement to finally finish this dissertation, and for taking the time to review its contents. I could not finish paying my tributes to OPT without mentioning Fernando Vieira, my colleague in arms, without whom life at OPT would be a lonely path, we've had similar ways at OPT and I really hope he finishes his thesis soon, as I'm keeping an extra bottle of champagne closed.

I would like to thank Prof. Ademar Aguiar for the update in state of the art technologies, for the help on organizing the contents of this thesis and for the deep encouragement to proceed without goal deviations. I also would like to thank Prof. Augusto Sousa for understanding a busy life in the software industry and for the help with the burocratic aspects of completing this thesis.

At last, but not the least, my loving gratitude to my wife Olga and my son David, for the weekends I haven't been able to be a present husband and father, for Olga's support and patience in replacing my time near David, and for providing me with the best part of my life…

Luís Filipe Ferreira

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Abbreviations

AOM	*Adaptive Object Modelling*
AOSD	*Aspect Oriented Software Development*
API	*Application Programming Interface*
CASE	*Computer Aided Software Engineering*
DSL	*Domain Specific Language*
FV-RAD	*Field Values based Rapid Application Development*
GIST	*Gestão Integrada de Sistemas de Transportes*
GSD	*Generative Software Development*
GP	*Generative Programming*
GUI	*Graphical User Interface*
J2EE	*Java 2 Enterprise Edition*
MDA	*Model Driven Architecture*
MDD	*Model Driven Development*
MDE	*Model Driven Engineering*
MDSD	*Model Driven Software Development*
WWW	*World Wide Web*
WPF	*Windows Presentation Foundation*
MOF	*Meta-Object Facility*
OCL	*Object Constraint Language*
OMG	*Object Management Group*
OO	*Object Oriented*
OPT	*Optimização e Planeamento de Transportes, SA*
ORM	*Object Relational Mapping*
PDM	*Platform Dependent Model*
PIM	*Platform Independent Model*
PSM	*Platform Specific Model*
RAD	*Rapid Application Development*
RUP	*Rational Unified Process*
SF	*Software Factories*
SQL	*Structured Query Language*
UI	*User Interface*

UML	*Unified Modelling Language*
VB	*Visual Basic*
VS	*Visual Studio*
XMI	*XML Metadata Interchange*
XML	*Extended Markup Language*
XP	*Extreme Programming*

1 Introduction

Software development is still a growing business with an increased history in applying new methodologies for its production. It is however strange to notice that, after all this time, it generally still comes down to the manual writing of thousands or millions of lines of code. In an era where the human error factor has been largely compensated through the use of automation based processes and redundant quality systems, it is discouraging to observe how such archaic, low level, error prone processes are still the most applied practices in IT. The price is still being paid and it is reflected in software quality and in deadlines that keep meeting failure.

Software development is slowly raising its abstraction level, and releasing humans from the tedious repetitive tasks of low level programming. It is now time to relax our finger tips and embrace the next paradigm in software development by applying finger toes, to our models…

1.1 Methodologies and RAD

Early application development methodologies were typically devised as a waterfall like model [Royce'87], where a series of disciplined and well defined phases take place from requirement analysis and application design to the final implementation stages. These more rigorous approaches were intended to minimize the cost of possible future changes by predicting all system requirements and translating those into a big well thought design up front.

The problem is that, in more evolving environments, where requirements tend to be added or changed more frequently, it may happen that by the time the “final” design has reached its implementation phase, the system has lost its utility by failing to comply with the latest requirements. This is especially true when customers are only able to decide on their actual needs by interacting with some sort of early version of a system prototype.

Although predictive methodologies are still in use, more recent approaches to development have progressively become more adaptive to changing requirements. Application development has evolved into a more iterative and incremental process (ex.

RUP [JBR'99]). The idea was to minimize the time between gathering requirements and producing the first or the next software release, being it an intermediate prototype or a specific application component.

Some methodologies, like Rapid Application Development (RAD), presented by James Martin in 1991 [Martin'91], have set changing requirements as their stepping stone to development. RAD encouraged the rapid production of application prototypes in short successive development cycles, supported by CASE tools, as a way for the developer to validate and gain immediate feedback on customer's requirements.

The formal methodology as described by James Martin is no longer practiced, but its principles are still in use. Current Agile Software Development methodologies (ex. SCRUM [SchwaberBeedle'02], XP [BeckAndres'05]) share a lot of those principles by reducing the time between picking the next priority requirements and releasing the next software version to a minimum, and thus bringing developers and stakeholders closer together in the development process.

Although somehow lost in its original form RAD has now assumed a new broader meaning. Whenever software automation tools or frameworks are in place, the RAD acronym rises as the buzzword of choice which generally translates into speeding up the time from requirement or design changes to implementation results.

1.2 Development at OPT

OPT (Optimização e Planeamento de Transportes, SA) is the company providing the organizational context for this dissertation. Its mission is to provide excellence in innovative and optimized systems for transport planning, management and public information.

OPT is the joint result of two different sorts of expertise, one related to operational research techniques in the field of transportation and optimization of resources, and another dedicated to software development. The core product of the company is the GIST system, a client-server modular system which allows for public transport companies to plan their offer and manage their resources in an optimized way. Major companies in Portugal use this system in a daily basis to manage their vehicle fleets and drivers. There are other important products at OPT and the company is also very committed to several projects related to public information.

Another important project OPT is involved with is the development of a light version of the GIST system (GIST Light - Public Transport Planner). This version is intended for smaller public transport companies and for research purposes within the academic community. The idea is to provide a simple document based application that provides a useful decision support system for the management of vehicle and driver schedules.

Depending on the type of project OPT has different strategies for the development process. Basically, there is a more strict documentation oriented process following several standards that is applied to larger projects with several stakeholders, and there is another more agile milestone oriented process that is used for instance in smaller projects where requirements aren't clearly defined upfront, or long projects whose duration is an important factor for getting requirements outdated.

Although different development methodologies are used, there is a set of common aspects that these share:

- Even in larger projects some agility is always in place, in the sense that

requirements are rarely set up-front and development is always done in several iterations and oriented towards the next highest priority requirements.

- Extensive use of evolving prototypes for validating, finding new requirements, and demonstrating progress.
- Modelling is detached from implementation; no software automation tools are used.
- Resort to UML class diagrams in design phase as the top modelling artefact.
- Object oriented models like UML class diagrams are also used as the preferred mean to discuss conceptual issues.
- A huge effort of the development process is spent either on programming the same recurring patterns repeatedly or trying to put these patterns in a generic library that is used extensively throughout the project. These patterns extend from functional logic to user interface and persistence.
- The choice of which programming patterns to use, most of the times, could be easily inferred by analysing the conceptual model, along with some additional configuration detail.

1.3 Motivation and Goals

The aforementioned aspects of the development process at OPT have set the prelude to the urging need of a tool that would easily and rapidly translate the modelling effort involved in the conceptual design of applications into some form of usable "material" like a functional library or a prototype. This "material" could be used for testing or demonstration purposes and it would still play an important role as a design proofing tool. However, the real impact in productivity should be achieved by using it as the foundation backbone for the remaining development effort, by allowing it to integrate smoothly with the implementation in an evolving way.

In a nutshell, for the modelling effort to become more profitable and provide added value to each model, it should be able to answer some of the needs that arose from the development process at OPT. These needs extend from requirements and design issues to every aspect of the implementation process like functional logic, user interface and persistence:

Requirements

- Validating and gathering requirements within stakeholders through the use of rapid prototypes.

Design

- Testing the consistency of design models.
- Using models to discuss and verify the impact of design decisions.
- Base the implementation in design models.

Functional Logic

- Rapid transition from model to model-aware domain library.
- Attaching functionality to models by integration with implementation tools.

- Overcoming model semantic limitations.
- Running a model for testing purposes.

User Interface

- Raise intelligence level on current UI frameworks by making them model-aware.
- Automatic generation of model based user interface for prototyping.

Persistence

- Generating persistence schemas
- Automatic model based persistence.

The answer to these needs called upon the development of the framework in the scope of this thesis. It should be able to at least tackle some of the challenges that were being proposed. Being an inner development at OPT meant that, besides facilitating a better knowledge of its workings and use, there was an additional advantage that it could be tailored to fit company specific needs.

The "GIST Light" project described earlier, particularly a more limited pre-release version called "Bus Planner", finally triggered the will for this framework. The fact that it is a single user flat-file based application somehow limited the scope for the initial aim of the intended framework, reducing the risk for project dispersion.

Being a RAD framework that would rely on the description of entity Fields and allow the control of their changing Values, it was decided to name it "FV-RAD" (it seems all RAD related acronyms had been used up). It could stand as well for "Flat-file Version", "Fast Velocity", or “Framework Version", just take your pick.

Having decided on the needs and boundaries that would define the initial scope of this thesis, it was now time to have a clear understanding of what would be its main goals and constraints:

Goals

- To build a framework that allows for the integration of an application's conceptual model within its implementation, thus becoming model-aware.
- To demonstrate and test design models by rapidly producing executable prototypes.
- To allow for prototypes to evolve until a final release is reached, by progressively refining its functionality with the implementation tools (ex: code extensions).
- To spread the framework across all aspects of the implementation process: functional logic, user interface, and persistence.
- To apply this framework to a real project.

Constraints

- Models are based on a subset of UML class diagrams.
- Only single user flat-file based persistence should be supported.

1.4 Thesis Statement

Software conceptual models are currently used in various ways. They might be totally detached from the implementation and used solely for design planning purposes, or they might somehow integrate with the implementation throughout the development process. This gap between model and implementation is also reflected on the structure and level of detail provided by these models. In an environment with frequent evolving requirements, a high level of detachment generally imposes a low level of detail so that the effort on keeping these models up-to-date is reduced; highly detailed models would tend to limit model usage to an initial design baseline.

The bottom line is that a low level of interaction between model and implementation adds little value to each model. Shortening this gap and providing model usage and integration through all the development process, is one of the challenges we face today. Doing it in a way that smoothly integrates with the technology and tools provided by the implementation process of a specific organization, is another challenge that is faced in the scope of this thesis.

The statement of this thesis is that, by embedding the model in the implementation, through the use of a framework inspired on Adaptive-Object-Modelling techniques and supported by a simple configuration process, we are able not just to make the implementation model-aware but also to adjust and close model semantics to a particular implementation technology. The bridge is established between highly abstract constructs provided by models and low level control provided by specific implementation tools. The advantages are obvious; the model-implementation gap is shortened in a way most suitable to developer needs. Models will have a direct impact on application development results and the organization will benefit from their added value and use.

Also, by providing an initial "raw" implementation of the model, through the framework's interpretation of the model's domain, and by adding an intelligent User-Interface library that is model-aware and some type of persistence mechanism (ex: XML), all main aspects of an application spectrum should be covered, and the ability to provide a fully working prototype should be acquired. The application core will be centred on the execution of its domain model. Translating requirements into working prototypes will be effortless, and final project outcome will be reached through the progressive refinement of implementation details. This refinement process should extend model semantics and provide additional functionality by "filling the holes" where the framework lacks its grasp.

The framework hereby described is not intended to be a complete environment but rather a simple practical tool, suited and familiar to a particular development process, and inspired on premises that resemble the initial RAD goals established by James Martin.

1.5 Thesis Outline

The first chapter gives an introduction on RAD, modelling, and how modelling integrates the development process. It proceeds by putting these in the perspective of the hosting company and identifying the needs that originated this work. Finally the motivation and goals that led to this thesis are presented and concludes with the thesis statement.

Chapter 2 gives a state of the art analysis of modelling strategies and model oriented development. Special emphasis is put in generative software development and AOM. These approaches are finally classified and compared in the last section.

Chapters 3 and 4 present the framework (FV-RAD) developed by the author in the scope of this thesis. After an initial contextualization, with specific technical goals and limitations intended for the first release (chapter 3), main technical issues are described in detail for the full understanding of the framework's architecture.

Chapter 5 gives a practical approach to using the developed framework. Use case considerations are explained initially. Examples are presented in the scope of a simple demonstration and the "Bus Planner" project currently under development at OPT (modelling issues).

Chapter 6 presents final results and conclusions, and discusses the next steps for evolving the framework.

Finally, some references and appendixes are provided as support for the reader of this thesis.

2 Modelling and Development

Modelling is an integral part of almost every development process in use today. As methodologies evolve, models are getting closer to the problem space rather than imposing a specific solution. Future trends are becoming directed towards finding the best modelling languages and architectures for solving general purpose or specific domain oriented problems. It is thus important to situate models in the current development context and analyse how current approaches deal with the gap between highly abstract modelling languages and low level platform oriented implementation assets.

2.1 Modelling

2.1.1 The Need for Models

Design models play an important role in software development. Whether of a general purpose nature like UML based models [BRJ'05, RJB'05] or custom built to suit a particular software domain like DSLs [DKVCzarneckiEisenecker'00, '00], they capture system variability into design abstractions that are used as the baseline for the implementation process. They also provide a way of formalizing requirements into structural and behavioural constructs that define system concepts, functional logic, and constraints. Other important characteristics of software models are presented next:

- Models resume a reality or a solution to a problem.
- Models are able to define a conceptual plan (master plan).
- Models may translate design choices and direct the implementation of software.
- Models define a common language for discussing and understanding problems and solutions.
- Models are succinct, they don't have to draw the whole picture but rather synthesise the main structural and behavioural aspects of a system. Also, a small set of related modelling constructs has the ability to pass a lot of information

through their huge semantical power. In a rough way, models allow the definition of very much with very little; this particularly applies to graphical modelling.

- Models are independent from implementation technology. A decrease in abstraction implies an additional weight in complexity and detail as you get closer to specific implementation technology.
- Models for design purposes must be computational as they can be tested and simulated; this also means they must be syntactically and semantically consistent (unambiguous).

As methodologies evolved from more predictive to more adaptive, the importance of models, as a way to rapidly translate design into prototypes or into implementation was considerably more demanding. Stakeholders want to be able to see results from the early stages of the development process in order to validate their compliance to requirements, and developers want to continuously probe for costumer needs. The highly synthetic and semantical power of models supported by the right set of tools allows just for that to happen.

2.1.2 Metamodelling

Metamodels are models used for defining model structure. They are important in the context of the specification of the UML standard for modelling, which uses MOF (Meta Object Facility) as the meta-metamodel for the definition of the meta-models that give support to the UML specification [OMG'09]. Metamodelling can be seen as a multi-level structure where each level describes instances from the previous level. The OMG (Object Management Group) has 4 metalevels, M0 for final instances (objects), M1 for the models with classes describing the objects, M2 for the metamodels with classifiers describing the models, and finally M3 for the meta-metamodels that describe metamodels (see Figure 2.1) .

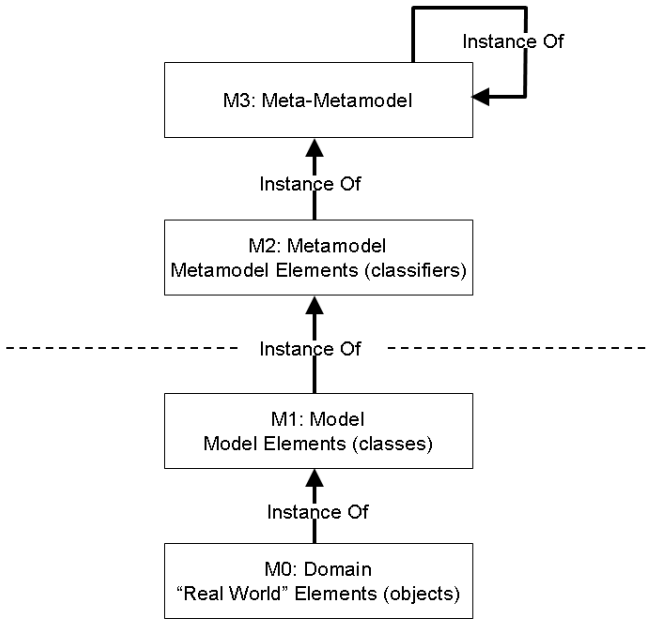


Figure 2.1 - The four metalevels of OMG

Metamodels are also used for the construction of Domain Specific Languages (DSLs), by describing the abstract syntax of such languages (graphical or textual). They will be used as the basis for model-validation, model-to-model and model-to-code transformations in the context of generative methodologies (see sections 2.4, 2.5 and 2.6). They are also used for the definition of tools and frameworks that are able to adapt to the respective domain (see section 2.7).

2.2 Software Reuse

Software reuse is about increasing the level of productivity in software development [ClementsNorthrop'02]. It's been quite some time since subroutines were the only way of software reuse. From then, successive evolutionary steps have raised the level of software productivity and progressively reduced the need to write code (see Figure 2.2), although still not enough to satisfy the market demand for more and higher quality software.

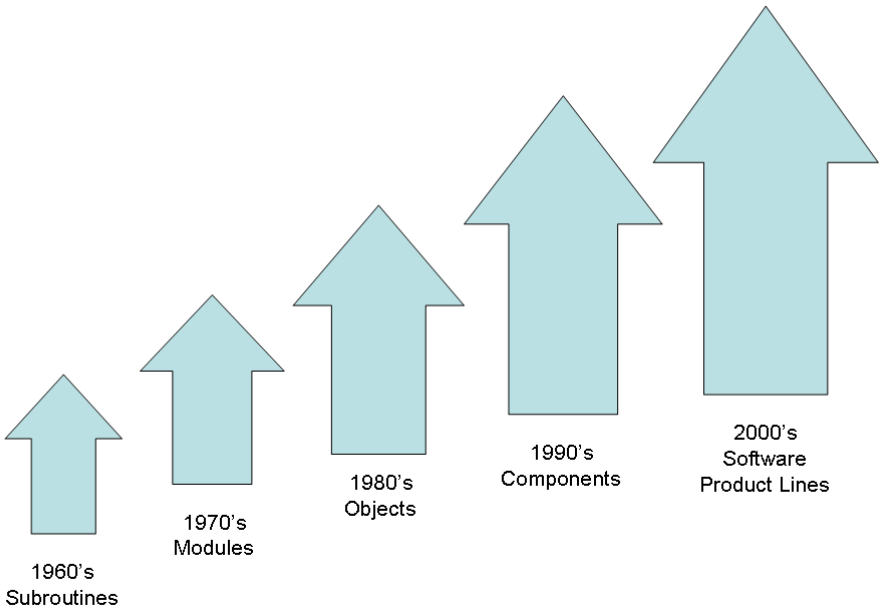


Figure 2.2 - Software reuse, from past to present

Object oriented programming [Meyer'97], component based development [SGM'03], object oriented frameworks [FayadSchmidt'97, Johnson'92, Lewis'95], and the study and classification of important design patterns [GoFFowler'03, '95] have all been important breakthroughs for software reuse. The combined use of these and other emerging technologies like aspect-oriented programming [Laddad'03], at different abstraction layers, and a clear shift towards a paradigm for design reuse, through modelling and development of software production lines, has led to the current state of the art in software reuse through generative software development methodologies [Czarnecki'04] (also see sections 2.4, 2.5 and 2.6).

Models have never been as important for software reuse as they are today. As the level of abstraction for software development raises, modelling artefacts like Domain Specific Languages (DSLs) provide the ideal mean of expressing these abstractions and for translating these into a reusable architecture. The emphasis is no longer on composing an architecture from general components and frameworks, but rather on generating an architecture from DSL based configurations, isolating the developer from the cross-cutting concerns that are part of the architecture's infrastructure.

Adaptive Object Modelling (AOM) techniques [YBJ'01] have also been an important part in software reuse by empowering the user/developer to make run-time changes to the application by editing models based on general purpose DSLs. These models are interpreted at run-time by specialized frameworks, allowing the application to easily adapt to new requirement changes without the need for extra coding or compilation (see section 2.7).

The market demand for more and higher quality software is still far from being fulfilled, but recent generative, adaptive technology trends and others open a new window for the future, where models and model oriented development will definitely play an important role.

2.3 Development with Models

In this section, a comparison is made between different model oriented strategies in development methodologies. This analysis is made from the perspective of dealing with the model-implementation gap and its impact on model usage.

2.3.1 Detached Modelling

In this strategy models are totally detached from the implementation.

This is still one of the most used model based development strategies. Models are particularly useful at the beginning of the development process in order to guide the implementation process and they are used as a reference there upon. Unless it is a critical system or a big project with few evolving requirements where a more detailed specification is needed, these models should be kept simple in order to illustrate main system functionality and to reduce the effort on keeping the models updated as requirements evolve.

2.3.2 Executable Modelling

This strategy is based in executable models that embed the implementation.

Some tools allow the definition of models for every aspect of the development process, from functional logic to user interface and persistence. These general purpose tools may even include some kind of high level programming language like OCL (Object Constraint Language) [RichtersGogolla'99] to detail model constraints or operations. Although these tools are considerably powerful, the problem is that they lack flexibility in low level control of technology. The conceptual and technological gap between existing modelling and implementation technologies has prevented good support for true integration between high level modelling and low level implementation constructs. Combining the power of a high level modelling and low level implementation technology into a single fully integrated development tool (no code

generation) is still a challenge to be overcome. An interesting attempt has been done by [RFBO'01] trying to devise an architecture for a UML virtual machine. There's also a trend on applying UML virtual machines for MDA [MellorBalcer'02].

Another important aspect is that these are general purpose *one size fits all* abstract modelling languages (as opposed to DSLs), not oriented to a specific domain, which means there will be a semantic gap between these models and the domain.

2.3.3 Design-Time Modelling

Roundtrip Engineering

This strategy tries to synchronize the models with the implementation.

This is typically achieved through code generation and reverse engineering techniques (roundtrip engineering). Unless there is a deep integration of modelling tools within the development environment and its libraries, the effort put on synchronizing implementation code with modelling constructs, particularly after initial code generation phases, may be discouraging. When the programmer starts adding additional code and manually changes the implementation, it will be difficult to decide whether this code should be reflected in the model or kept "hidden" within the implementation. Even small things like changing the name of an attribute or adding a parameter may have to be synchronized, adding an additional overhead to the development effort. Models may end up being too much detailed and their abstraction level reduced in order to comply to a specific development environment and programming language. CASE tools typically explore this kind of modelling orientation [KSSSZ'02] (which is probably also why their success has been quite disappointing).

Generative Development

This strategy generates the implementation from models. Manual written code is added but no reverse-engineering is allowed [Czarnecki'04].

Generative software development generates all infrastructure code from DSL based models. These are highly abstract modelling languages that try to match a particular domain in the problem space (see sections 2.4, 2.5 and 2.6). By being domain oriented and more focused on the problem rather than on the solution, they are isolated from the specific platform where the implementation is due, thus ensuring better independence from technology variation or evolution. This high degree of abstraction also means that reverse engineering is practically impossible, as it would impose a level of implementation based detail on models (from the solution space) that is contradictory to its goals.

Some tools may focus on full code generation, but the aim is to provide code generation for the entire domain architecture infrastructure and add code to fill the gaps where the models or the generator are unable to cope with.

Generative methodologies are also directed toward the implementation of software production lines for given software system families.

2.3.4 Run-Time Modelling

In this strategy the model is embedded in the implementation. The implementation is model aware, and directed by the interpretation of the model.

This scenario is a good trade-off between the high level abstraction of a model and low level control of implementation technology. The abstraction level of the model is not compromised because the model doesn't have to be aware of the implementation technology but rather the opposite. By embedding the model, the decision on how the implementation attaches to its structure and behaviour is left to the implementation itself. As such it opens the possibility for the rising of tools and frameworks that manage this integration process. These may go from simple user interface gadgets, to more complex entity life-cycle management frameworks with prototyping capabilities and full support for model semantics.

Adaptive Object Modelling [YBJ'01] (see section 2.7) provides an approach with an architectural style for this kind of methodology and the framework developed within this thesis follows some of its principles and inspiration.

2.4 Generative Programming

Generative Programming (GP) [Czarnecki'04], has been the inspiration behind some of the most advanced approaches to modelling and development in use today like Model-Driven Software Development and Software Factories which will be presented later (sections 2.5 and 2.6).

It became popular mainly through Krzysztof Czarnecki's and Ulrich Eisenecker's book on *Generative Programming* [CzarneckiEisenecker'00], who defined GP as follows:

Generative Programming is a software engineering paradigm based on modeling software system families such that, given a particular requirements specification, a highly customized and optimized intermediate or end-product can be automatically created on demand from elementary, reusable implementation components by means of configuration knowledge.

The main focus in GP is software reuse. It advocates that traditional forms of reuse like Object Oriented Programming, Frameworks, Components and even Design Patterns, have been unable *per se* to deliver the promise of software reuse. A shift of paradigm is needed towards modelling and developing software system families rather than individual systems. GP is a system-family approach (also known as product-line engineering) which exploits the commonalities among systems of a given problem domain and manages its variabilities through a systematic approach. The creation of a system-family member is automatically generated from system specifications that are able to express those variabilities in one or more textual or graphical domain-specific languages (DSLs). The emphasis is on the configuration of the problem space and its automated transformation to the solution space through the use of domain-oriented modelling languages, rather than developing and composing individual components into a final application from the start (see Figure 2.3).

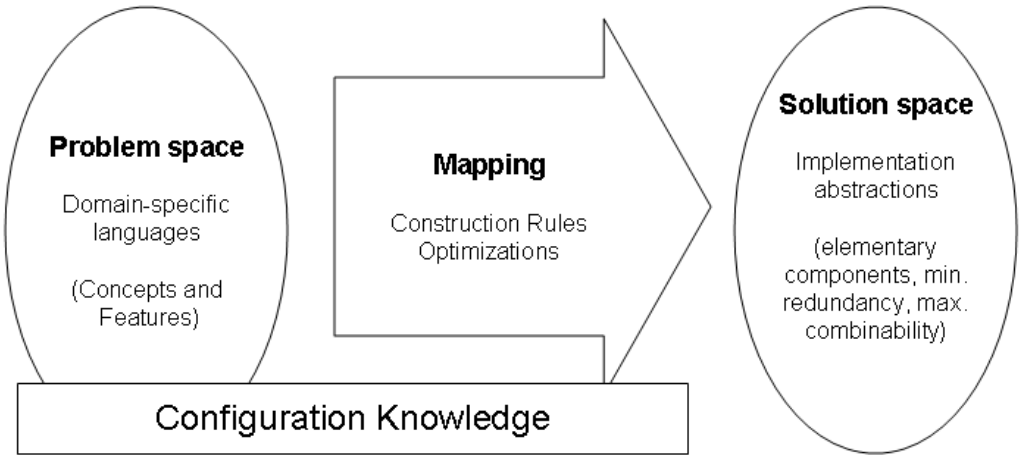


Figure 2.3 - Mapping between problem space and solution space (adapted from [Czarnecki'04])

Typical GP systems separate development into two processes, *domain engineering* and *application engineering*. Domain engineers define the structure of the DSLs needed to tackle a particular domain, and produce the necessary reusable assets (components, generators, analysis and design models, user documentation, etc.) that will be used by application engineers to transform their DSL specifications into implementation abstractions like elementary components connected through some glue generated code.

The transformation in Figure 2.3 can be viewed recursively. Someone's problem space may be someone else's solution space, thus several transformations may be chained together to produce a final solution. At the same time several problem related spaces may map into the same solution space (ex: different aspects of a problem represented using different DSLs). Also the same problem space may produce results in several solution spaces. These related spaces and transformations end up producing a graph that corresponds to the idea of a *network of domains* [Neighbors'80] where the solution space of a domain exposes a DSL that is implemented by transformations to other DSLs in other domain implementations.

The mapping from problem to solution space may also benefit from an *aspect-oriented* approach [Laddad'03] [WebAOSD] that will allow for the composition of components in the solution space into well encapsulated aspect based modules. This isolates the application developer from the cross-cutting concerns that will be part of the domain infrastructure.

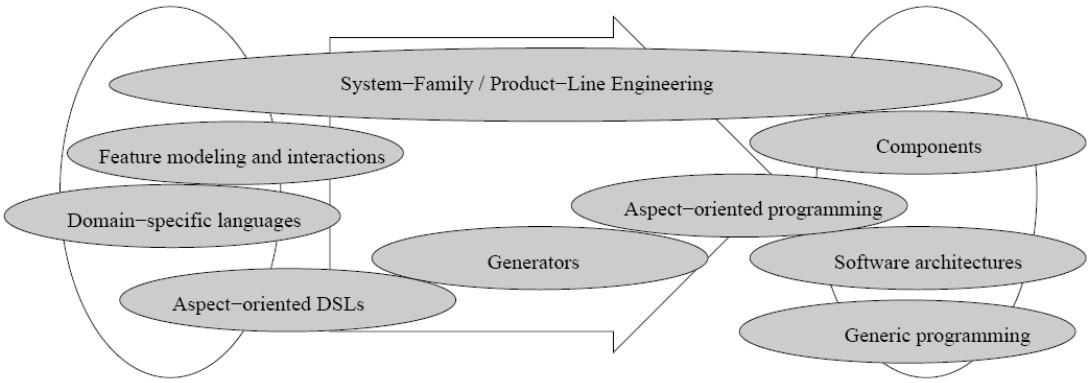


Figure 2.4 - Generative programming and related fields (extracted from [Czarnecki'04])

Figure 2.4 shows a perspective on how GP's related fields intersect with the problem-mapping-solution spaces. For the current status on GP you may consult Krzysztof's web site on [WebCzarneckiHelsen].

2.5 Model-Driven Software Development

Model-Driven Software Development (MDSD) [StahlVölter'06], also known as Model-Driven Development (MDD) and Model-Driven Engineering (MDE), is a horizontal approach to modelling based on Domain Specific Languages (DSLs), model transformations and generative techniques. It has a strong orientation towards domain related aspects of software development rather than programming or computational ones. The emphasis is on the engineering principles that lead to the enhancement of development efficiency, quality, maintainability and reusability. This is achieved through the automation of all redundant artefacts that repeatedly populate and define an application's infrastructure. Redundancy is delegated to a generative software architecture that knows all the construction principles and programming models from the various layers and aspects of a specific domain and is able to compose and assemble a domain related application from its building blocks. Infrastructure code is generated from formal models using one or more transformation steps (model-to-model or model-to-code, see Figure 2.5). Cross-cutting implementation aspects will be centred in one place, for example in the transformation rules, just like infrastructure bugs. This *separation of concerns* [Laddad'03] promises better software maintainability by avoiding redundancy and by isolating technological changes. Additional application domain specific code is then added through protected code areas or using well known design patterns [Frankel'03].

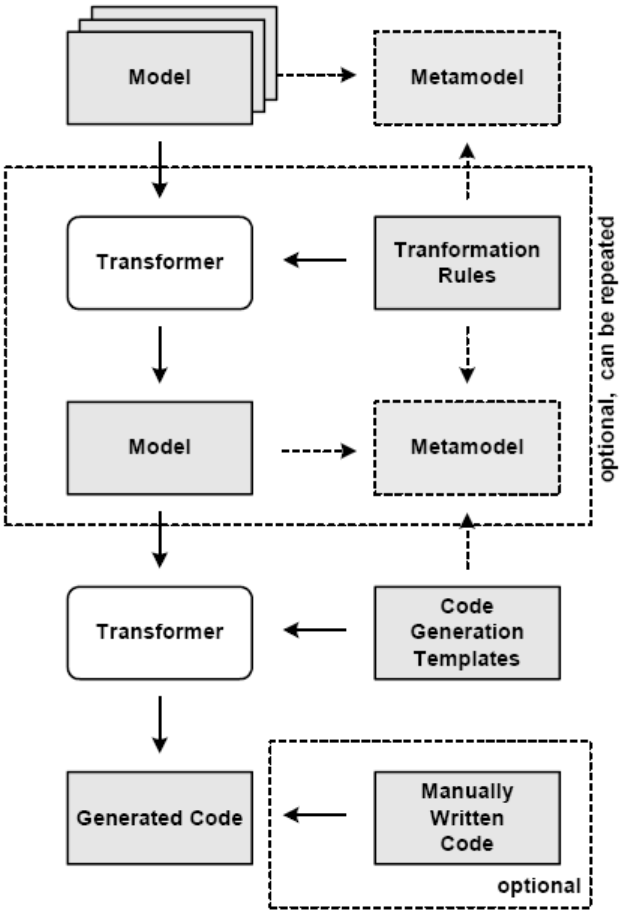


Figure 2.5 - MDSD, from model to code (extracted from [WebVölter])

Complexity is managed through highly abstract, problem oriented, modelling languages (DSLs) for the programming and configuration of various system aspects. This means that modelling artefacts will be focused more in the problem rather than the solution and are isolated as possible from its platform implementation. This level of abstraction imposes a forward only generative process, since the semantic gap between models and implementation code is just too high to allow reverse engineering.

MDSD clearly separates the development of the domain architecture infrastructure from the development of the domain related application. This separation defines the assignment of team roles as domain architects and application developers within a MDSD project.

Figure 2.6 presents a classified overview of the core concepts involved in MDSD. These concepts are centred around three important aspects: the DSLs that define a specific domain in the problem space for a given software family, the models built on those DSLs by application developers, and the transformation between these models and the target platform. These aspects will be further detailed in the next subsections.

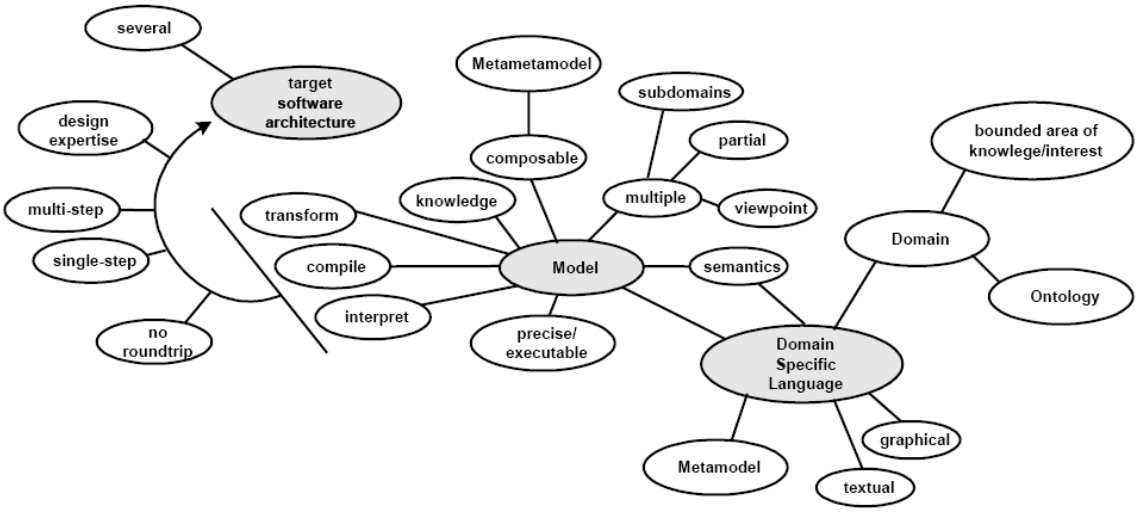


Figure 2.6 - MDSD Core Concepts (extracted from [WebVölter])

2.5.1 Domain Architecture

Building a domain architecture [Evans'04] demands a deep knowledge of a particular domain and may be figured as a two step process. The first step should be the domain analysis and manual generation (modelling and coding) of a reference model/implementation where all best practices and development patterns have been put to use, and where all required frameworks and supporting technologies (platform) have been set. The second step should derive the domain architecture from this reference model/implementation, not just in terms of the meta-models and domain specific languages that define the abstract and concrete syntax and semantics of the reference domain models, but also the transformation process and rules that will eventually result in the static code that defines the domain infrastructure on which application developers will build upon.

The resulting artefacts will be the meta-models and DSLs that will comprise the domain related aspects of that software system family, the templates and model transformations that will direct the generative process, and the support frameworks and material that will be the base of the semantically rich platform on which applications are built. These artefacts are not end pieces of a first phase waterfall based development process but rather a continuous work in progress from domain architects that, just like their application developer counter-parts, should have an iterative and incremental approach to implementing and improving the architecture.

Once architectures, models, and transformations have been defined, they can be used in the sense of a software production line for the production of diverse software system families. This is the manufacturing orientation of MDSD. As we can see, the focus is more directed towards finding the right development methodology for a given domain related problem through a specific platform rather than implementing a generic development environment as a *one for all* process.

2.5.2 Application Development

In MDSD, application developers are released from the tedious task of having to program the same constructs over and over again whenever they build a new domain

related application or whenever they incrementally add a new feature to it. The domain architecture is devised by architects and it will formalize and support that domain. Application developers may use the reference model/implementation as an orientation guide, and may concentrate on what they do best, designing the application by modelling it using the DSLs defined in the domain architecture, and coding the remaining domain specific logic (business logic) that was left out of the static generation process. Figure 2.7 shows a simple generative architecture used by application developers to devise a solution starting from a model written in a particular DSL and integrating manually written code to fill application specific aspects left out of the infrastructure. The resulting artefacts will be the DSL models, generated static code, and extended domain logic code that could not be expressed using the DSL.

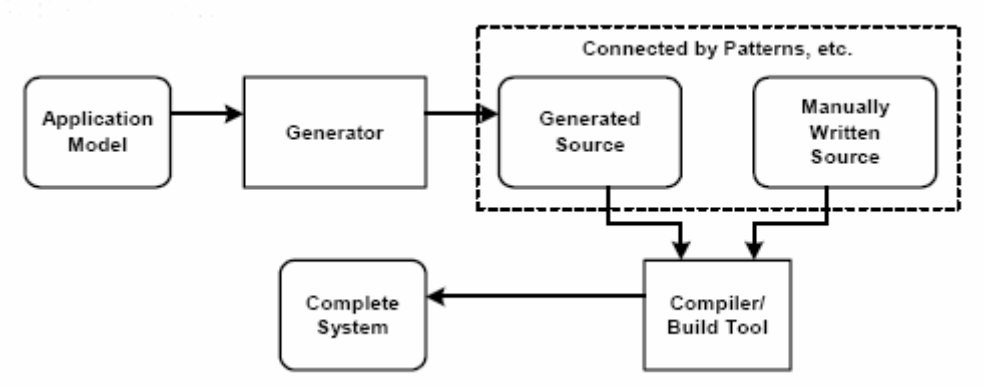


Figure 2.7 - A generative architecture (extracted from [WebVölter])

2.5.3 Model Driven Architecture

Model-Driven Architecture (MDA) [Frankel'03] is a standardization initiative from the OMG (Object Management Group) with respect to model-driven development. It does not cover the entire MDSD spectrum but may be regarded as a specialization of MDSD (see Figure 2.8). The primary motivations were interoperability (through standardization) and portability (platform independence) of software system.

MDA uses MOF (Meta Object Facility) as the meta-metamodel, for the definition of metamodels. As expected from the OMG, UML plays a central role in MDA which recommends the use of UML profiles [FuentesValecillo'04] as a concrete syntax for a DSL. OMG has even made some adaptations in the context of UML 2.0 to ensure it all fits well. OCL expressions are used to specify static semantics.

A domain model in MDA can be independent from platform (PIM - Platform Independent Model) or platform specific (PSM - Platform Specific Model). Transformations may occur between models (recommended) or directly from PIM-to-code. Platforms are also described via a metamodel. PDMs (Platform description Models) are used in order to enable transformation to platform specific models. OMG's QVT (Query/View/Transformation) is expected to be the standard used for model-to-model transformations by defining the conversion process between source and target metamodels.

Another objective of many MDA representatives is to provide a foundation for executable UML models [MellorBalcer'02], whether they are interpreted by a UML virtual machine or completely compiled to a target platform through model transformations. By using general purpose models to be directly executed on a lower-

level platform we are in fact raising the abstraction level of a programming language based on models, meaning there will be a semantic gap between this language and a specific domain.

Basically, MDA instantiates MDSD with a set of standards that clearly define the mapping of a model to an existing platform.

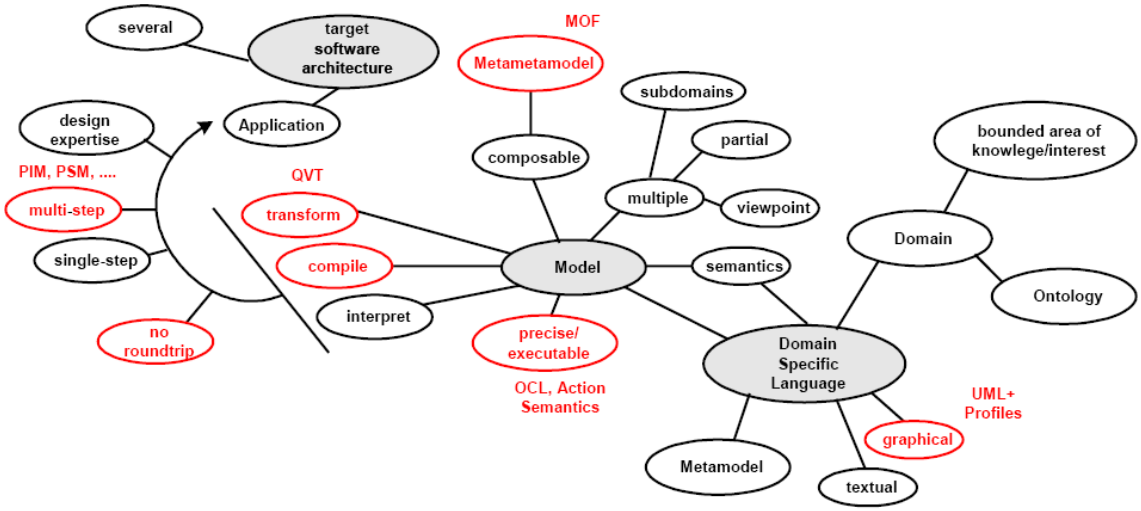


Figure 2.8 - MDA specialization on MDSD (extracted from [WebVölter])

2.5.4 Architecture Centric MDSD

Architecture centric MDSD (AC-MDSD) is a specialization of MDSD that conceptually overlaps with MDA. The aim is to provide an architecture oriented domain (ex: architecture for client-server business applications) by generating the architecture infrastructure for that domain from specialized DSLs called *design languages*. These languages are usually based on UML profiles and contain architectural concepts that are as abstract as possible.

The generation process will typically create an implementation framework that contains the architectural infrastructure code (the *skeleton*). This is usually achieved through single-step model-to-code transformations based on templates. Manually written code is then added to the implementation in protected areas or through suitable design patterns to complete a finished product (application).

Design languages, templates and target platform will constitute the generative architecture for supporting a given software system family.

2.6 Software Factories

The concept of “software factories” was introduced by Microsoft [GreenfieldShort'03] [GreenfieldShort'04] to define a broad approach whose final intent is the industrialization of software development. This intent should provide the means through which application assembly becomes more cost effective through systematic reuse of development assets and processes. Microsoft’s vision encompasses the

establishment of software supply chains focusing on the mass customization of software products.

By looking at the complete product-line engineering process, sometimes referred as “doing product lines the Microsoft way”, software factories are much wider in scope than MDSD. In fact, model-driven development is one of the main cornerstones on which software factories rely and they share much of its concepts and techniques. The convergence of software product lines, component-based development and model-driven development, and the integration of these into a cohesive approach that supports new IDE oriented tools and practices are the key ideas that thrive from the innovation axis of software factories.

As in MDSD [StahlVölter'06], software factories have two essential roles in the development process, one more directed towards the product line development that culminates in the production of a software factory, and another that uses the software factory for the development of a software product or product family.

2.6.1 Product Line Development

A software product line separates the commonalities and known forms of variation of a specific product family in order to automate their development [ClementsNorthrop'02, CzarneckiEisenecker'00, Parnas'76].

The product line developer will start by defining a set of DSLs for that product family. A simple factory could be based on a framework that addresses a specific domain, and the DSL would reflect the variability points in the framework to be filled through code generation. However, it is not always possible to build a framework for the implementation of a highly abstract DSL. In that case, progressive transformations to less abstract models may be needed before producing the executables. When models stack like this it becomes useful to categorize them as a layered grid. That is the next step in the product line development.

The layered grid for categorizing models has columns to represent specific concerns like presentation, business, persistence, deployment, etc. The rows represent decreasing levels of abstraction like conceptual, logical and implementation layer. Each cell will represent a viewpoint from which software can be specified (see Figure 2.9).

By positioning the DSLs within the grid and defining the mappings between the cells where partial or full automation is supported, a graph of viewpoints is produced that will describe the set of specifications and transformations needed to produce a software product. This graph is called a “software schema”. Figure 2.10 presents a simple software schema instantiating the viewpoints for the layered grid in Figure 2.9 for the production of web based business applications.

Domain Specific Languages	***Business***	***Information***	***Application***	***Technology***
Conceptual	▪Use cases and scenarios ▪Business Goals and Objectives	▪Business Entities and Relationships	▪Business Processes ▪Service factoring	▪Service distribution ▪"Abilities" strategy
Logical	▪Workflow models ▪Role Definitions	▪Message Schemas and document specifications	▪Service Interactions ▪Service definitions ▪Object models	▪Logical Server types ▪Service Mappings
Implementation	▪Process specification	▪DB schemas ▪Data access strategy	▪Detailed design ▪Technology dependent design	▪Physical Servers ▪Software Installed ▪Network layout

Figure 2.9 - A layered grid with different viewpoints for categorizing models (extracted from [GreenfieldShort'03])

After the software schema is defined, production assets must be built, like editing tools and automation tools for transforming models, and processes used for describing the use of implementation assets. All these assets will be used by product developers to implement product family members, and will be collected into an artefact called a "software template".

A software factory is finally reached when a software template is plugged into an existing IDE (like Visual Studio), all assets will be integrated as an automated product line where software product customization and assembly may take its place.

Software factories may also be used to produce other software templates that will integrate other software factories of more specialized family members. This opens the way for the formation of automated supply chains for full customization of software family members.

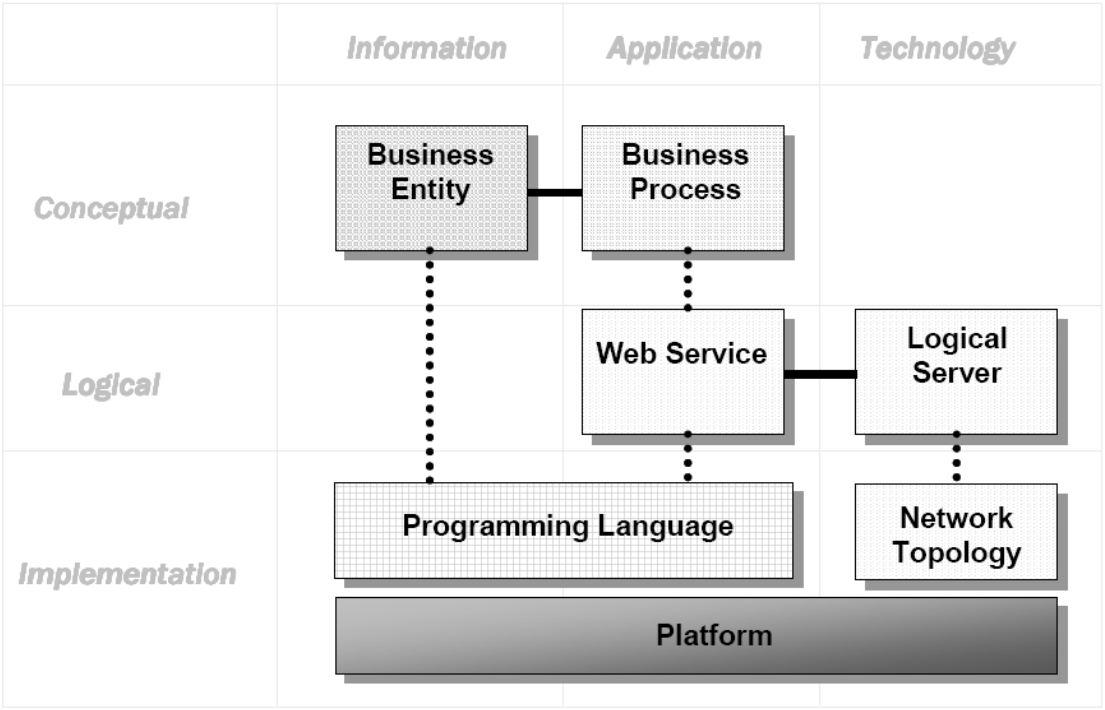


Figure 2.10 - A Software Schema (extracted from [GreenfieldShort'03])

2.6.2 Product Development

By using a software factory (see Figure 2.11), product developers will be provided with all the necessary editors, tools, and specifications to rapidly assemble family members. After configuring the software factory appropriately, they will build DSL based models for each viewpoint within the "software schema" and there will be tools for translating those into lower abstraction models or into executables. Final results will be reached through progressive refinement of the models and through framework completion of specific member details, until all the software schema is fully populated on every existent viewpoint. At times, a bottom up approach may be used, by generating the necessary test components upfront that will be used for testing the various pieces of the working product as development progresses.

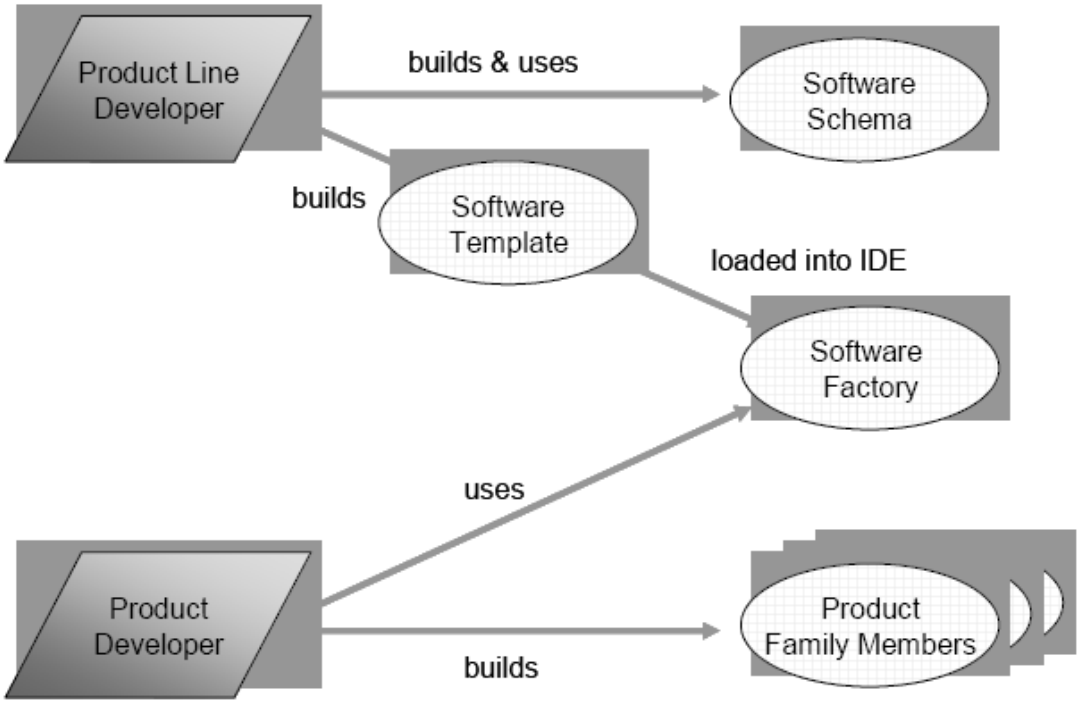


Figure 2.11 - Overview of a Software Factory (extracted from [GreenfieldShort'03])

2.7 Adaptive Object Modelling

Some problem domains are characterized by frequent changes in requirements or by the constant need from users to configure and extend the resulting application. These problems demand for a highly flexible system that is able to dynamically adapt to new requirements, without the need for programmers to keep changing the code and building new versions of the system. A recurring architectural style for dealing with this consists of persisting the application domain as metadata outside the application code. This data may be a description of classes, attributes and relationships, as well as business rules for the validation of constraints and for performing operations. The application is then responsible for reading and interpreting the metadata at runtime and for translating it into the structural and behavioural logic that will drive its execution. This kind of system has been called an Adaptive Object Model (AOM) architecture [YBJ'01], as it allows for the domain model to be changed at runtime with immediate effect on the application behaviour that will rapidly adapt to the new business requirements. AOM also leads to the definition of a domain-specific language (DSL), this is the modelling language to be used by domain experts for describing entities, which needs to be interpreted by the system.

2.7.1 AOM Design Patterns

An Adaptive Object Model also defines a pattern for a recurrent object model structure used by typical run-time modelling architectures for adapting the application to domain changes in metadata (see Figure 2.12).

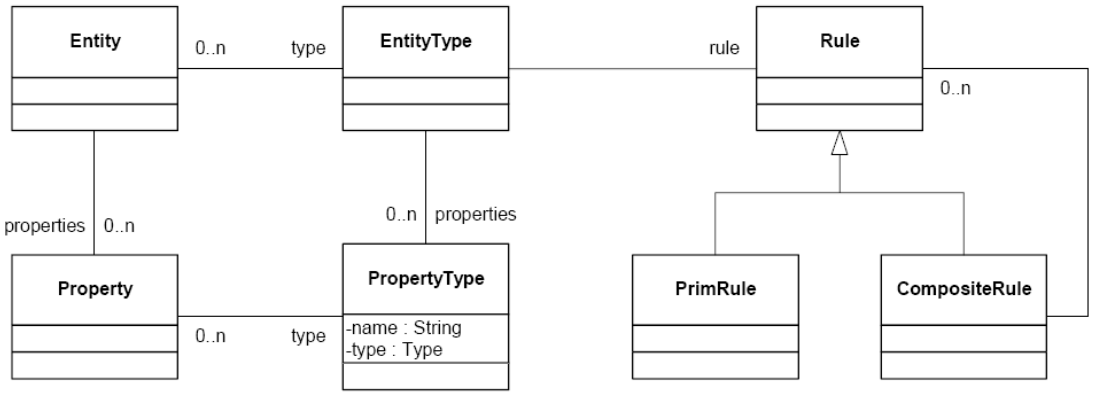


Figure 2.12 - AOM Common Structure (extracted from [YBJ'01])

This meta-model is based on a set of smaller design patterns, and will be responsible for loading the metadata, interpreting it, and changing the application behaviour and integrity rules, accordingly.

The *TypeObject* pattern [JohnsonWoolf'97] is used to decouple instances (objects) from their classes (types) so that those classes may be implemented as instances. It allows for classes to be created dynamically at run-time without the need for recompilation. This pattern is used in Figure 2.12 to separate an Entity from its EntityType and a Property from its PropertyType .

Entities have attributes which are implemented through the *Property* pattern [JosephYoder'98]. This pattern enables individual objects to augment their state by providing mechanisms for accessing, altering, adding, and removing properties or attributes at run-time. This can be done using a dictionary, vector or lookup table. Each property within a given entity will refer to its type and hold a particular value for that type.

Associating Properties to Entities at each abstraction level (instances and types) by combining the *TypeObject* and *Property* patterns forms a square shaped pattern like the one shown on the left side of the picture. This pattern, called *TypeSquare*, is a very common theme in many AOM architectures. It shows that an EntityType defines a set of Property Types, one for each Property of the Entities assigned to that EntityType.

The patterns presented till now are more directed towards a structural description of the domain, but the behavioural aspect of AOM is also a very important issue. The *Strategy* pattern [GoF'95] is used to define the behaviour of Entity Types. Basically, a *Strategy* is an object that represents an algorithm. Strategies are represented in the model as *RuleObjects* [Arsanjani'01]. These Rules may be used for validating purposes by enforcing constraints or for implementing operations on Entity methods. This pattern might also be used to validate Properties through their PropertyType. A Rule may be a simple primitive rule (PrimRule) or may be a composition of other rules (CompositeRule). Rules can be built up at run-time to represent a particular workflow process or a validation procedure. Lookup tables, grammar-oriented approaches [Arsanjani'01], workflow architectures [Manolescu'00], or other approaches may be used for defining rules.

Relationships, also known as Associations or Accountabilities, are properties that refer to other entities. These could be implemented by deriving the Property class into Attribute and Association sub-classes. However, Entity-Relationship modelling in

AOM usually separates attributes from relationships. A way to do this is to use the *Property* pattern twice, one for simple attributes and other for associations. Associations (AccountabilityType) would then refer to the Entity Types involved on the relationship.

Other important design patterns for building adaptable systems, used in conjunction with the above, are *Composer*, *Interpreter* and *Builder* [GoF'95]. *Composer* is used for building dynamic tree like structures for types and rules while *Interpreter* and *Builder* are used for building the structures from the metadata and for their run-time interpretation.

2.7.2 Extended Architecture

Figure 2.13 shows an extended version of the AOM architecture adapted from the AOM site [WebAOM].

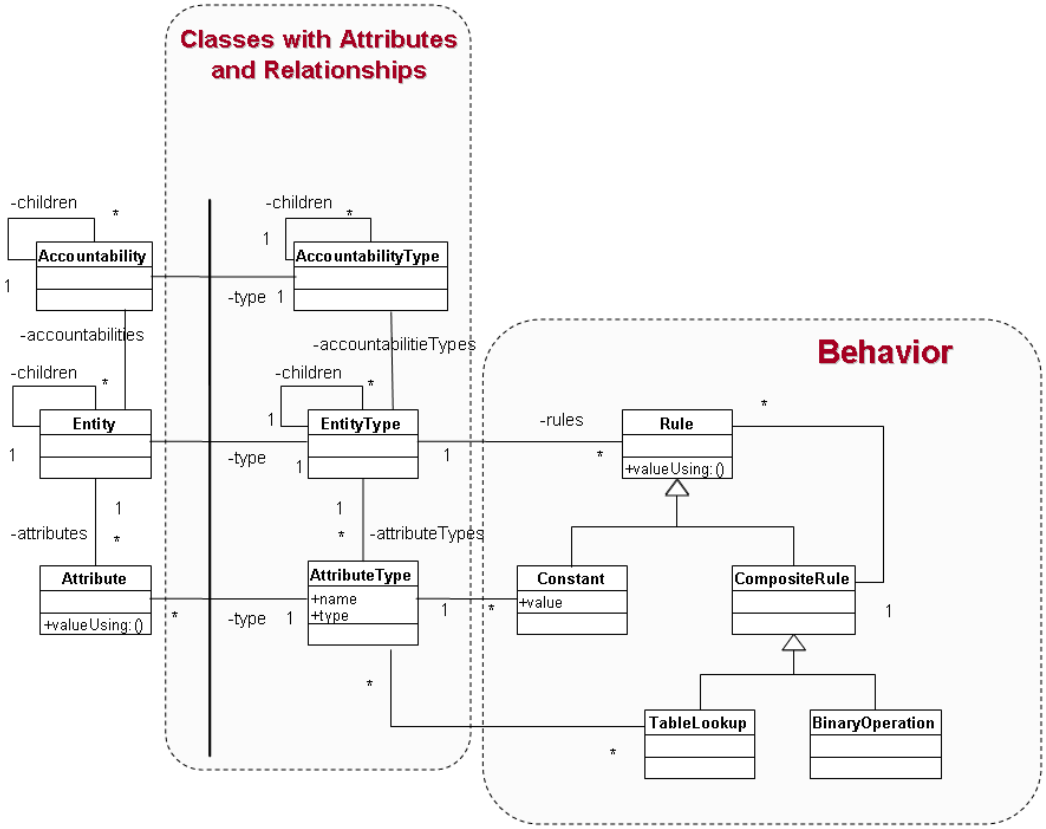


Figure 2.13 - AOM Extended Architecture (adapted from [WebAOM])

The right side, related to information that is persisted in the metadata store, highlights the structural (classes, attributes and relationships) and behavioural aspects that define the *Knowledge level* of the system with available Types and Rules. The *Operational level* (at the left) represents all instances assigned to those Types and on which the Rules are to be applied. This level is related to application data that is typically persisted in a specific domain database.

The above architecture is still a general reference for an AOM architecture from which new concepts may build upon. A new architecture could for instance be able to support component modelling where each component would aggregate some classes from a generic domain to be reused in similar applications [CDLM'05].

2.7.3 Developing AOM applications

Developing AOM applications involves several activities:

- Defining the business entities, their properties, rules and relationships. This is where the domain experts take an important role.
- Developing an engine for instantiating and manipulating those entities. This activity typically implies building a framework for reading and interpreting at run-time the metadata that was defined in the previous activity. This is one of the more important and complex activities in this process. However the difficult part is doing it for the first time. After that, the acquaintance with the design patterns is established, and it is just about reusing the same architecture. This framework may also include other aspects of the dynamic adaptation to requirements like User Interface automation. An AOM always involves the development of some kind of framework. The alternative is to use an existing one, if it exists.
- Developing tools for creating, editing and storing the metadata descriptions that will be loaded an interpreted in run-time.

Figure 2.14 presents a typical architecture for an AOM application. Metadata is stored in XML files. These files are parsed and interpreted at run-time by using the *Interpreter* and *Builder* patterns mentioned earlier. Metadata is then structured for a specific component responsible for instantiating and manipulating the domain objects through their type descriptions (entity types). These objects (entities) may then be persisted to a database.

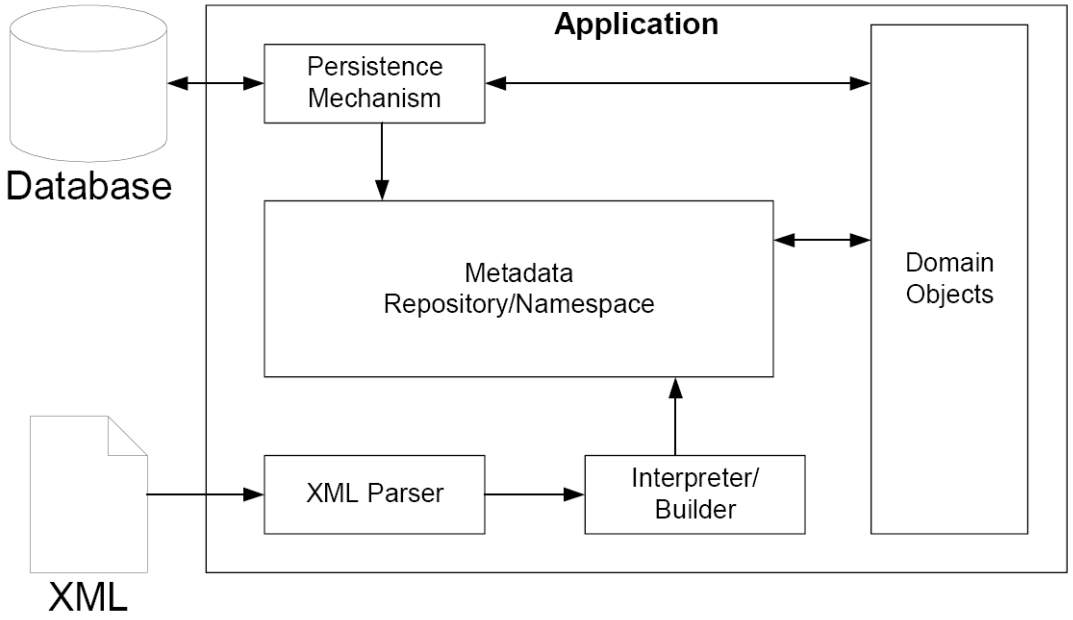


Figure 2.14 - AOM Application (extracted from [YBJ'01]

2.7.4 Advantages of AOM

The main advantage of AOM is ease of change. Changes in business requirements may be put to work immediately by editing the metadata, probably by domain experts, without the need for programmers to change application code.

Also, AOM projects will be smaller in terms of the number of classes that experts have to maintain. Classes that would normally be encoded in the application program are now encoded in a database. General concerns for "running" these classes will be embedded in the framework.

Another advantage is shortening the gap between domain experts and developers. Domain experts can now take a more active role on the definition of the application structure and may work closer to developers to ensure the application complies with the requirements.

As a direct result from the above mentioned factors, the time to market an application can also be reduced. Developers' main concern is to ensure that the framework is able to deal with the different meta-types, properties and rules for that domain. After that, it is just a question of completing the domain structure.

2.7.5 Disadvantages of AOM

The main disadvantage of AOM systems is the complexity involved in their conception. Building the metadata interpretation engine, and understanding the metamodel and its inner workings is not an easy task. Programmers are not used to having classes defined in the database, outside the application code. The initial start-up cost, for setting up this framework, is higher than usual. Also, support tools and GUIs are required for the definition of the DSL and for storing the metadata.

Another disadvantage is poor performance. Interpreting the metadata is not as fast as embedding the classes in code for compilation and binary execution. The behavioural aspect of AOM with more or less complex structures for representing constraints and operations poses a considerable overhead on execution time. However, this lack of speed is not considered as important by AOM's authors as the lack of understanding mentioned earlier.

2.8 Comparison on Model Oriented Approaches

After going through some of the current modelling strategies in several development approaches it is now time for some general conclusions. Table 2.1 presents an overview of the different approaches for model oriented development. Column description is the following:

- Development approach: name of the model oriented approach for development.
- Model Abstraction: the level of abstraction typically supported by models through that approach.
- Model Integration: how models integrate with that development strategy.
- Developer Threads: which roles are imposed on the development process to assemble a final product (application).
- Methodologies: methodologies that currently support that approach.

Table 2.1 - Comparing Model Oriented Approaches

Development Approach	Model Abstraction	Model Integration	Developer Threads	Methodologies
Detached Modelling	High	-	Application developer	Traditional development
Executable Modelling	High (general purpose)	Model aware	Application developer	Executable UML (MDA), UML virtual machines
Roundtrip Engineering	Low	Model-to-code. Code-to-model (reverse eng.)	Application developer	CASE tools
Generative Development	Very High (DSLs)	Model-to-model, Model-to-code (reverse eng.)	Domain architecture developer (product line), Application developer	GP, MDSD, Software factories
Run-time Modelling	High	Model aware	Framework developer, Domain expert	AOM

3 The FV-RAD Framework

After introducing the motivation and goals that led to this project (Chapter 1) and a brief analysis on the current state of the art in model oriented development (Chapter 2), it is now time to present and contextualize the framework that was developed in the scope of this thesis.

3.1 Introduction

Application development is typically structured around three important issues (see Figure 3.1):

- **Application Logic**. For executing the application domain in compliance with the established UI and Persistence mechanism. This also defines the platform environment on which the application is implemented. Currently the main development platforms are ".Net" (with support for different language flavours) or Java based (ex: J2EE). The logic will typically have a separate component for the Domain, UI and Persistence aspects of the application.
- **User Interface (UI)**. For allowing the users to interact with the application, enter input data and obtain required outputs. It might be a simple console based interface, a desktop graphical interface, a complex web oriented interface, or another type of user interface.
- **Persistence mechanism**. For keeping important data stored for use and persisted through different application sessions. It might be a relational/transactional database like ORACLE or SQL Server, an object-relational framework like Hibernate or OpenAccess, a simple file based "load/save" mechanism, or other.

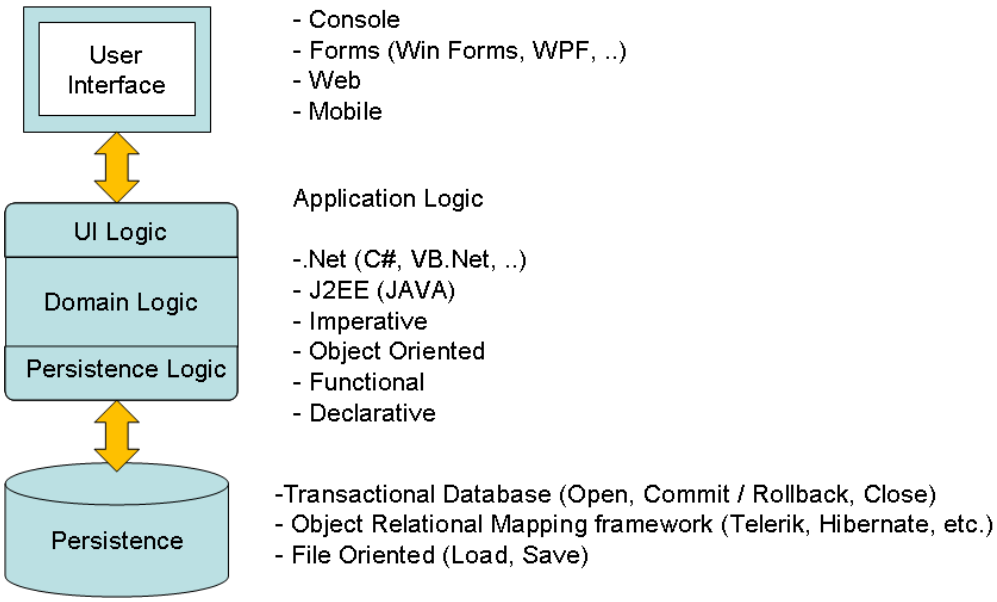


Figure 3.1 - Typical application structure

Models play an important role in the development process (see section 2.1). In a way they act as the Master Plan that directs the implementation process (see Figure 3.2). As so, if a model is complete enough, we should be able to obtain an implementation, or at least a running prototype based on its definition.

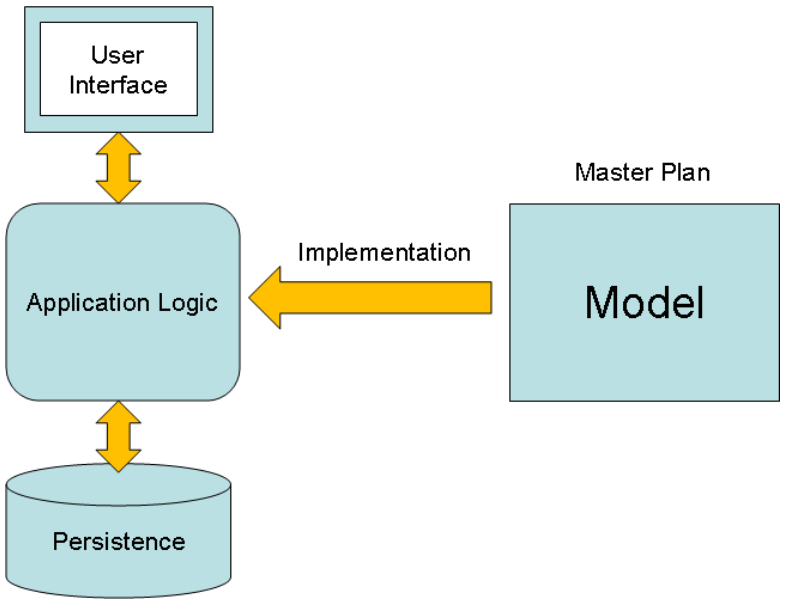


Figure 3.2 - The importance of models

It would be interesting to have a tool that would be able, for a given model and target platform, to produce an implementation or a skeleton that could be extended with some additional logic (optional) to make it fully functional. We could call that tool from an OO language with statements like the following:

```
Implementation = UserTools.BuildApplication(
    Model,
    TargetPlatform {LogicType, UIType, PersistenceType}
) + [LogicExtensions];
```

Generative methodologies (see Chapter 2) try to accomplish that by generating all the application code for a given software system family based on a highly abstract domain oriented model, to which some manually written code (logic extensions) may be added for producing the final application. Although the models should be platform independent (based on DSLs), the domain architecture is typically generated with a particular platform in mind:

```
Implementation = UserTools.BuildAppForDomainAndPlatform(
    Model
) + [CodeExtensions];
```

In an environment where requirements are constantly changing and model experimentation is considered an important asset (ex: interaction with stakeholders), it would be interesting to be able to run the application directly from the model without the need to setup a development environment or having to wait for final compilation. Logic extensions would be supplied in binary format (libraries). The logic platform would have to be established, as the tool itself would be built around it:

```
UserTools.RunApplication(
    Model,
    UIType, PersistenceType, [LibraryExtensions]
);
```

The run-time environment provided by the FV-RAD framework that was implemented in the scope of this thesis is based on this approach. General goals were described in section 1.3, and section 3.4 details the technical goals behind the development of this framework.

In order to simplify the development of an initial version, the UI has been targeted at Windows Forms while Persistence has been targeted at XML based files:

```
UserTools.RunWinFormsXMLBasedApplication(
    Model,
    [LibraryExtensions]
);
```

3.2 AOM versus FV-RAD

FV-RAD is a run-time modelling framework that fits nicely with the AOM approach described in section 2.7 which has also been a source of inspiration for its development. They both have a metadata based infrastructure which defines a model that is interpreted at run-time, and they both share some of the patterns used in the design of their metamodels like the *TypeObject*, *Property* and *TypeSquare* patterns. There are however some main differences or variations from AOM's privileged architecture:

- FV-RAD's metadata is more oriented towards structure rather than behaviour. This doesn't mean that patterns like *Strategy* couldn't be used for rules on operations and constraints. But in this implementation, behavioural aspects are delegated towards code extensions that define the operations on entities and the constraints on values, entities and domain.
- FV-RAD shortens the distance between model and implementation (model-implementation gap) by embedding associations in fields, rather than having a general *Accountability* type to define the associations separately from the properties that characterize the entities (which AOM privileges). By sharing associations with fields, the semantic gap between the model and the implementation technology (objects using fields to reference other objects) is shortened which facilitates the interpretation process. However, it is still possible to get the inverse field from the other side of the association, although inverse field synchronization is not yet implemented.
- Fields in FV-RAD benefit from the extension mechanism which means that there might not be a state for that field but, instead, its value is obtained through a calculation process. Also, by setting a value to a field we might be changing the state of several other fields through some procedure. This is similar to Properties in ".Net".
- FV-RAD is focused in modelling a "full domain", not just a segment of a domain. The concept of a *DomainWorld*, which is an instance of a *DomainModel*, has been added to fill this premise. DomainWorlds manage all their internal state, including the state of their entities. Any changes to a *World* may be verified and cancelled (like an object oriented transaction). Also, some mechanisms are provided for automatic entity life-cycle management (reference counts).

3.3 Modelling Artefacts

There are currently several modelling artefacts available. These may go from general purpose modelling languages like UML to domain specific languages (DSLs) like the ones used in generative methodologies. FV-RAD has adapted a variation on UML class-association diagrams as its modelling language. The reasons behind this choice are the following:

- **General purpose**. Being general purpose oriented, the choice of a widely used modelling standard like UML became obvious.

- **Wide acceptance**. UML class diagrams are the most used modelling artefact in the hosting company (OPT) and most probably in other companies in the world.
- **Added value**. Although UML has several modelling artefacts for different purposes (use case diagrams, sequence diagrams, activity diagrams, etc), class diagrams end up being the conceptual design central models where structure and behaviour are gathered in a cohesive scope with more added value to the application designer.
- **Prototyping**. Focused on defining structural and behavioural elements, UML class diagrams are easily prone to design prototyping and validation.

3.4 Technical Goals

We have already stated the main general goals that motivated this project. In this section we present specific technical goals for the development of the FV-RAD framework:

- Focused on run-time adaptation of UML class-association based diagrams.
- Providing an interface for the definition of general purpose metadata.
- Providing a base implementation for the metadata interfaces, including the definition of base data types for the definition of entity fields.
- Providing an engine for the run-time interpretation of models based on the metadata.
- Creating intelligent User Interfaces based on the knowledge of metadata.
- Creating User Interface automatisms for the execution of model based prototypes.
- User Interfaces will be implemented for Windows desktop.
- Persistence will be implemented through XML based files.

4 FV-RAD Implementation

The choice of target platform as “Microsoft .Net C#” is not only a technical based choice. It reflects the hosting company’s development culture that is currently more cantered in Microsoft’s tools and also the experience of the author of this thesis. Microsoft, with Visual Studio, also has very good support for the development of user interfaces, which eases the burden on the implementation of the user interface infrastructure. Although several compromises have been made in order to fulfil project deadlines, these were carefully planned so as to minimize the impact on the framework’s evolution.

4.1 Architecture

The architecture of the FV-RAD framework presented in Figure 4.1, reflects the pursue of the technical goals presented in section 3.4.

Components have been layered according to a bottom up approach that starts with the definition of the metadata and ends up with the execution of UI automated model based prototypes. Below each title is the name of the “.Net” assembly where each component is located.

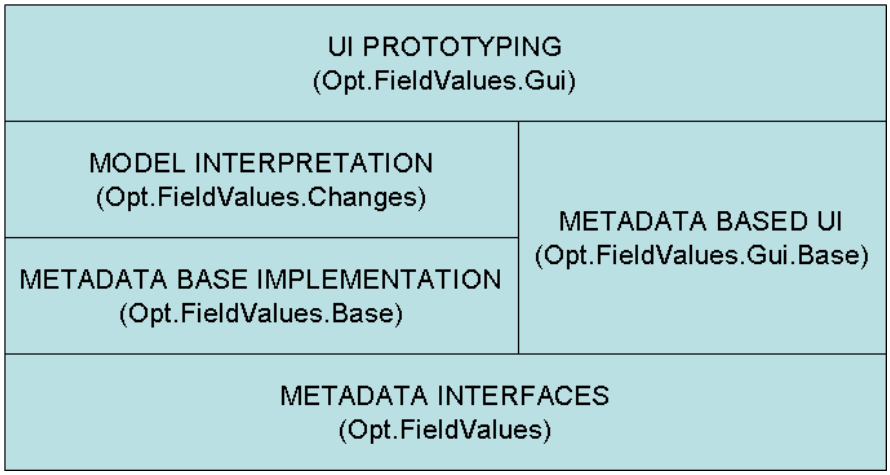


Figure 4.1 - Architecture of the FV-RAD framework

The components that make up this architecture are described in Table 4.1, and will be explained in greater detail in the following sections.

Table 4.1 - FV-RAD components and assemblies

METADATA INTERFACES **(Opt.FieldValues)**	Definition of the abstract interfaces needed for representing the metadata (ex: *IEntityType, IField, IFieldType*).
METADATA BASE IMPLEMENTATION **(Opt.FieldValues.Base)**	Provides a base implementation of the metadata interfaces including an initial set of base data types for typifying fields (ex: *FTInt, FTString, FTEnum, FTReference*).
MODEL INTERPRETATION **(Opt.FieldValues.Changes)**	Extends the metadata interfaces with additional interfaces needed to support the interpretation of domain models (ex: *IDomainModel, IElementType, IDomainWorld, IElement*). Grows on the base implementation of metadata interfaces to provide an implementation of the new interfaces. Manages state changes to domain data. It also provides an extension mechanism for providing additional functionality with code.
METADATA BASED UI **(Opt.FieldValues.Gui.Base)**	Provides an increased level of abstraction to UI widgets by making them aware of the metadata interfaces used for viewing and editing meta-based data (ex: *FieldTypeEditor, FVListView*).
UI PROTOTYPING **(Opt.FieldValues.Gui)**	Uses metadata based widgets to provide full UI automation for the execution of prototypes that use the "model interpretation" component for running models (ex: *ElementEditor, ElementsList, ElementEditorForm, FVPrototype*).

4.2 Metadata Interfaces

The *Metadata Interfaces* component is about providing a set of abstract interfaces for the definition of metadata. The fact that these are not concrete implementations ensures isolation from the specific implementation one might provide and allows for the development of additional metadata based applications and tools not fully domain oriented.

Figure 4.2 shows a diagram with the main interfaces provided by this component. A recurring feature in these interfaces and others that will be provided later is the use of *Label* properties for textual descriptions of some elements; the purpose is to establish a bridge with other UI oriented components without the need for additional resource mapping utilities.

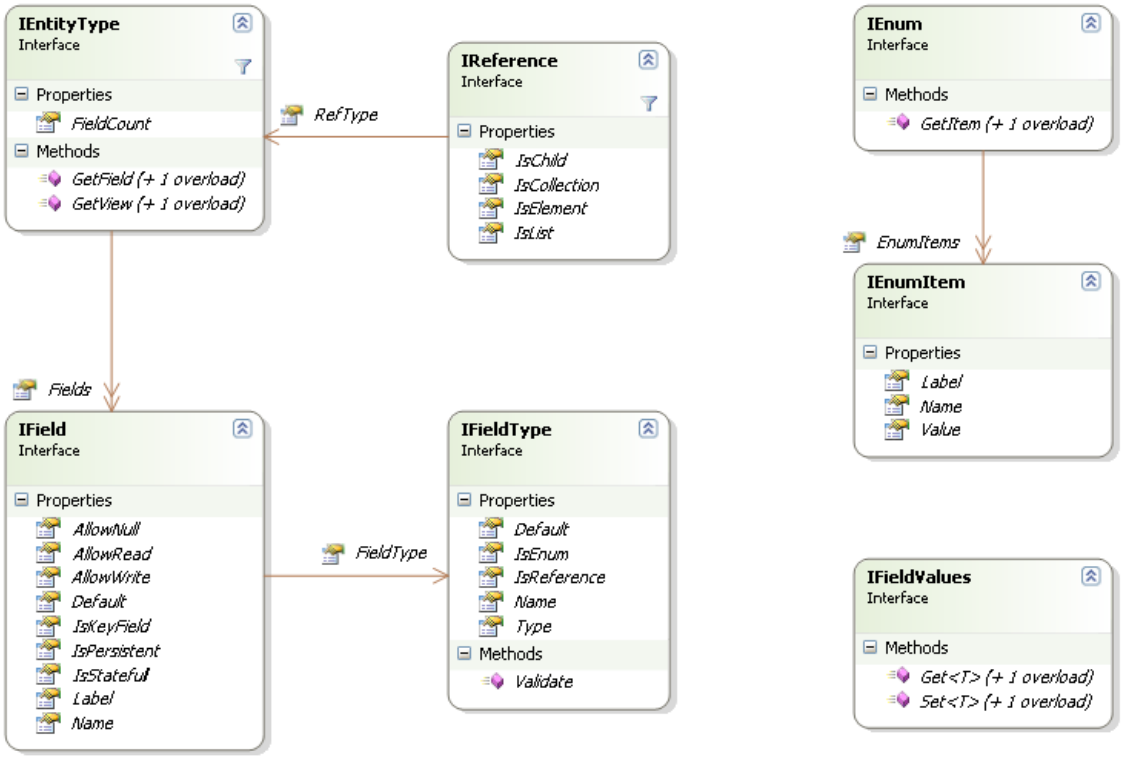


Figure 4.2 - Metadata base interface definitions

Here's a description of the main interfaces:

- ***IEntityType***
  Used for describing an entity type. It has a list of fields which may be fetched by field name or by a field index ("*GetField*"). Fetching with an index allows for speeding up access to field values in case they are stored in an array like data structure.
  There's also the possibility of creating named views on that entity. A view is a list of field names (these might also be composed field names like "Employee.Department") used to access a subset of the entity's data. Views are fetched through "*GetView(viewName)*" and each entity type has a default view that may be fetched when no arguments are used with "*GetView()*".
  Entity operations are still not supported in this version, although an *IOperation* interface has been assigned for that purpose.

- ***IField***
  Entity field descriptors. The field is identified by a short name "*Name*" property and there's a textual description of the field name in the "*Label*" property. There may also be a default value assigned to that field ("*Default*"

property). Each field has a specified data type ("*FieldType*" property). There is also a set of additional boolean classifiers that are presented in Table 4.2.
In the future, reference fields in binary associations will provide an inverse reference to the field which presents the role on the other side of the association (see *IReference*).

- ***IFieldType***
  Used for describing field data types. These are also very important for UI automation purposes where there will typically be a mapping from a field type to a specific UI widget for the edition of field values. Field types may be primitive (ex: Int or String), references to one or several entity elements ("*IsReference == true*") or enumerations ("*IsEnum == true*"). There is also a validation procedure for field values of this type ("*Validate*").

- ***IReference***
  Used for describing reference field types, which are the associations in UML class diagrams. References may be single (one element), unordered (collection) or ordered (list).
  A reference points to the *EntityType* of its elements ("*RefType*" property). Although not represented in the diagram, a reference also has an optionally assigned "*IReferencePicker*" which is used for returning elements that may be added to the reference field (automation purposes).
  The "*IsChild*" property is very important for the automated management of the life cycle of entities. It allows the implementation of UML composition qualifiers in associations (composite aggregation) and denotes a containment relationship between father and child (referenced) types. Shared aggregation is still not supported.
  Association cardinality will be implemented in the next version.

- ***IEnum, IEnumItem***
  Allows the definition of enumerated data types.

- ***IFieldValues***
  This is an important interface used for getting and setting field values in entity elements. In a way FV-RAD owes its name to this interface. Field values may be fetched by field name or field index (performance) and generics are used to typify input and output values.

- ***IFilter***
  This is a simple utility interface not present in the diagram that applies a filter to an entity element and returns a boolean to assert that the element verifies it or not.

Appendix A shows the code for the all the interfaces hereby described.

Table 4.2 – Field boolean classifiers

IsStatefull	This indicates if this is a field with an assigned state value (true) or if it should behave like a ".Net" inferred property, and have an associated procedure for getting and setting a value (false).

IsKeyField	This isn't quite the *Key* meaning we're used to, as the field or set of fields (might be used in more than one field for the same entity type) that uniquely identifies an entity. Instead it is used to define the default field(s) to be presented when referencing this entity type (more UI oriented).
IsPersistent	States if the value of this field is to be persisted in a database (true) or session oriented (false).
AllowNull	The field allows Null values.
AllowWrite	Permission to set values on this field (true) as it could be internally assigned (false).
AllowRead	Permission to get values from this field (true) as these could be only accessed internally (false).
IsUnique	Not implemented. Could be used to ensure the uniqueness of some fields for this entity type (no two entities with the same values for these fields).
IsUniqueInParent	Not implemented. In a composite association this could be used to ensure the uniqueness of some fields for child entities with the same parent container (no two entities with the same values for these fields in the same parent container).

4.3 Base Implementation and Data Types

This component (*Metadata Base Implementation*) gives a base implementation for the *Metadata Interfaces* described previously. Figure 4.3 shows the main classes for this component including a base implementation for entity types ("*EntityType*"), fields ("*Field*") and the filtering utility ("*Filter*").

As we can see, there is also a singleton static class ("*FT*") for accessing the implementation of the base data types used to define entity fields (ex: "*FT.Date()*"). It is possible through this class to define general enumeration types and additional domain types (like ORACLE domains). These data types are presented in more detail in Figure 4.4.

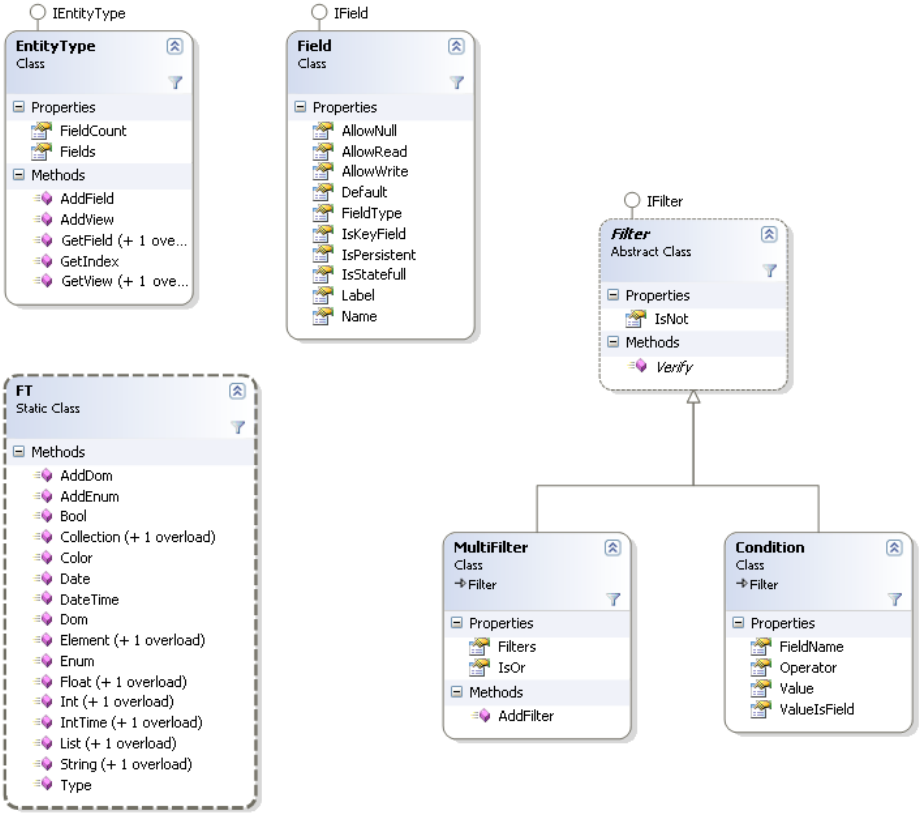


Figure 4.3 - Base implementation of metadata Interfaces

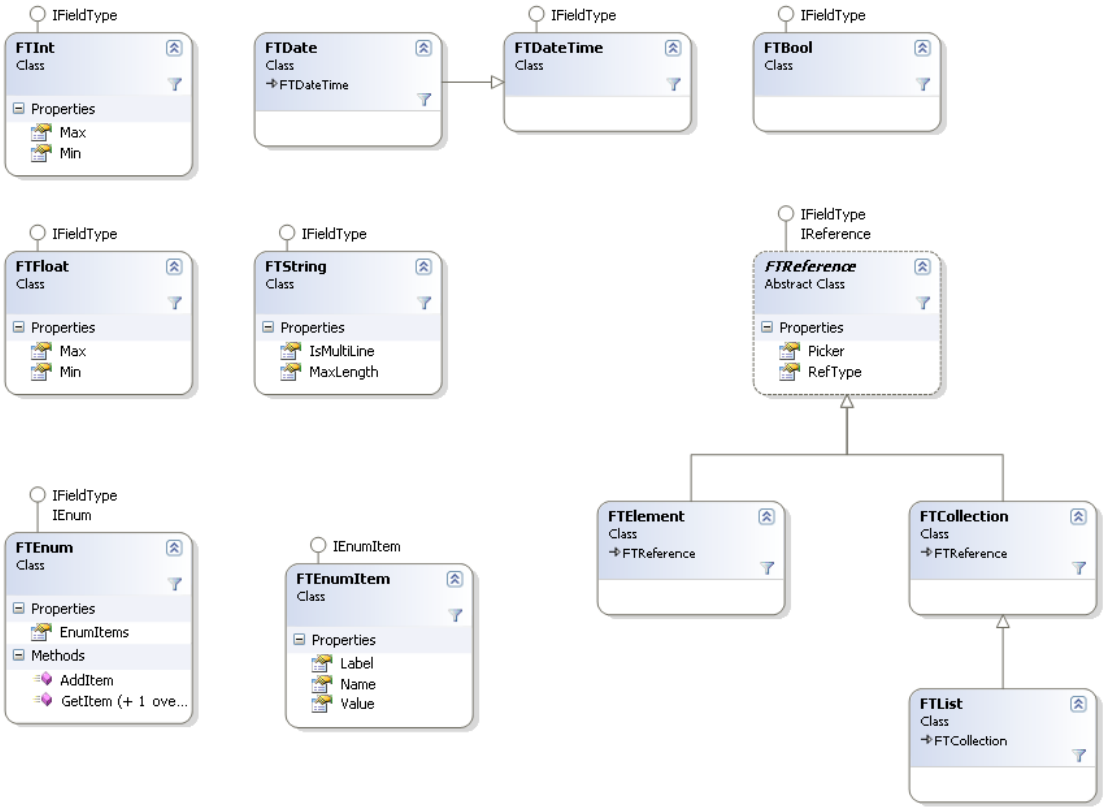


Figure 4.4 - Base definition of data types

4.4 Model Interpretation

The *Model Interpretation* component provides additional interfaces and implementations that grow on the previous components and provide the foundation for the interpretation of models. Interpretation here means applying the definition of a model to create and make changes to data in a model based domain. This data that makes-up an instance of a given domain model is designated a *World* or a "*DomainWorld*".

4.4.1 Interpretation Goals

The main goals devised for the interpretation engine were the following:

- Interpretation of a DSL based on UML class diagrams
- Single inheritance support
- Composite associations management
- Management of entities state and life-cycle
- Support for Object Oriented Transactions (only one level)
- Referential Integrity management (through reference counts)
- Creation of an event log with all changes to data
- Ability to define behaviour and constraints through code extensions
- Persistence of data in XML files

4.4.2 Models and Worlds

Figure 4.5 presents a general perspective of the interpretation engine. The metamodel (model that defines the models which are instances of the metamodel) has been implicitly defined in code through the classes (which for this purpose are the meta-classes) that make the interpretation component (see section 4.4.3). An explicit implementation (defining a model with the structure of the metamodel) has not been completed yet, that would allow for loading and saving the models itself in the same XML based format used to store model instances data (worlds).

Models are instances of the metamodel. They provide a base implementation of entity types called *ElementTypes* (FV-RAD's classes) for characterizing entity instances in the real world. They have fields that define how entities are structured and related and how they might behave (through code extensions). In a way models define how worlds may transit from a given state to the next.

Worlds are instances of models and they must comply with their model definition structural and behavioural constraints. Descriptions of real-world entities are provided in the form of *Elements* which are instances of *ElementTypes* that have an instantiated value for each of its fields. World data may be saved in a XML based file (".fvx").

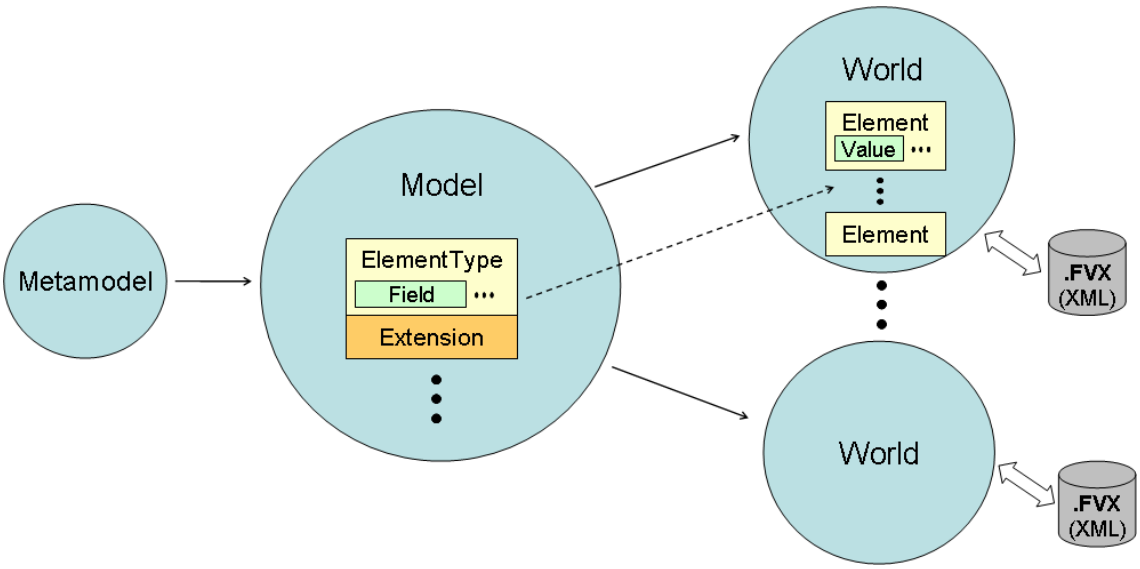


Figure 4.5 - Models and Worlds

4.4.3 The Metamodel

FV-RAD's metamodel (see Figure 4.6) is a model that defines the structure of FV-RAD's models. The interpretation component has a class (or interface) for each of the elements presented in this metamodel.

AOM's *TypeSquare* pattern is used twice, once for *DomainModel-ElementTypes* vs *DomainWorld-DomainElements*, and another for *ElementType-Fields* vs. *DomainElement-FieldValues*. In other words, *DomainWorld-DomainElement-FieldValue* are instances of *DomainModel-ElementType-Field*. Instances may be changed through the abstract interface *Changeable* ("*IChangeable*" in code), and the model elements control how these changes may occur.

ElementTypes may inherit and extend their definition from other types (*BaseType* 1-N association), Multiple inheritance (N-N) is not supported yet.

Fields have type definitions called *FieldTypes*. These types may describe a relationship between *ElementTypes* through a *Reference* field type that points to the referenced *ElementType*. This relationship may be a composite aggregation (*IsComposite*, "*IsChild*" in code) which defines a containment association between element types.

In the case of a binary association (which is maintained both ways), the *Field* used for the reference may also indicate the inverse field in the *ElementType* of the other side to allow for automatic management of synchronized references (not implemented).

Explicit operations although represented (*Operation*) have not yet been implemented.

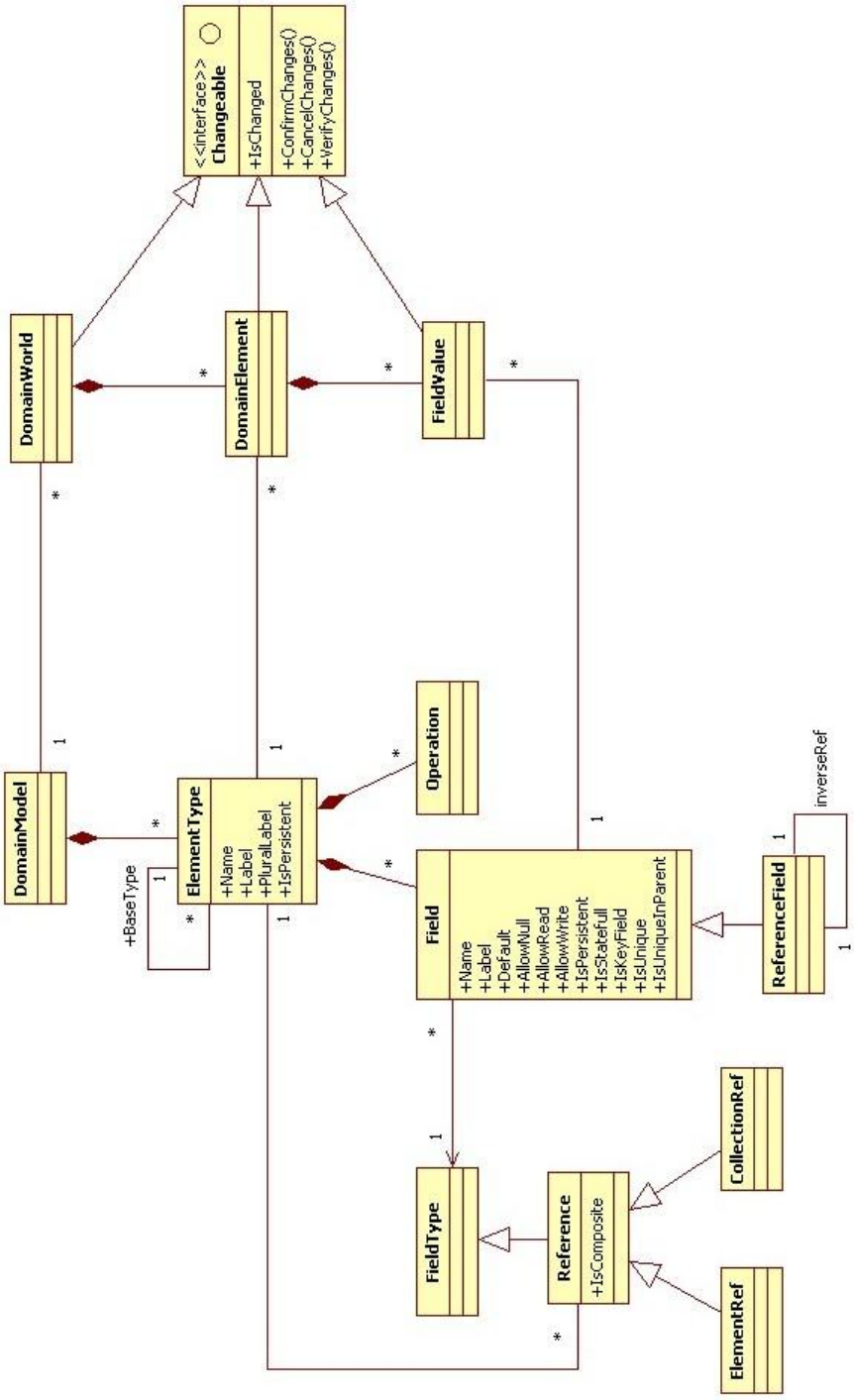


Figure 4.6 - FV-RAD UML based Metamodel

4.4.4 Implementation

The implementation process started by the definition of new abstract interfaces able to comply with the intended metamodel that was previously shown. These interfaces grow on the metadata interfaces to provide the needed structure for model interpretation (see Figure 4.7).

Figure 4.7 - Model interpretation Interfaces

Appendix B provides the code for the interfaces hereby provided. Here's a general description on each one of those interfaces:

- ***IChangeable***
  Provides the ability to make changes to domain data (meaning domain worlds, elements, and field values). This is the base interface for object oriented transaction processing.
- ***IState***
  Represents a changeable state of a set of field values. It also allows fetching previous field values (prior to changes).
- ***IDomainModel***
  A domain model. It has a name, a version, and a set of element types. Also enables the creation of new *DomainWorlds*.
- ***IElementType***
  Element types support inheritance through a *BaseType*, they have labels for user interface purposes, and their instances may be persistent or not ("*IsPersistent*").
  Another important property is the "*IsHomeType*" boolean classifier. If we imagine a compositional data tree that holds all the elements of a domain world, this property indicates that this is a home type, meaning that instances of this type are located in the root of that composition tree. In terms of user interface this means that access to those instances would be provided in a root menu. In future versions this will be an inferred property (by looking at the "*IsChild*" boolean classifier in associations).
- ***IDomainWorld***
  Holds all the data from a domain model instance. It allows for the creation, changing, and deleting of domain element instances whose life cycle it manages. It also has events for controlling all changes that occur in its data.
- ***IElement***
  An instance of an *ElementType*. It has operations for changing its state. Collection based fields (associations) are changed by adding or removing elements. The "*Parent*" is used for holding the parent element in a composite association where the parent object fully manages the life-cycle of its children (see the "*IsChild*" property).
- ***IDomainElement***
  A domain element is an instance of an *ElementType* that belongs to a *DomainWorld*. There are properties for managing this entity's life-cycle within that World, like saying if it is a new element, or if it has been changed or deleted within the current transaction.

In order to allow for object oriented transactions (verify, confirm or cancel changes), a specific mechanism was devised to allow for a *DomainWorld* (and its *DomainElements*) to get back to their previous state (when evoking "*CancelChanges()*"). This mechanism implied that collection field values also had to present a mechanism for recovering their previous state. This led to the implementation of new collection types that were devised for that purpose whose associated set of collection interfaces is presented in Figure 4.8. The last level of inheritance in these interfaces is needed for creating collections of elements with concrete implementations of the *IElement* interface.

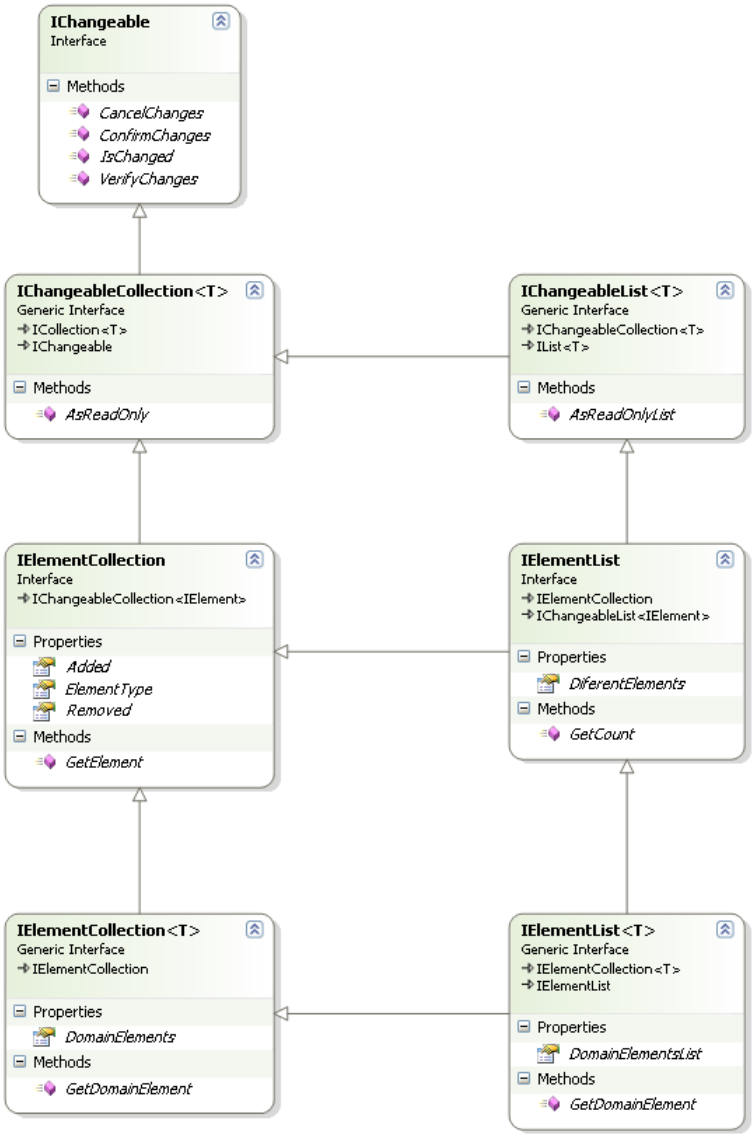


Figure 4.8 - Transaction based collections

Figure 4.9 presents the concrete implementation classes for some of the interfaces discussed earlier that make up the interpretation engine. An important issue regarding these classes is the implementation of a mechanism for life-cycle management of domain elements (see "*Parent*" and "*RefCount*" properties in DomainElement). When deleting a model element this basically works like this:

- A domain element is deleted by executing the statement "*world.RemoveElement(domElement);*"
- Recursively, by looking at the "*IsChild*" property of all its reference fields (associations), all its children are also removed (and their children's children, and so on).
- At some point the operation is confirmed by executing the statement "*world.ConfirmChanges()*".
- At this point all deleted instances (and other) are verified to check if there are references from existing elements pointing to them. This referential

integrity check is performed through the "*RefCount*" property that is permanently updated by the system.

- If referential integrity is violated, then an exception is triggered and changes are not committed; otherwise all the changes will be committed through the domain's data.

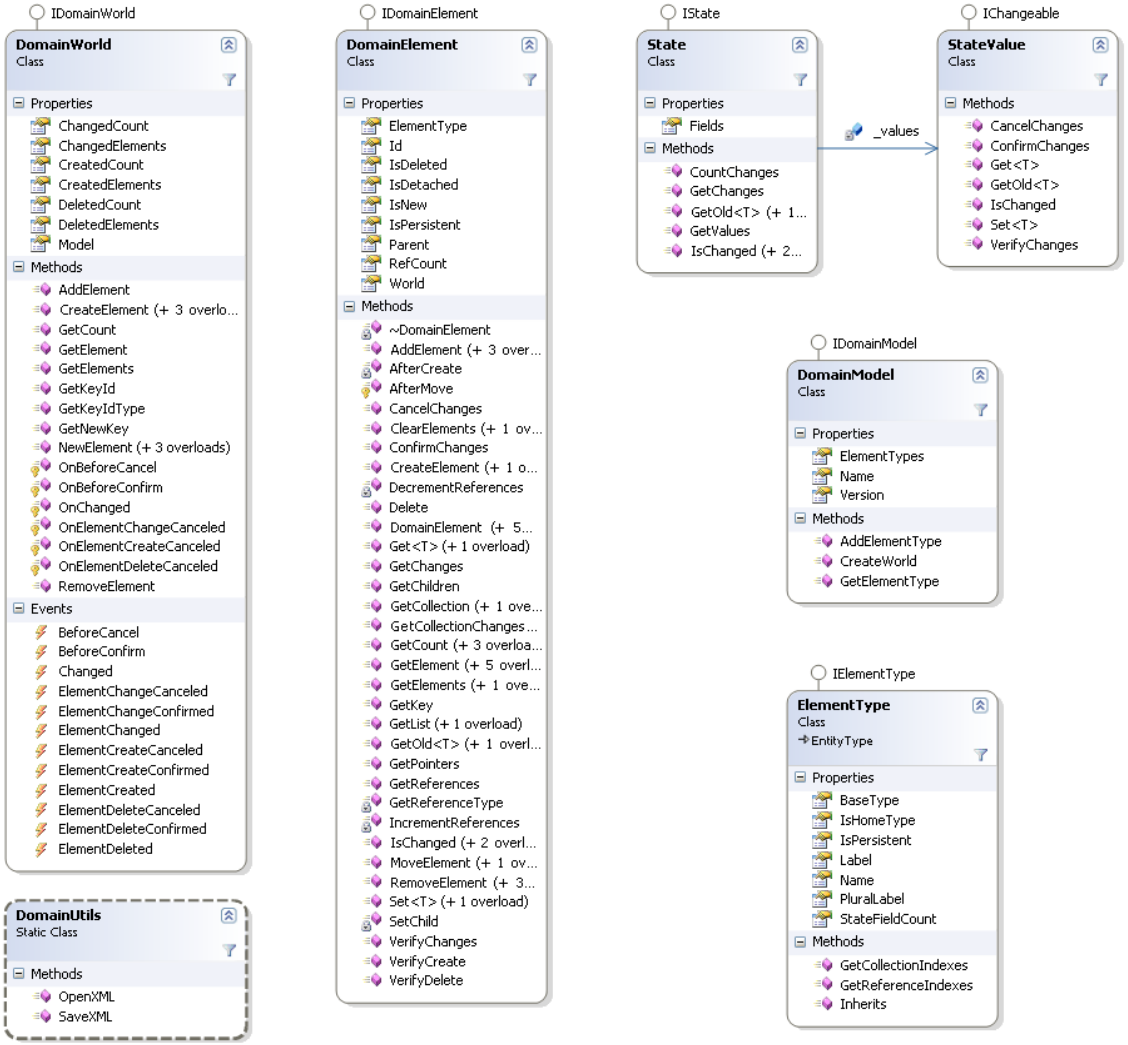


Figure 4.9 - Concrete classes for model interpretation

4.5 User Interface and Prototyping

The user interface components will not be discussed in detail since they are out of the scope of this work. Although their development has been supervised by the author of this thesis, their implementation has been achieved by a team member (also involved in the persistence mechanism) to whom the author presents his deepest thanks.

As mentioned earlier, there are basically two UI related components, one that provides basic UI controls based on the metadata interfaces, and another that grows on the latter to provide full automation of windows desktop prototypes based on the model interpretation interfaces.

The textual descriptions used in the UI are obtained through the "*Label*" (and "*PluralLabel*") properties provided on these interfaces.

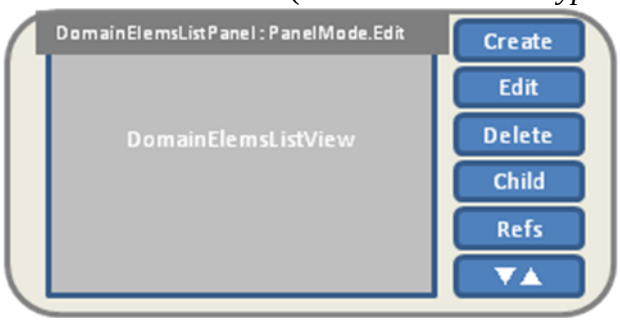
FieldTypes are used as a mean to associate a basic UI gadget to a data type. Basically there is a mapping mechanism between *FieldTypes* and UI gadgets for the visualization and edition of field instances of that data type.

Some of the existing controls are the following (a short image layout of each control is also provided after each description):

- **Field Editors**
  Used for editing field values. They are composed of a label and a *FieldType* based control. This includes a Combo Box based control for enumerations and for choosing single element references.

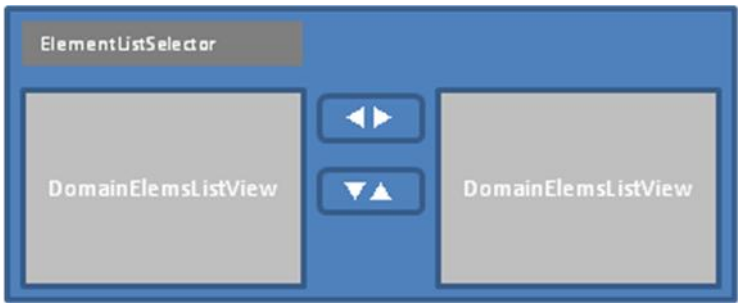
- **Multi Field Editors**
  Used for editing several field values in a single panel.

- **List Editors**
  Used for editing lists of domain elements. There will be buttons to access every child (composite) and referenced collection fields on a selected element. These are also available in the form of grids that allow for in-cell edition of field values (each cell is a *FieldType* based control).



- **Collection Selectors**
  Used for adding, removing, and ordering elements in a collection field. The *ReferencePicker* mentioned earlier (section 4.2) is used to populate the

"Available" elements list.



- **DomainElement editors with Tabbed Panels**
  Used for editing the data of a domain element.
  The first tab is a general purpose multi field editor for basic fields and there is an additional tab for each collection field (composite or referenced).

All these controls are resizable and have properties for defining the geometrical adaptation to their containers. For each of them there's a possibility of choosing the actual fields to be used in visualization or for editing. Composed fields are allowed, for instance, we could say we want the "Department.Boss.Name" field presented in an Employees list. All field properties of the *IField* interface are used to present data accordingly either while editing a single element or an element list.

The difference between composite and reference collection fields is that the first allows the creation and removal of elements on the collection (see List Editors) and the latter only allows for adding and removing existing elements from the collection (see Collection Selectors).

These controls are also available within full working prototype oriented forms. One of the basic problems on using these forms is that domain changes (in the model interpretation layer) are single level. This means that there is no way for a "OK/Cancel" form to call another "Ok/Cancel" based form, since the *DomainWorld* will only support cancelling on the first form (otherwise, cancellation on the second form would also cancel operations on the first form). This has led to the cautious use of edition modes in those forms particularly with the choice of "Ok/Cancel" and "Close" based forms. The latter provide operations that are directly committed when "Cancel" is not allowed. The final prototype editing architecture is presented in Figure 4.10.

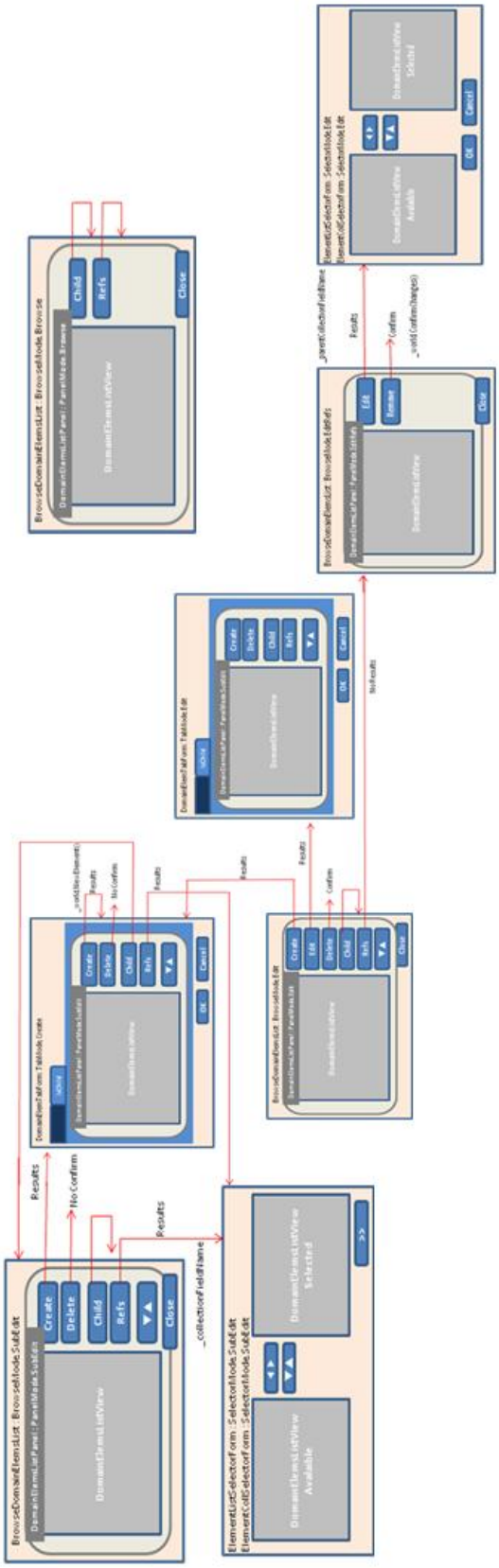


Figure 4.10 - Prototype editing architecture

5 FV-RAD in Action

5.1 Use Cases

FV-RAD, on its current state, may be partially or fully applied, depending on usage goals. Three typical use cases have been identified:

- **Generic database applications**
  These applications typically persist their data in a relational database. Referential integrity is directly supported on the database. Here the metadata interfaces and their base implementation components may be used together with the metadata based user interface component. Reporting, filtering, data import/export, and general user interface development will benefit from a higher level of abstraction to allow for faster implementation and run-time configuration.
  OPT is using these components for the development of the next version of the GIST system.
- **Document persisted applications**
  These are the applications that benefit the most from this framework. Full model interpretation may be used to manage the entire domain's data. Full user interface automation is used initially to provide working prototypes that progressively get refined with manual or metadata based user interface controls for a better user experience and for overcoming the framework's limitations.
  OPT is using these components for the development of a flat-file light version of GIST, called GIST Light, and a pre-release more limited version called "Bus Planner" (see section 5.3).
- **Prototyping**
  Prototyping, whether for design validation purposes or as a mean to rapidly provide initial working versions of an application to be tested near the stakeholders, fits neatly with the framework's goals. Full use of the framework is applied for this purpose.
  The lack of a modelling file format (models still have to be defined in code) is currently the biggest limitation for this intent and is the next priority in

the framework's development (by reusing its own data format). After this is done, sharing a prototype will be as easy as putting a Model file and its instance (a World file) in an email (an additional library with binary domain extensions may also be sent) and sending it to the stakeholder. The stakeholder only has to own a copy of the prototype execution environment. He can make run-time changes to the model and returns its suggestions also in the form of a running prototype.

As the framework grows to support other types of application structure and persistence mechanisms, as well as new user interface paradigms, the spectrum of application may broaden to provide a general purpose model oriented run-time environment for the development of adaptive applications.

5.2 Demonstration

In this section, a brief demonstration of building a running prototype is provided based on a specific model definition (*Company* model). All the code for this demonstration is provided in Appendix C. The steps for building the prototype are the following:

- Model definition
- Model implementation
- Extending the model
- GUI invocation (prototype execution)
- Testing (persistence in XML - ".FVX")

5.2.1 Model Definition

The *Company* model is presented in Figure 2.1. A Company may have several departments and employees. Each Department has several Employees and an Employee may only work in a single Department. An Employee may be assigned for managing one or more Departments' activities. Each Employee may have several Degrees of some type. The types allowed are "basic", "high school", "graduation", "bachelor", "post-graduation", "masters" and "Phd". Degrees are contained in the structure of an Employee (composite).

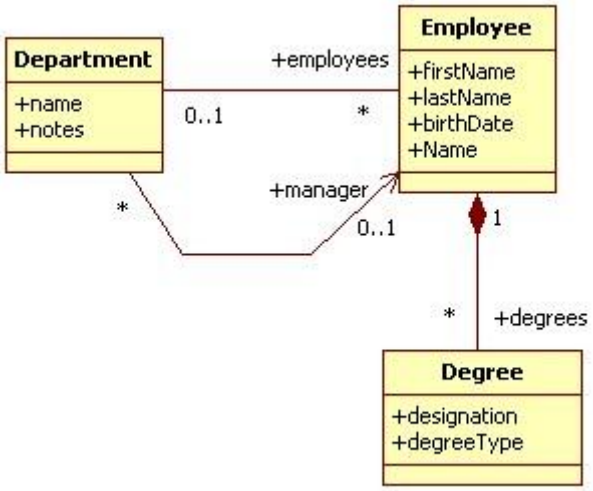


Figure 5.1 -The "Company" model

Composite associations are important indications in the model as they provide the means for managing the life-cycle of entities (removing an Employee implies removing its Degrees and a Degree is created directly in the Employee that contains it).

The definition of this model may then be presented as a tabular description of all the entity types and their fields, like the one in Table 5.1. This data is the basis for the implementation of this model in FV-RAD.

As we can see there is a clear distinction between basic fields and the fields responsible for describing the associations. The latter have additional columns for describing the association roles they are involved in.

The *Name* field in the Employee should be the result of the concatenation of the *firstName* and *lastName* fields. As so it must be declared as a stateless field (*IsStatefull = false*).

Model: **company** Vers: **1.0**

Element Type			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStatefull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				Reference	ElementType	isChild						
department	✓	✓	employees	Collection	employee		✓		✓		✓	✓
			manager	Element	employee		✓		✓	✓	✓	✓
			name	String(40)			✓	✓	✓		✓	✓
			notes	String			✓		✓		✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStatefull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				Reference	ElementType	isChild						
employee	✓	✓	degrees	Collection	degree	✓	✓		✓		✓	✓
			firstName	String(20)			✓		✓		✓	✓
			lastName	String(20)			✓		✓		✓	✓
			birthDate	Date			✓		✓		✓	✓
			Name	String(40)				✓				✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStatefull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				Reference	ElementType	isChild						
degree		✓	designation	String(80)			✓		✓		✓	✓
			degreeType	Enum(degreeType)			✓		✓		✓	✓

Table 5.1 - "Company" model definition

5.2.2 Model Implementation

Because a textual DSL has not still been devised for the definition of the models, the data definition presented previously in tabular format is not directly perceived by the framework. As so, it must be programmed in code with the help of the *Model Interpretation* component. Figure 5.2 presents the definition of the *Employee* type.

There are additional elements for giving textual designations on entities and fields. These will be used in the UI automation process. The "*IsHomeType*" property for indicating a root type is described in section 4.4.4 (in *IElementyType*). Root types will be accessed from the initial window of the prototype.

Fields only have to define the boolean classifiers that differ from the defaults. We can see that the *Name* field is classified as not persistent ("*p-*") neither statefull ("*s-*") nor writeable ("*w-*") and that it is a key field ("*k+*"). The "*c+*" classification of the *degrees* field collection indicates that this is a composite reference containing all the child elements created within.

```
// Company Model Definition

// Element Types

...

ElementType employeeType
    = new ElementType("employee", "Funcionário", "Funcionários");
employeeType.IsHomeType = true;
model.AddElementType(employeeType);
...

// Employee

// Fields
elemType = employeeType;
elemType.AddField(new Field("firstName", FT.String(20), "Primeiro Nome"));
elemType.AddField(new Field("lastName", FT.String(20), "Ultimo Nome"));
elemType.AddField(new Field("birthDate", FT.Date(), "", DateTime.Now,
                            "Data Nascimento"));
elemType.AddField(new Field("Name", FT.String(), "p- s- w- k+", "Nome"));
elemType.AddField(new Field("degrees", FT.Collection(degreeType, "c+"),
                            "Habilitações"));
...
```

Figure 5.2 - Defining the "Employee"entity type

Enumerated field types like the one for enumerating the different types of degrees (don't confuse with the *Degree* element type), may be defined as follows:

```
// Degree Type enumeration
enumType = new FTEnum("degreeType");
enumType.AddItem("none", 0, "Nenhuma");
enumType.AddItem("basic", 1, "Básico");
enumType.AddItem("high school", 2, "Secundário");
enumType.AddItem("graduation", 3, "Licenciatura");
enumType.AddItem("post-graduation", 4, "Pós-graduação");
enumType.AddItem("masters", 5, "Mestrado");
enumType.AddItem("Phd", 6, "Doutoramento");
FT.AddEnum(enumType);
```

Figure 5.3 - Defining the "degreeType" enumeration

Subsequent references to this enumeration type may be accessed through the "*enumType*" variable or through "*FT.Enum("degreeType")*". Remaining model definition is presented in Appendix C.

5.2.3 Extending the Model

Model code extensions will be explained through the implementation of the Employee's *Name* field. FV-RAD does not have a modelling language for describing behaviour like for instance saying that "*Name = firstName + ' ' + lastName*". As so this will have to be implemented in code. The implementation is provided by overriding the method used for accessing field values ("*Get<T>(...)*" method), in "*employee*" entities. To do that, one must ensure that there is a specific class for the entities where this method will be overridden. Since a *DomainWorld* only instantiates *DomainElement* generic objects one must force it to instantiate "*Employee*" classes whenever they are created, and that is done by overriding the "*NewElement(...)*" method of a sub-class of *DomainWorld* called "*CompanyWorld*" that manages all *Company* entity instances (see Figure 5.4).

```
public class CompanyWorld : DomainWorld
{
    public CompanyWorld()
        : base(Company.Model)
    {
    }

    public override IDomainElement NewElement(
                                        IElementType elementType, string key)
    {
        switch (elementType.Name)
        {
            case "employee":
                return new Employee(key);

            default:
                return base.NewElement(elementType, key);
        }
    }
}
```

Figure 5.4 - Extending a "DomainWorld"

We may now proceed to define a "*Employee*" class for overriding the "*Get*" method that accesses field values and imposing the calculation of the *Name* field (see Figure 5.5).

```
public class Employee : DomainElement
{
    public static int firstNameIndex;
    public static int lastNameIndex;
    public static int NameIndex;

    static Employee()
    {
        firstNameIndex = Company.EmployeeType.GetIndex("firstName");
        lastNameIndex = Company.EmployeeType.GetIndex("lastName");
        NameIndex = Company.EmployeeType.GetIndex("Name");
    }

    public Employee(string key)
        : base(Company.EmployeeType, key)
    {
    }

    public override T Get<T>(int fieldIndex)
    {
        object result;

        if (fieldIndex == NameIndex)
        {
            // "Name" calculation
            result = FirstName + " " + LastName;
        }
        else
        {
            return base.Get<T>(fieldIndex);
        }

        return (T)result;
    }

    public string Name
    {
        get { return this.Get<string>(NameIndex); }
    }

    public string FirstName
    {
        get { return this.Get<string>(firstNameIndex); }
        set { this.Set<string>(firstNameIndex, value); }
    }

    public string LastName
    {
        get { return this.Get<string>(lastNameIndex); }
        set { this.Set<string>(lastNameIndex, value); }
    }
}
```

Figure 5.5 - The "Employee" extended entity type

5.2.4 Prototype Invocation

After the model implementation is complete, it is time to invoke the prototype by executing the statements in Figure 5.6.

```
// GUI automation

FVPrototype proto = new FVPrototype();
proto.Start(Company.Model);
```

Figure 5.6 - Prototype invocation

The initial window of the prototype is then launched with the home entity types available for editing (see Figure 5.7). In this window it's also possible to open or save a document with the edited data.

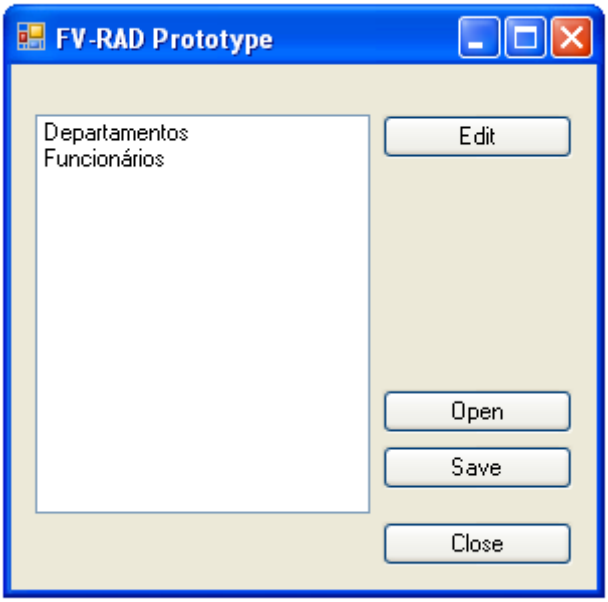


Figure 5.7 - Prototype main window

Selecting an entity type like "Departamentos" and pressing "Edit" launches a window with all available Departments with the possibility of creating, editing or deleting Departments, and provides access to the Departments' collection references (like its Employees). Figure 5.8 presents the window output after selecting the first element in the list for editing launching a new window for the edition of a single Department (Portuguese resource based windows).

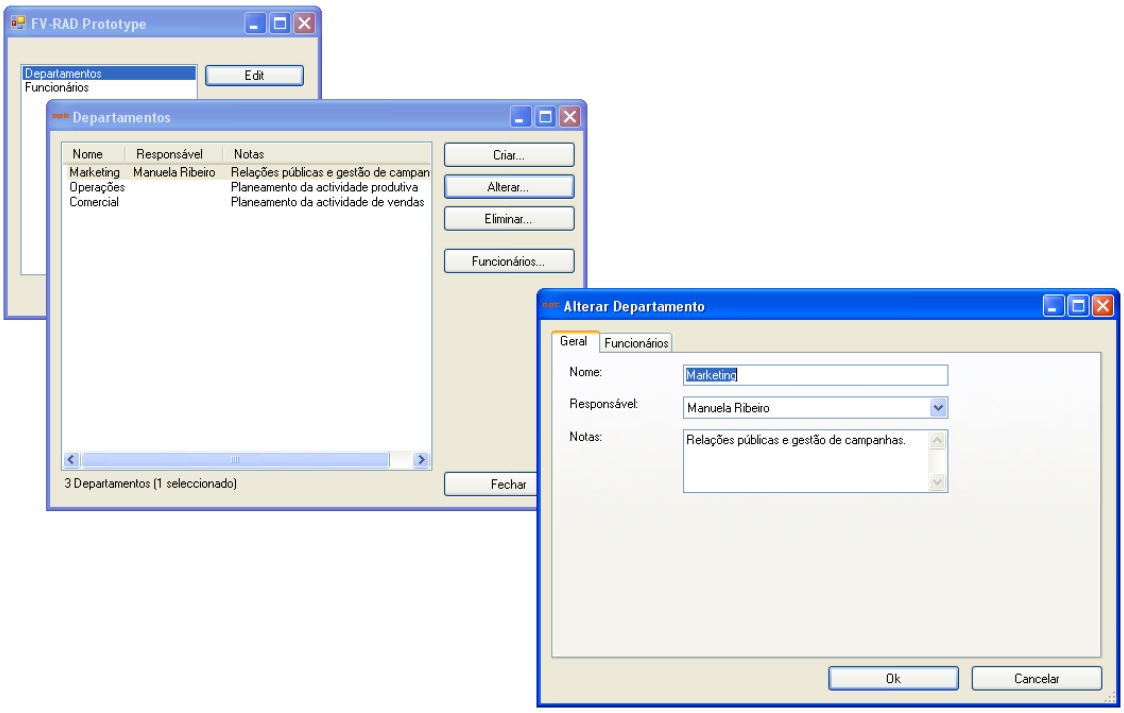


Figure 5.8 - Running the "Company" prototype

The prototype is able to generate a log of all object oriented transactions with the changes that occurred in the entities. For instance, when opening a new ".FVX" document for this domain, a load operation is executed for the creation of all data from the document within the *DomainWorld* in a single transaction. The output for this log is presented in Figure 5.9. As you can see there is also an indication of reference count changes on every entity.

```
World changes BEGIN.
['department:1' initialized]
Created 'department:1'
['department:2' initialized]
Created 'department:2'
['department:3' initialized]
Created 'department:3'
['employee:1' initialized]
Created 'employee:1'
['degree:1' initialized]
Created 'degree:1'
[Add 'degree:1' to 'employee:1'.degrees]
['degree:1' ref 1]
['degree:2' initialized]
Created 'degree:2'
[Add 'degree:2' to 'employee:1'.degrees]
['degree:2' ref 1]
['employee:2' initialized]
Created 'employee:2'
['degree:3' initialized]
```

```
Created 'degree:3'
[Add 'degree:3' to 'employee:2'.degrees]
['degree:3' ref 1]
['degree:4' initialized]
Created 'degree:4'
[Add 'degree:4' to 'employee:2'.degrees]
['degree:4' ref 1]
['employee:3' initialized]
Created 'employee:3'
['employee:4' initialized]
Created 'employee:4'
['employee:5' initialized]
Created 'employee:5'
['employee:6' initialized]
Created 'employee:6'
['employee:7' initialized]
Created 'employee:7'
[Set 'department:1'.manager to 'employee:7']
['employee:7' ref 1]
[Add 'employee:6' to 'department:1'.employees]
['employee:6' ref 1]
[Add 'employee:7' to 'department:1'.employees]
['employee:7' ref 2]
World changes CONFIRM.
```

Figure 5.9 - FV-RAD's Domain Log

5.2.5 Testing and Persistence

Testing the prototype is an important task. Code tests may be implemented just as any other application by calling the model interpretation engine and experimenting with the entities. Other tests may be UI centred and the persistence mechanism plays an important role by providing an easy way to transport domain data across the stakeholders. The ".fvx" XML based files generated by FV-RAD are also very readable by direct edition in a text or XML editor allowing for direct manipulation of the data. Figure 5.10 presents the document contents for the domain data that generated the log in Figure 5.9. XML schema generation isn't yet supported by FV-RAD.

```
<?xml version="1.0" encoding="utf-8"?>
<company version="1.0.0">
    <department key="department:1" name="Marketing" manager="employee:7">
        <notes>Relações públicas e gestão de campanhas.</notes>
        <employees>
            <ref key="employee:6" />
            <ref key="employee:7" />
        </employees>
    </department>
    <department key="department:2" name="Operações">
        <notes>Planeamento da actividade produtiva</notes>
        <employees />
    </department>
    <department key="department:3" name="Comercial">
        <notes>Planeamento da actividade de vendas</notes>
        <employees />
    </department>
    <employee key="employee:1" firstName="Luís" lastName="Ferreira" birthDate="1968-10-
```

```
16">
        <degrees>
            <degree key="degree:1" designation="Engenharia de Sistemas e Informática"
degreeType="graduation" />
            <degree key="degree:2" designation="Informática" degreeType="post-
graduation" />
        </degrees>
    </employee>
    <employee key="employee:2" firstName="Fernando" lastName="Vieira" birthDate="1971-
03-28">
        <degrees>
            <degree key="degree:3" designation="Matemática e Ciências da Computação"
degreeType="graduation" />
            <degree key="degree:4" designation="Informática" degreeType="post-
graduation" />
        </degrees>
    </employee>
    <employee key="employee:3" firstName="Sara" lastName="Silva" birthDate="0001-01-
01">
        <degrees />
    </employee>
    <employee key="employee:4" firstName="João" lastName="Castro" birthDate="0001-01-
01">
        <degrees />
    </employee>
    <employee key="employee:5" firstName="Sara" lastName="Meireles" birthDate="0001-01-
01">
        <degrees />
    </employee>
    <employee key="employee:6" firstName="Lurdes" lastName="Ribeiro" birthDate="0001-
01-01">
        <degrees />
    </employee>
    <employee key="employee:7" firstName="Manuela Ribeiro" birthDate="0001-01-01">
        <degrees />
    </employee>
</company>
```

Figure 5.10 - FV-RAD's documents (".FVX")

5.3 Applying FV-RAD to "Bus Planner"

FV-RAD has been successfully applied to the "Bus Planner" project at OPT (see Figure 5.11). The discussion on this implementation will be centred on the model transformations that took part in the model definition process. The resulting model definition data is presented in tabular form in Appendix D.

This is an application that allows a Bus Company to manage its resources, namely in terms of the trips offered to the public and the lines (routes) they are assigned to, the bus duties needed to fill those trips, and the driver duties needed for driving those buses. The full model is presented in Figure 5.12. It has been sectioned in two parts, one for modelling the transport network and another for trip and resource scheduling purposes, so the classes that join those two segments appear twice.

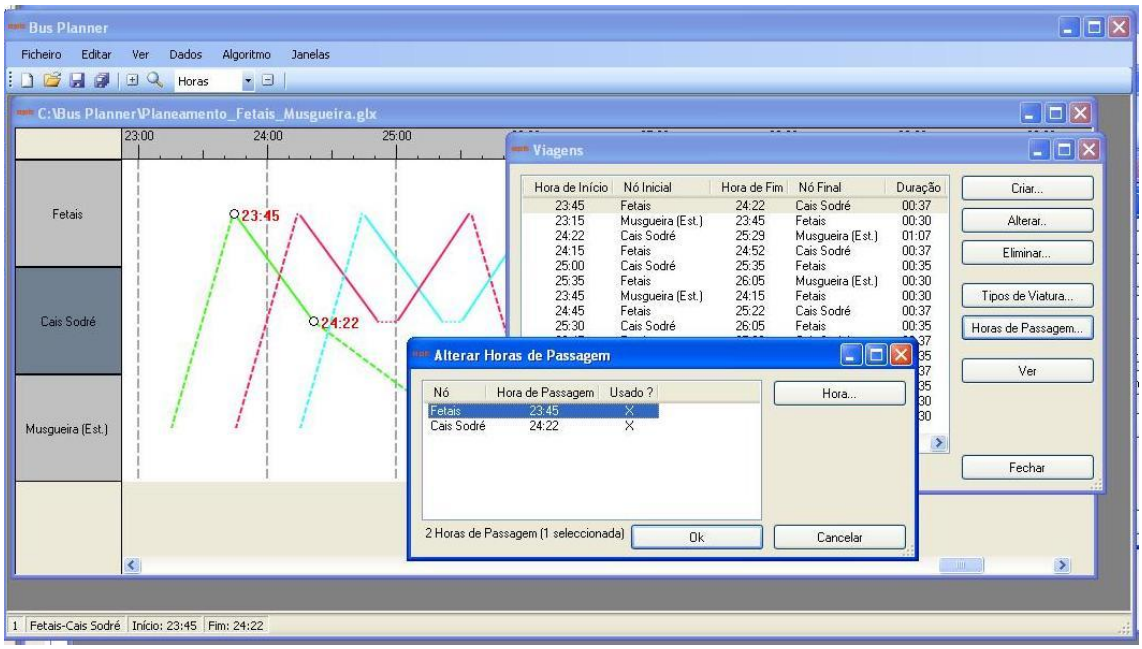


Figure 5.11 - BusPlanner application

The model presented has some features that cannot be directly implemented with FV-RAD's framework, which are the following (base knowledge of UML class diagrams is assumed):

- **Association Classes**
  These are classes that characterize associations. In fact these classes are associations with modelled structure and behaviour. They are not directly supported by FV-RAD. Examples are the *LinePath* and *PathNode* association classes.
- **Shared Aggregation**
  This is the general case of aggregation where several parent container objects may share the same contained child object. Only composite aggregation is supported in FV-RAD. Examples are the *BusDuty* and *DriverDuty* being able to share *WorkBlock* instances.
- **Binary Associations**
  These are associations that are to be implemented both ways. FV-RAD is still not able to automatically synchronize references in both roles of the association. An example is the N-N *Trip-WorkBlock* association that needs *Trip.WorkBlocks* and *WorkBlock.Trips* role fields synchronized at all times.

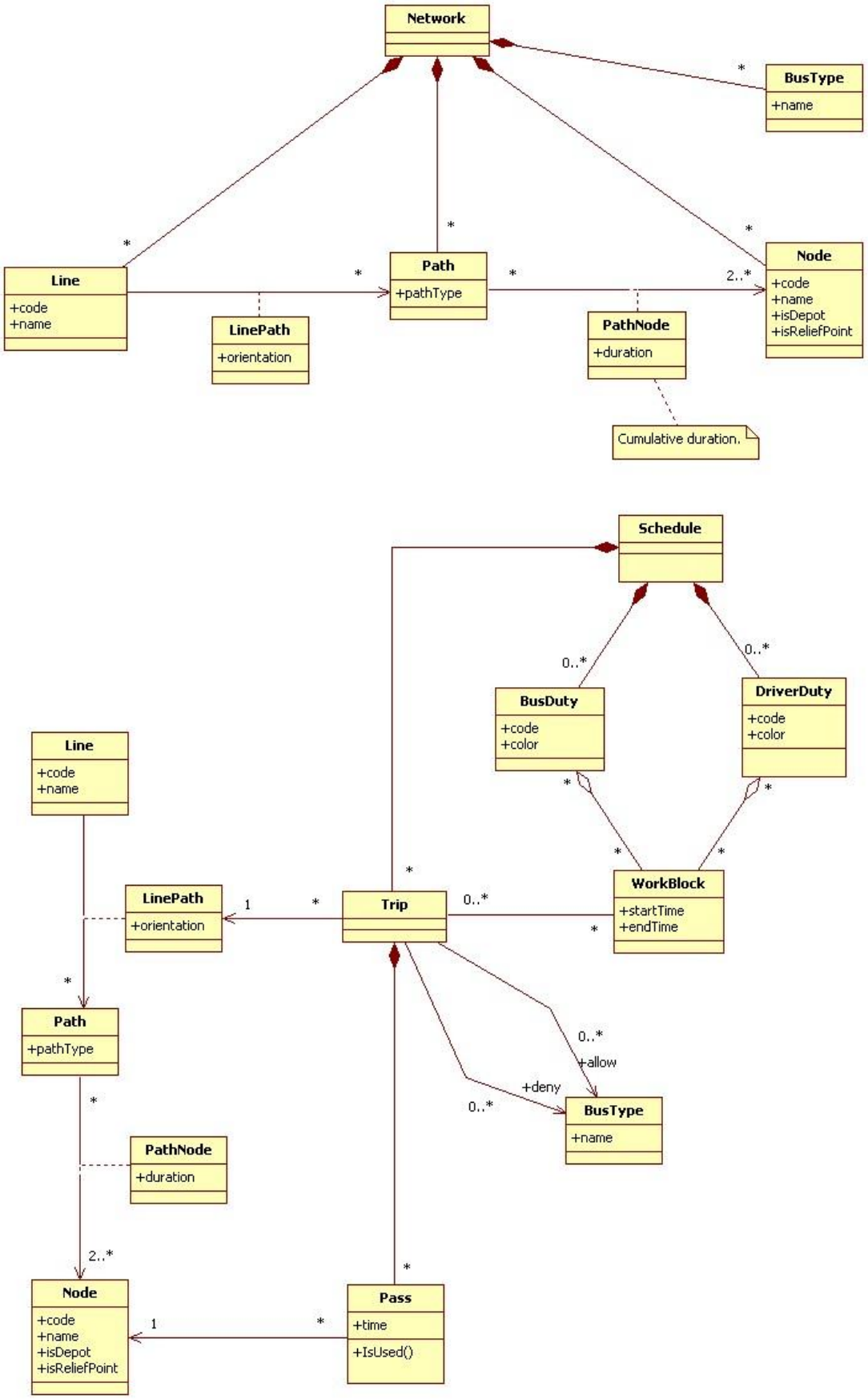


Figure 5.12 - BusPlanner model diagram

The association classes are dealt by a simple transformation process by converting the N-N directed association class C in Figure 5.13.

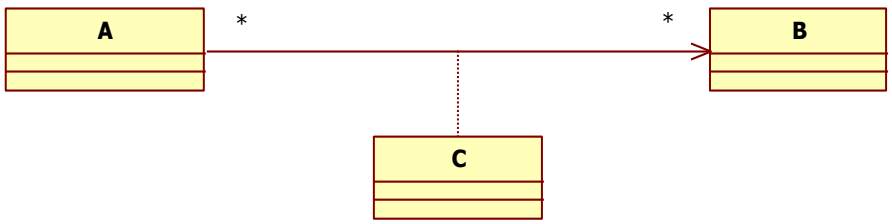


Figure 5.13 - FV-RAD and Association Classes

Class C is then converted into a class whose elements are contained (composite) in the source class A and where those elements point to single B instances, although several Cs may point to the same B (see Figure 5.14).

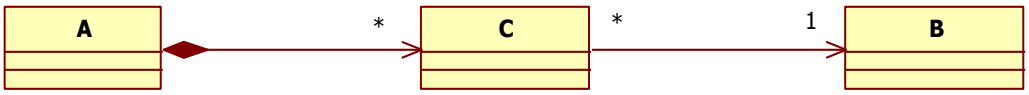


Figure 5.14 – Converting a N-N directed Association Class

Shared aggregation may be transformed into composite aggregation by a transformation process that tries to find a compatible parent class for *WorkBlock* going up the composition hierarchy. In this case the most suitable class is *Schedule*. The next step is putting WorkBlocks contained in Schedules, instead of DriverDuty and BusDuty where the aggregation construct is transformed into regular references.

Implemented binary associations must have the synchronization process managed with code extensions, so that when an element is added or removed in one side the opposite reference must be added or removed in the other side of the association.

The transformation process has to be processed case by case taking FV-RAD's limitations into consideration. The resulting transformed diagram for this model is presented in Figure 5.15 and its conversion to tabular data is presented in Appendix D.

BusPlanner has benefited from FV-RAD with increased development speed and early deployment of initial prototypes that were progressively refined till final release. UI data manipulation was not the only benefit provided by FV-RAD. Automatic persistence of data and the ability to use data change events for controlling the update of the graphical representation presented in Figure 5.11 were also important gains that allowed for the rapid development of this application.

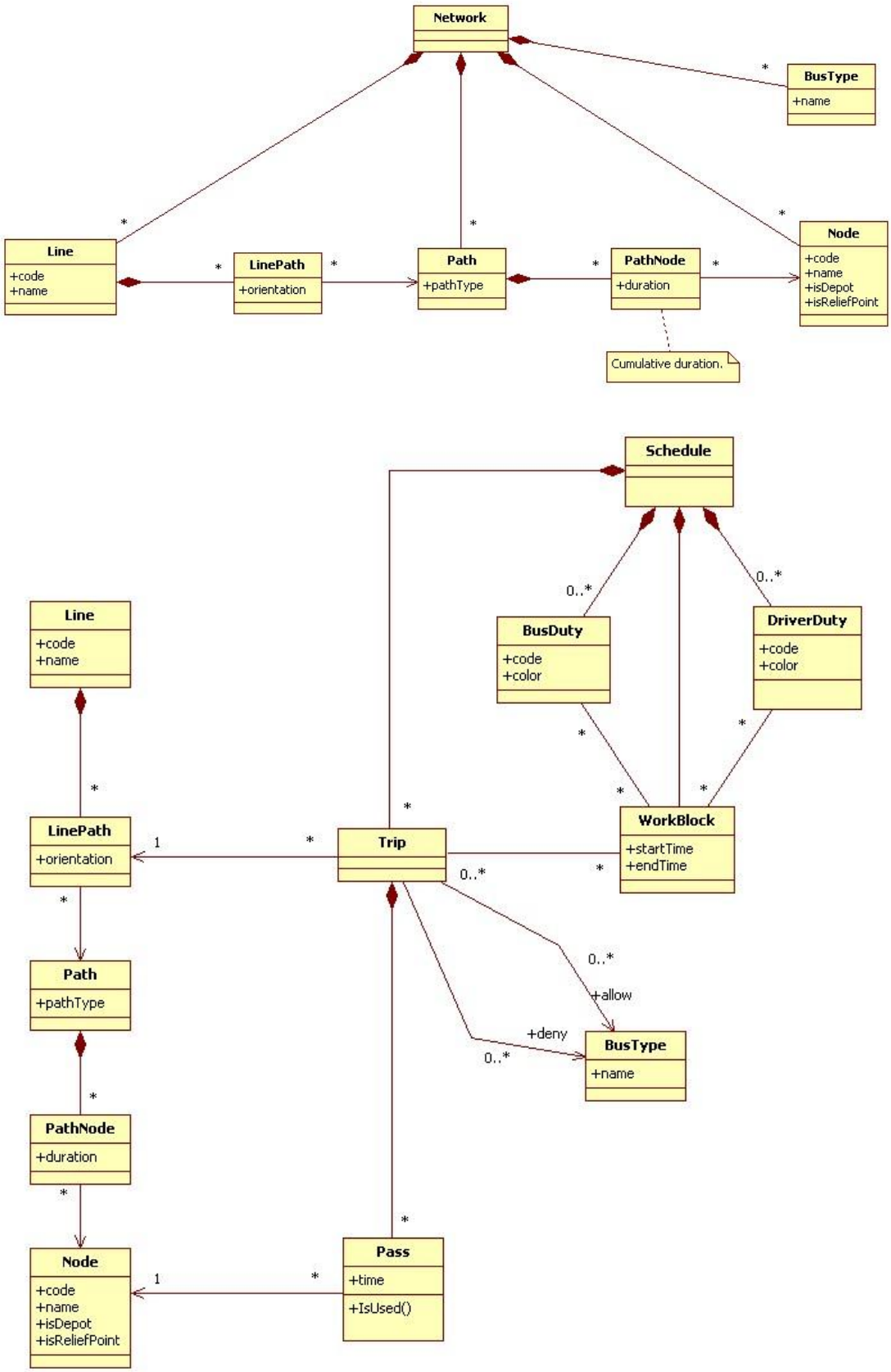


Figure 5.15 - BusPlanner transformed model adaptation

6 Conclusions

Models are becoming the most important artefacts in software development. Their integration in the development process is a fundamental aspect of current software methodologies. It is the next step in raising the abstraction level on development tools and languages.

There are currently several important trends in model oriented development from which the following two have been highlighted in this thesis:

- One that uses design-time generative software methodologies to build the application or to generate reusable assets for building a family of domain related applications. This is based in highly abstract Domain Specific Languages that provide an ideal mean for domain experts to express a problem and for developers to build the infrastructure that generates the solution.

- Other that uses adaptive methodologies for interpreting metadata based models at run-time and providing the means for rapid changes to a model aware application through its model definition.

FV-RAD fits the latter with a general purpose approach for interpreting an adaptation of UML class based models. It has a broad scope by covering important aspects as domain logic, persistence and user interface. It also flavours several use cases, from a platform that allows for an increased level of UI automation and utilities based on metadata, to a complex full automation prototype provider for running models with optional code extension mechanisms. These mechanisms are used for overcoming its limitations and for refining an application till final release is reached.

6.1 Goal Analysis

Initial goals were ambitious and there were high expectations which have been more than partially fulfilled. Several accomplishments have been realized in this project:

- **Layered architecture**
  A general layered architecture has been devised for metadata based applications, for the run-time interpretation of UML class based models, and for running fully automated prototypes. The architecture has been set upon abstract interfaces for making the API as general as possible and a base implementation has also been provided.
- **Metadata based applications**
  By being able to support intermediate metadata based UI automation and metadata based utilities it has proven to be a valuable platform for general purpose applications. These may be client server applications based on a relational database that don't need full model running capabilities, like the GIST system whose next version is being developed using this approach.
- **Document based applications**
  Flat file persisted applications are a natural candidate for using this framework. They may start with a rough full prototype draft implementation, with automated user interface and persistence, and they get progressively refined with model changes and code extensions for achieving final results. The "BusPlanner" project at OPT has clearly benefited from this rapid approach.
- **Running prototypes**
  Running model based prototypes is a good way of testing design options and concepts. FV-RAD provides the means for running these models without the need of a development environment or application setup, which is ideal for sharing these prototypes with the stakeholders. It also provides automatic persistence with a portable XML based format (".FVX") that may be easily edited or exchanged over email.
- **In House**
  Although its commercial exploration is an option, the fact that this is a inner development gives OPT a firsthand knowledge of its benefits and limitations and the ability to make it fit for its own needs.
- **Model learning platform**
  One important aspect of using this framework which has been noted at OPT it is its ability to be used as an academic tool for teaching about conceptual models in application design. By running a model based prototype the student is rapidly able to analyse the impact of his modelling decisions on the final application.

Also there have been some problems and limitations, some of which have already been stated. These have somehow affected the ease of use and also have prevented a broader spectrum of appliance for this framework:

- **Modelling format and tools**
  The lack of a modelling format for persisting models is one of the main drawbacks of this version. This is particularly harmful for prototyping

purposes, as it imposes the need to code the model definition using the framework which for a first-time user means learning the framework's API. Also a tool for building these models or for importing a base model definition in a standard format (ex: XMI – XML Metadata Interchange) and adapting them for its use would also be of great value. Currently OPT defines models with StarUML (open source), then produces a transformed version with the same tool after which there is an Excel template where this definition is put in tabular format before being implemented in FV-RAD.

- **Complexity**
  Learning to use the framework's API, depending on the use scope, may take a while. The learning curve is particularly higher with respect to code extensions. This may be a problem, especially with a first time use team for a short time constrained project. This is however compensated with rapid development gains after the framework has been tackled.
- **Performance**
  Performance is not a concern when using the basic layer for metadata based applications. However it is an important factor when using the full model interpretation engine to manage data. For instance, field values are stored as objects, their state is replicated for managing changes (ex: cancelling changes), and entity lifecycle is managed manually besides the regular garbage collection process of the implementation platform. For performance constrained applications this might be an important limitation.
- **Database persistence**
  There is currently no support for database persistence, particularly multi-user databases. These applications may only benefit from the basic metadata layer. In fact, although the model interpretation API tried not to compromise the future addition of this feature, it has never been intended for first releases. Model interpretation is currently directed toward in-memory processing of domain data that is persisted in flat-files.

Changes are already being made to overcome some o these and other limitations, these include a partial rewrite of the user interface layers for automation and prototyping (for WPF – Windows Presentation Foundation).

It is also important to distinguish this framework from current object-relational technology (there's been some confusion). Object relational tools (ex: Hibernate, OpenAccess, etc.) provide direct mapping of class instances (objects) to relational databases. Besides the obvious fact that FV-RAD does not currently support database persistence, the substantial fact still remains that ORM frameworks work at the implementation level by facilitating changes to data in objects, which get synchronized with the database. These objects follow an already determined class structure. FV-RAD works at a higher level of abstraction (the model), where the implementation platform is a secondary concern and higher semantic constructs like composition and field classification may be applied. Another example of this is the proliferation of label descriptions for supporting things like UI automation and reporting tools. Also, FV-RAD is about run-time adaptation of applications to new requirements which in ORM tools may only be directed towards the mapping mechanism (a new field can't be added by changing the mapping file unless it has also been added to the class in code and re-compiled).

6.2 Future Work

FV-RAD is still an evolving framework with several limitations and a growing prospect. It is already being used in some projects at OPT and there are several improvements being prepared for the next releases:

- **Explicit metamodel**
  Explicitly defining FV-RAD's metamodel using its own modelling schema is an almost finished task. It will allow for the execution of a prototype describing a model and for reusing the same persistence format for models and domain data.
- **Visual DSL**
  A visual DSL for describing FV-RAD's models would be an extremely helpful tool that would ease the learning curve for the execution of prototypes.
- **Schema generation**
  Currently, data is saved to a XML file (".FVX") whose structure depends on the model. It would be nice to also generate a XML schema for the automatic validation of data for that model.
- **Multi-level changes**
  Only single level transactions are currently supported. Multi-level transactions would be of great interest particularly for UI automation, as several levels of "OK/Cancel" data editors would be easily supported.
- **Undo / Redo**
  Document based applications typically have an Undo/Redo feature. In FV-RAD it should be based on the ability to undo or redo full transactions.
- **Binary associations**
  Binary associations have to be managed through code extensions. A feature that would allow for automatic synchronization of references in both roles of these associations would be very welcome.
- **Shared aggregation support**
  Only composite aggregation is currently supported. Shared aggregation native support would bypass the need for additional model transformations.
- **Unique fields and indexes**
  These would provide for additional data validation and improve system performance in more complex operations.
- **Improved UI support**
  The UI layers are already being improved. There is still no support for inheritance in the UI prototypes and WPF support is being implemented. Web based support would also be of great value.
- **Model conversion**
  As prototypes evolve, all the domain data from previous model versions may be lost, unless the framework is prepared for learning the differences between consecutive versions for automatic data conversion.
- **Behavioural constructs**
  As typical of AOM systems it would be of great value the support for behavioural constructs at the model level that would overcome the need for code extensions in some validation and operational procedures.

An interesting vision for the future is one where the developer only has to send two data files (model and domain data) to enable the stakeholder to test and validate or suggest changes to the prototype. Another way to do this would be loading the model in a web site that would be ready to provide an automatic web based UI for model execution and sharing between the stakeholders.

In the long run more ambitious trends could be followed:

- **Multi-user database support**
  The run-time automation of multi-user model based prototypes is a complex task. For that reason it has been excluded from the first release. Changes to the modelling structure would most surely have to occur to make this possible. The potential gains however are huge. Even more when those prototypes could be refined to become production releases. Combined with a web user interface, full web application support could be a reality not far from reach.
- **Cloud computing**
  Running models in the cloud is a very ambitious plan that is far from being accomplished. Cloud computing is a new technology waiting to be explored and still limited in terms of data support. If this support could be provided through a higher level of abstraction through general purpose model based data support, then building a web service could be as easy as defining a model, implementing some extensions, and executing it in the cloud. These domain oriented data services could be provided together with an additional UI automated or partially automated layer for full application support.

These are just some speculating ideas. The baseline is that by raising the level of abstraction through the use of model oriented technologies the possibilities are immense. The model-implementation gap gets shorter to a point where the implementation is merged with the model. This merging process may be directed by the implementation or by the model itself (model embedded or implementation embedded). Application development gets faster as things like data management, persistence and user interface get fully or partially automated, with the possibility of being further refined by using lower level implementation technology. Quality is improved as cross cutting concerns get implanted in this infrastructure, and a higher level of response to requirement changes is provided by the early deployment of working prototypes that may be validated and even changed by the stakeholders.

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Appendix A - Metadata Interfaces

This is the code for FV-RAD's metadata interfaces described in section 4.2.

```
namespace Opt.FieldValues
{
    /// <summary>
    /// The set of fields that describe an element's typed interface.
    /// </summary>
    public interface IEntityType
    {
        int FieldCount { get; }

        IField GetField(string fieldName);
        IField GetField(int fieldIndex);

        int GetIndex(string fieldName);

        IEnumerable<IField> Fields { get; }

        IEnumerable<string> GetView();  // Default view
        IEnumerable<string> GetView(string viewName);
    }

    /// <summary>
    /// An element's external or internal (statefull) data field.
    /// </summary>
    public interface IField
    {
        /// <summary>
        /// Field name used to identify it in the element.
        /// </summary>
        string Name { get; }

        /// <summary>
        /// Field name used to label user interface elements.
        /// </summary>
        string Label { get; }

        /// <summary>
        /// Field data type.
        /// </summary>
        IFieldType FieldType { get; }

        /// <summary>
        /// Default value when a new element is created.
        /// </summary>
        object Default { get; }
```

```
    /// <summary>
    /// External read permission.
    /// </summary>
    bool AllowRead { get; }

    /// <summary>
    /// External write permission
    /// </summary>
    bool AllowWrite { get; }

    /// <summary>
    /// Should this field be saved when persisting data in a file
    /// or database.
    /// </summary>
    bool IsPersistent { get; }

    /// <summary>
    /// Is this field part of its element internal state.
    /// </summary>
    bool IsStatefull { get; }

    /// <summary>
    /// Is "null" an allowed value?
    /// </summary>
    bool AllowNull { get; }

    bool IsKeyField { get; }

    //bool IsUnique { get; }
    //bool IsUniqueInParent { get; }
    //
    //int ReverseFieldIndex { get; }  // Binary associations.
}

public interface IFieldType
{
    string Name { get; }
    Type Type { get; }
    object Default { get; }

    /// <summary>
    /// Is this field type a reference to one or several elements.
    /// </summary>
    bool IsReference { get; }

    bool IsEnum { get; }

    void Validate(object value);  // Throws exception on error.
}

/// <summary>
/// Describes a field type used to reference one or several
/// elements.
/// </summary>
/// <remarks>
/// A typical association between two element types.
/// </remarks>
public interface IReference
{
    IEntityType RefType { get; }
    bool IsChild { get; }   // Aggregation (composition)
    //bool IsSharedChild { get; } // False => Composition,
    //                            // True => Shared aggregation.

    bool IsElement { get; }
    bool IsCollection { get; }
    bool IsList { get; }

    IReferencePicker Picker { get; }  // Fetches elements that may be picked
                                      // to be added.
    //// Cardinality
    //int MinCount { get; }
    //int MaxCount { get; }
}

public interface IEnum
{
```

```
        IEnumerable<IEnumItem> EnumItems { get; }

        IEnumItem GetItem(string name);
        IEnumItem GetItem(int value);
    }

    public interface IEnumItem
    {
        string Name { get; }

        int Value { get; }

        string Label { get; }
    }

    /// <summary>
    /// This is the interface that every element should implement to get or set its
    /// field values.
    /// </summary>
    public interface IFieldValues
    {
        T Get<T>(string fieldName);
        T Get<T>(int fieldIndex);
        void Set<T>(string fieldName, T value);
        void Set<T>(int fieldIndex, T value);
    }

    public interface IFilter
    {
        bool Verify(IFieldValues element);
    }
}
```

Appendix B - Model Interpretation Interfaces

This is the code for the model interpretation interfaces described in section 4.4.4.

```
namespace Opt.FieldValues.Changes
{
    /// <summary>
    /// Generic interface used to control and cancel changes to something.
    /// </summary>
    public interface IChangeable
    {
        bool IsChanged();

        /// <summary>
        /// Verifies and confirms changes.
        /// Throws an exception if confirmation is not possible.
        /// </summary>
        void ConfirmChanges();

        void CancelChanges();

        /// <summary>
        /// Verifies if confirmation is possible.
        /// </summary>
        /// <returns>
        /// Returns true if the changes made may be confirmed without
        /// Error.
        /// </returns>
        bool VerifyChanges();
    }

    public interface IState: IFieldValues, IChangeable
    {
        bool IsChanged(string fieldName);
        bool IsChanged(int fieldIndex);

        T GetOld<T>(string fieldName);
        T GetOld<T>(int fieldIndex);

        IList GetValues();
        IEnumerable<IStateChange> GetChanges();
        int CountChanges();
    }

    /// <summary>
    /// A Model defines the type of Elements (ElementType) and rules that associated
```

```
/// Worlds may have.
/// </summary>
public interface IDomainModel
{
    string Name { get; }
    string Version { get; }
    IElementType GetElementType(string typeName);
    IEnumerable<IElementType> ElementTypes { get; }

    IDomainWorld CreateWorld();
}

/// <summary>
/// An ElementType is a repository of Fields. Some fields may be inherited
/// by a single base Element Type (multiple inheritance not supported yet.
/// </summary>
public interface IElementType: IEntityType
{
    string Name { get; }
    string Label { get; }
    string PluralLabel { get; }
    bool IsPersistent { get; }
    int StateFieldCount { get; }
    IElementType BaseType { get; }
    bool IsHomeType { get; }

    bool Inherits(IElementType superType);

    IEnumerable<int> GetReferenceIndexes();
    IEnumerable<int> GetCollectionIndexes();
}

/// <summary>
/// A World is a repository of Elements that follows a specific Model
/// </summary>
public interface IDomainWorld : IChangeable
{
    IDomainModel Model { get; }

    IEnumerable<IDomainElement> CreatedElements { get; }
    IEnumerable<IDomainElement> DeletedElements { get; }
    IEnumerable<IDomainElement> ChangedElements { get; }

    IDomainElement GetElement(string key);
    string GetNewKey(string typeName);
    IEnumerable<IDomainElement> GetElements(string typeName);

    IDomainElement CreateElement(IElementType elementType);
    IDomainElement CreateElement(string key);   // Assumes the Key has type
                                                // information. Use carefully
    IDomainElement CreateElement(IElementType elementType, string key); // Calls
                                                                        // "NewElement"

    // "NewElement" Requires "AddElement" after to accept the element.
    IDomainElement NewElement(IElementType elementType);    // Generates the key.
    IDomainElement NewElement(string key);      // Assumes the key has type
                                                // information. Use carefully
    IDomainElement NewElement(IElementType elementType, string key);    //
                                // IMPORTANT: Override to instantiate to user classes

    //// Can't override both, only one may be used to instantiate user classes
    //IDomainElement NewElement(IElementType elementType, int id);        //
    //                          // IMPORTANT: Override to instantiate to user classes

    // Operations (changes to world)
    void AddElement(IDomainElement element);
    bool RemoveElement(IDomainElement element);
    void ChangeElement(IDomainElement element);

    // EVENTS

    event WorldEventHandler Changed;
    event WorldEventHandler BeforeConfirm;
    event WorldEventHandler BeforeCancel;

    event ElementEventHandler ElementCreateConfirmed;
    event ElementEventHandler ElementDeleteConfirmed;
```

```
    event ElementEventHandler ElementChangeConfirmed;

    event ElementEventHandler ElementCreateCanceled;
    event ElementEventHandler ElementDeleteCanceled;
    event ElementEventHandler ElementChangeCanceled;

    event ElementEventHandler ElementCreated;
    event ElementEventHandler ElementDeleted;
    event ElementEventHandler ElementChanged;
}

/// <summary>
/// An Element is a repository of Field Values that comply to a
/// specific Element Type.
/// </summary>
public interface IElement: IFieldValues, IChangeable
{
    string GetKey();
    IElementType ElementType { get; }
    IElement Parent { get; }

    bool IsPersistent { get; }
    IEnumerable<IStateChange> GetChanges();
    IEnumerable<ICollectionChange> GetCollectionChanges();

    bool IsChanged(string fieldName);
    T GetOld<T>(string fieldName);
    IElement GetElement(string fieldName, string key);
    IElement GetElement(string fieldName, int listIndex);
    IElement GetElement(string fieldName);
    void AddElement(string fieldName, IElement element);
    void AddElement(string fieldName, IElement element, int listIndex);
    void MoveElement(string fieldName, int fromIndex, int toIndex);
    bool RemoveElement(string fieldName, IElement element);
    void RemoveElement(string fieldName, int listIndex);
    void ClearElements(string fieldName);
    IEnumerable<IElement> GetElements(string fieldName);
    ICollection<IElement> GetCollection(string fieldName);
    IEnumerable<ICollectionChange> GetCollectionChanges(string collFieldName);
    IList<IElement> GetList(string fieldName);
    int GetCount(string fieldName);
    int GetCount(string fieldName, string key);
    IElement CreateElement(string fieldName);

    bool IsChanged(int fieldIndex);
    T GetOld<T>(int fieldIndex);
    IElement GetElement(int fieldIndex, string key);
    IElement GetElement(int fieldIndex, int listIndex);
    IElement GetElement(int fieldIndex);
    void AddElement(int fieldIndex, IElement element);
    void AddElement(int fieldIndex, IElement element, int listIndex);
    void MoveElement(int fieldIndex, int fromIndex, int toIndex);
    bool RemoveElement(int fieldIndex, IElement element);
    void RemoveElement(int fieldIndex, int listIndex);
    void ClearElements(int fieldIndex);
    IEnumerable<IElement> GetElements(int fieldIndex);
    ICollection<IElement> GetCollection(int fieldIndex);
    IEnumerable<ICollectionChange> GetCollectionChanges(int collFieldIndex);
    IList<IElement> GetList(int fieldIndex);
    int GetCount(int fieldIndex);
    int GetCount(int fieldIndex, string key);
    IElement CreateElement(int fieldIndex);
}

/// <summary>
/// A DomainElement is an Element that belongs to a World (DomainWorld).
/// </summary>
public interface IDomainElement : IElement
{
    IDomainWorld World { get; }

    bool IsNew { get; }
    bool IsDeleted { get; }
    bool IsDetached { get; }

    bool VerifyCreate();
    bool VerifyDelete();
```

```
        bool Delete();
    }
}
```

Appendix C - Prototype Demonstration

This is the code for the Company demonstration example shown in section 5.2 (Department-Employee).

```
using Opt.FieldValues.Base;
using Opt.FieldValues.Changes;
using Opt.FieldValues.Gui;
...

namespace Opt.FieldValues.Demo
{
    public static class Company
    {
        public static IDomainModel Model;
        public static IElementType DepartmentType;
        public static IElementType EmployeeType;
        public static IElementType DegreeType;

        static Company()
        {
            Model = new CompanyModel();
            DepartmentType = Model.GetElementType("department");
            EmployeeType = Model.GetElementType("employee");
            DegreeType = Model.GetElementType("degree");
        }
    }

    public class CompanyModel : DomainModel
    {
        public CompanyModel()
            : base("company")
        {
            // Company Model Definition

            // Element Types

            ElementType departmentType
                = new ElementType("department", "Departamento", "Departamentos");
            departmentType.IsHomeType = true;
            this.AddElementType(departmentType);

            ElementType employeeType
                = new ElementType("employee", "Funcionário", "Funcionários");
            employeeType.IsHomeType = true;
            this.AddElementType(employeeType);

            ElementType degreeType
                = new ElementType("degree", "Habilitação", "Habilitações");
```

```
        this.AddElementType(degreeType);

        // Fields by Element Type

        ElementType elemType;
        FTEnum enumType;

        // Department

        // Fields
        elemType = departmentType;
        elemType.AddField(new Field("name", FT.String(40), "Nome"));
        elemType.AddField(new Field("manager", FT.Element(employeeType), "n+",
                                    "Responsável"));
        elemType.AddField(new Field("notes", FT.String(), "Notas"));
        elemType.AddField(new Field("employees", FT.Collection(employeeType),
                                    "Funcionários"));

        // Employee

        // Fields
        elemType = employeeType;
        elemType.AddField(new Field("firstName", FT.String(20), "Primeiro Nome"));
        elemType.AddField(new Field("lastName", FT.String(20), "Ultimo Nome"));
        elemType.AddField(new Field("birthDate", FT.Date(), "", DateTime.Now,
                                    "Data Nascimento"));
        elemType.AddField(new Field("Name", FT.String(), "p- s- w- k+", "Nome"));
        elemType.AddField(new Field("degrees", FT.Collection(degreeType, "c+"),
                                    "Habilitações"));

        // Degree

        // Degree Type enumeration
        enumType = new FTEnum("degreeType");
        enumType.AddItem("none", 0, "Nenhuma");
        enumType.AddItem("basic", 1, "Básico");
        enumType.AddItem("high school", 2, "Secundário");
        enumType.AddItem("graduation", 3, "Licenciatura");
        enumType.AddItem("post-graduation", 4, "Pós-graduação");
        enumType.AddItem("masters", 5, "Mestrado");
        enumType.AddItem("Phd", 6, "Doutoramento");
        FT.AddEnum(enumType);

        // Fields
        elemType = degreeType;
        elemType.AddField(new Field("designation", FT.String(50), "Designação"));
        elemType.AddField(new Field("degreeType", FT.Enum("degreeType"),
                                    "Tipo de Habilitação"));
    }

    public override IDomainWorld  CreateWorld()
    {
        return new CompanyWorld();
    }
}

public class CompanyWorld : DomainWorld
{
    public CompanyWorld()
        : base(Company.Model)
    {
    }

    public override IDomainElement NewElement(IElementType elementType, string key)
    {
        switch (elementType.Name)
        {
            case "employee":
                return new Employee(key);
            default:
                return base.NewElement(elementType, key);
        }
    }
}

public class Employee : DomainElement
```

```
    {
        public static int firstNameIndex;
        public static int lastNameIndex;
        public static int NameIndex;

        static Employee()
        {
            firstNameIndex = Company.EmployeeType.GetIndex("firstName");
            lastNameIndex = Company.EmployeeType.GetIndex("lastName");
            NameIndex = Company.EmployeeType.GetIndex("Name");
        }

        public Employee(string key)
            : base(Company.EmployeeType, key)
        {
        }

        public override T Get<T>(int fieldIndex)
        {
            object result;

            if (fieldIndex == NameIndex)
            {
                // "Name" calculation
                result = FirstName + " " + LastName;
            }
            else
            {
                return base.Get<T>(fieldIndex);
            }

            return (T)result;
        }

        public string Name
        {
            get { return this.Get<string>(NameIndex); }
        }

        public string FirstName
        {
            get { return this.Get<string>(firstNameIndex); }
            set { this.Set<string>(firstNameIndex, value); }
        }

        public string LastName
        {
            get { return this.Get<string>(lastNameIndex); }
            set { this.Set<string>(lastNameIndex, value); }
        }
    }


    ...
    static void Main()
    {
        // GUI automation

        FVPrototype proto = new FVPrototype();
        proto.Start(Company.Model);
    }
    ...
}
```

Appendix D – Bus Planner Model Definition

Tabular definition of BusPlanner's model from section 5.3.

ElementType			Fields										
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
GLDocument	✓	✓	docSchedule	FT.Element	schedule	✓	✓		✓	×	✓	✓
			docNetwork	FT.Element	network	✓	✓		✓	×	✓	✓
			Notas	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields										
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
Network		✓	busType	FT.Collection	busType	✓	✓		✓	×	✓	✓
			lines	FT.Collection	line	✓	✓		✓	×	✓	✓
			paths	FT.Collection	path	✓	✓		✓	×	✓	✓
			nodes	FT.Collection	node	✓	✓		✓	×	✓	✓
			notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields										
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
Schedule		✓	trips	FT.Collection	trip	✓	✓		✓	×	✓	✓
			busDuties	FT.Collection	busDuty	✓	✓		✓	×	✓	✓
			driverDuties	FT.Collection	driverDuty	✓	✓		✓	×	✓	✓
			workBlocks	FT.Collection	workBlock	✓	✓		✓	×	✓	✓
			notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields										
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
BusDuty		✓	trips	FT.Collection	trip	×	×		✓	×	×	✓
			workBlocks	FT.Collection	workBlock	×	✓		✓	×	✓	✓
			code	FT.String(50)			✓	✓	✓	×	✓	✓
			color	FT.Color			✓		✓	×	✓	✓
			notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
DriverDuty		✓	workBlocks	FT.Collection	workBlock	✗	✓		✓	✗	✓	✓
			code	FT.String(10)			✓	✓	✓	✗	✓	✓
			color	FT.Color			✓		✓	✗	✓	✓
			notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
WorkBlock		✓	busDuty	FT.Element	busDuty	✗	✗		✗	✓	✗	✓
			busDuties	FT.Collection	busDuty	✗	✓		✗	✗	✗	✓
			driverDuties	FT.Collection	driverDuty	✗	✓		✗	✗	✗	✓
			trips	FT.Collection	trip	✗	✓		✓	✗	✓	✓
			startTime	FT.IntTime			✗	✓	✓	✗	✗	✓
			endTime	FT.IntTime			✗	✓	✓	✗	✗	✓
			tripsCount	FT.Int			✗		✗	✗	✗	✓
			notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
Trip		✓	linePath	FT.Element	linePath	✗	✓	✓	✓	✗	✓	✓
			startTime	FT.IntTime			✗	✓	✓	✗	✗	✓
			endTime	FT.IntTime			✗	✓	✓	✗	✗	✓
			duration	FT.IntTime			✗		✓	✗	✗	✓
			allowedBusTypes	FT.Collection	busType	✗	✓		✓	✗	✓	✓
			deniedBusTypes	FT.Collection	busType	✗	✓		✓	✗	✓	✓
			feasibleBusTypes	FT.Collection	busType	✗	✗		✓	✗	✗	✓
			busDuty	FT.Element	busDuty	✗	✗		✗	✓	✗	✓
			workBlocks	FT.Collection	workBlock	✗	✓		✗	✗	✗	✓
			passes	FT.List	pass	✓	✓		✓	✗	✓	✓
			notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
Pass		✓	node	FT.Element	node	✗	✓		✓	✗	✓	✓
			time	FT.IntTime			✓		✓	✗	✓	✓
			IsUsed	FT.Bool			✗		✓	✗	✗	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
BusType		✓	Name	FT.String(60)			✓	✓	✓	✗	✓	✓
			Notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
Line		✓	linePaths	FT.Collection	linePath	✓	✓		✓	✗	✓	✓
			code	FT.String(50)			✓	✓	✓	✗	✓	✓
			name	FT.String(100)			✓		✓	✗	✓	✓
			notes	FT.String()			✓		✓	✓	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
LinePath		✓	Line	FT.Element	line	✗	✗		✗	✗	✗	✓
			Path	FT.Element	path	✗	✓	✓	✓	✗	✓	✓
			Orientation	FT.Enum("PathDirection")			✓	✓	✓	✗	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
Path		✓	startNode	FT.String(50)			✗	✓	✓	✗	✗	✓
			endNode	FT.String(50)			✗	✓	✓	✗	✗	✓
			PathNodes	FT.List	pathNode	✓	✓		✓	✗	✓	✓
			PathType	FT.Enum("PathType")			✓	✓	✓	✗	✓	✓
			description	FT.String()			✗		✓	✗	✗	✓
			Notes	FT.String			✓		✓	✓	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
PathNode		✓	Node	FT.Element	node	✗	✓		✓	✗	✓	✓
			TotalDuration	FT.InTime			✓		✓	✗	✓	✓

ElementType			Fields									
Name	IsHomeType	IsPersistent	Name	FieldType			IsStateFull	IsKeyField	IsPersistent	allowNull	allowWrite	allowRead
				FT	Object Type	isChild						
Node		✓	Code	FT.String(50)			✓	✓	✓	✗	✓	✓
			Name	FT.String(100)			✓		✓	✗	✓	✓
			IsDepot	FT.Bool			✓		✓	✗	✓	✓
			IsReliefPoint	FT.Bool			✓		✓	✗	✓	✓