VDMTools

VDM++ Method Guidelines

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VDM++ Method Guidelines 2.0
— Revised for VDMTools v9.0.2

This document is subject to change without notice.

Contents

Abstract

The limitations of graphical models in object-oriented analysis are widely accepted. While superior for visualization, a graphical model is not enough for precise and unambiguous specification.

This document presents a methodology and tools that combine the benefits of graphical modeling in UML with a pragmatic and light-weight approach to formal modeling and validation in the object-oriented formal specification language VDM++, supported by **VDMTools**.

VDMTools provides round trip engineering between VDM++ and UML (Rational Rose). In this way, a user of UML gets access to enhanced analysis and validation facilities such as type checking and testing of executable models with automatic checking of annotations such as invariants and pre- and post-conditions.

1 Introduction

In object-oriented modeling the use of graphical visualization can help to master complexity and significantly increase the understanding of the “problem” being modeled. Graphical diagrams can give an abstract and high-level overview of a model, which, for example, can be of great value for analyzing requirements in the early phases of the software process. In the later phases, the diagrams can improve the documentation of the code, again by aiding general understanding.

Graphical models for analysis are suitable both for a software engineer and a client with no programming background. However, it happens that people have different perceptions of what a graphical model actually says. This lack of common understanding can be due to the complexity of a model, but even for small models it can be difficult to assess and review a model, and predict the exact consequences of the boxes and arrows that it contains.

In contrast, executable models are suitable for automating the assessment of models, allowing models to be validated early in the software development process. Combined with rapid prototyping capabilities for designing graphical front-ends, executable models can greatly reduce the incidence and severity of late rework so that products can be delivered on schedule and within budget. For example, by executing a model the engineer can get immediate feedback on his specification. And by extending a model with a graphical front-end matching the problem domain and activities of a client, the client can get a clear view of the specifier’s understanding of the requirements by interacting directly with the model via the front-end.

This document presents a methodology and tools to enhance object-oriented analysis and design by combining the benefits of graphical modelling in UML with those of executable models in the object-oriented formal specification language VDM++[1]. Formal specification can improve the modelling process by adding precision while keeping abstraction. Without precision it would not be possible to automate any parts of the validation process. Abstraction is vital in order to focus on the conceptual properties rather than their detailed and complex implementation. In addition to stating requirements in an unambiguous and structured way, precise models can be analysed and validated automatically using tools and techniques familiar to engineers, such as testing and rapid prototyping. IFAD calls its approach “Validated Design through Modelling” (VDM), which is supported by **VDMTools**. The document assumes that readers already have some familiarity with general object-oriented software develop-

[1] VDM++ is an object-oriented extension of ISO Standard VDM-SL. Standard VDM-SL does not provide a structuring mechanism, though VDM-SL supports modules. VDM++ supports UML-like classes and other OO concepts.

ment [Mey88, SM88, RBP+91].

1.1 VDM++ and UML

Roughly speaking, no two companies develop software in the same way. Even within one company the software process can vary among projects and people. In principle, VDM can be used as an add-on to improve any software process, whether object-oriented (using VDM++), structural (using VDM-SL) or ad-hoc (using either one). However, in this document, we focus on how UML and VDM++ can be used together. Moreover, we shall focus on how to construct a model without distinguishing between the typical phases of software processes such as requirements analysis and system design. This is because the main difference between the phases lies in the level of abstraction. The basic approach to constructing models and analysing them using **VDMTools** is the same.

In order to provide users with the complementary benefits of UML and VDM++, the VDM++ Toolbox, which is one toolset of **VDMTools**, offers the Rose-VDM++ Link [SCSa]. This facilitates an easy transition between UML and VDM++ models. It translates UML class diagrams automatically to VDM++ specifications, and vice versa, providing full round-trip engineering capabilities. Other aspects of UML like use cases can be employed independently of the VDM++ model. Typically use cases will precede a VDM development. Roughly speaking, a VDM++ model is really a textual, precise version of UML class diagrams incorporating all the details that are often missing or described vaguely using natural language there. Hence, the UML and VDM++ models are complementary and, in fact, can be seen as two views of the same model.

In the more recent versions of UML there is a notation called OCL (Object Constraint Language) which has many similarities with VDM++, e.g. pre- and post-conditions. However VDM++ is preferable to OCL because **VDMTools** enables validation based on testing principles. This can never be possible for OCL because it contains no executable subset.

This document does not provide complete introductions to UML, VDM++ nor the VDM++ Toolbox. For further information the reader can consult [GBR99, SCSb, SCSc].

1.2 Constructing a Model

The way a model is constructed is not only dependent on the choice of notation. The purpose of the model is of vital importance as well and is determined by the kind of analysis to be conducted. When designing a car, the purpose of one model may be to test the aerodynamics, the purpose of another to test the brake system, the purpose of a third to test the injection system, and so on. Each of these models can abstract away from aspects of the other models. For example, the models of the brake and injection systems can be analysed separately. The abstraction determines which details will be represented and which will be ignored because they are not relevant to the analysis. Abstraction is the tool to cope with complexity of the systems under construction.

After establishing the purpose of a model, the following list of steps can be a helpful guide to its construction:

1. Read the requirements.
2. Analyse the functional behaviour from the requirements.
3. Extract a list of possible classes or data types (often from nouns) and operations (often from actions). Create a directory by giving explanations to items in the list.
4. Sketch out representations for the classes using UML. This includes the attributes and the associations between classes. Check the internal consistency of the model in VDM++.
5. Sketch out signatures for the operations. Check the model's consistency in VDM++.
6. Complete the class (and data type) definitions by determining potential invariant properties from the requirements and formalising these.
7. Complete the operation definitions by determining pre- and post-conditions and operation bodies, modifying the type definitions if necessary.
8. Validate the specification using testing and rapid prototyping.
9. Implement the model using automatic code generation or manual coding.

Step 2 could either be dealt with using traditional use cases from UML or by making a few VDM definitions without any structuring. Most newcomers to VDM++ are probably going to make use cases but an example of the other approach is given in [Gro00].

Roughly speaking step 1 to 5 above are the parts that are carried out in a conventional object-oriented UML design. The only difference is that the VDM++ coupling is able to find more inconsistencies in step 4 and 5. However, as we will see later the remaining steps (6 to 8) are able to identify quite subtle and important design considerations that must be dealt with to ensure the integrity of the system.

In the following section we present the requirements for a simple alarm and expert scheduling system for a chemical plant. This is modelled in the rest of the document. Though the modelling process is described as a one-pass process in this document, a real development would usually be an iterative process. Furthermore, since the example used for illustration purpose here is so small we will omit step 2 from the list given above.

2 A Chemical Plant Example

This section presents the requirements for a simple alarm system of a chemical plant. The example is inspired by a subcomponent of a large alarm system developed by IFAD and was introduced in the VDM-SL book by Fitzgerald and Larsen [FL98]. We will develop and validate a model of the system using the facilities of the VDM++ Toolbox, including the Rose-VDM++ Link.

A chemical plant is equipped with a number of sensors that are able to raise alarms in response to conditions in the plant. When an alarm is raised, an expert must be called to the scene. Experts have different qualifications for coping with different kinds of alarm. The individual requirements are labelled R1-R8 for reference.

R1 A computer-based system is to be developed to manage the alarms of this plant.

R2 Four kinds of qualification are needed to cope with the alarms. These are electrical, mechanical, biological, and chemical.

R3 There must be experts on duty during all periods allocated in the system.

R4 Each expert can have a list of qualifications.

R5 Each alarm reported to the system has a qualification associated with it along with a description of the alarm that can be understood by the expert.

R6 Whenever an alarm is received by the system an expert with the right qualification should be found so that he or she can be paged.

R7 The experts should be able to use the system database to check when they will be on duty.

R8 It must be possible to assess the number of experts on duty.

In the next section we start the development of a model of an alarm system to meet these requirements.

3 Graphical Model in UML

We shall now develop our first model of the alarm system described above. The purpose of the model is to clarify the rules governing the duty roster and calling out of experts to deal with alarms. We construct a model in UML and use **VDMTools** to check its consistency. Whenever we wish to emphasise a methodological guideline specific to the UML/VDM++ combination we will highlight it by a small statement.

3.1 Creating a Directory

Following the guidelines for constructing a model, we first extract a list of possible classes and data types:

Potential classes and types (nouns)

- Alarm: required qualification and description
- Plant
- Qualification (electrical, mechanical, biological, chemical)
- Expert: list of qualifications
- Period
- System and system database? Probably this is a kind of schedule.

Using a UML tool such as Rational Rose this part of the directory would often be modelled in a class diagram; this is what is done in the next step in the guide. However, if the system to be designed is large it may be safer to systematically list all the potential classes and types in a directory as shown here.

Potential operations (actions)

- Expert to page: given alarm (involved: alarm operator and system)
- Expert is on duty: check when on duty (involved: expert and system)
- Number of experts on duty: given period presumably (involved: operator? and system)

Using a UML tool this part of the directory would often be described as use cases.

For this simple system we will let the above lists work as a dictionary of the main concepts in the system, though better explanations would be appropriate.

3.2 Sketching Class Representations

Having created a directory it is now necessary to explain what the difference is between a class and a type. In pure OO approaches there is no distinction and this has the consequence that one often gets a very large collection of classes and can therefore have difficulties in mastering the complexity due to the number of classes. In VDM++ there is a distinction between classes and types and we wish to use this to reduce the number of classes for our model. Generally speaking types correspond to what is known as container classes in conventional OO approaches. These are classes that simply have a number of attributes which users of the class can read and write.

Guideline 1: Nouns from a directory should be modelled as types if they have no "real" functionality (in addition to read/write) with respect to the purpose of the model.

Qualification from the dictionary above is an example of a noun that is better modelled as a type. Qualification is an enumeration type since it holds just four possible values and has no obvious functionality. If the purpose of our model included the different kinds of actions different experts could carry out depending upon their qualification, it would have been more natural to model qualification as a class.

Let us now consider alarm and expert from the dictionary. Both of these correspond to groupings of real objects in the physical world of our example, which co-exist and act independently. We will therefore model both of these as classes:

Alarm is a class with attributes *required qualification* and *description*. Description is a string that can be considered a type in the same way as *Qualification* (see Figure 1).

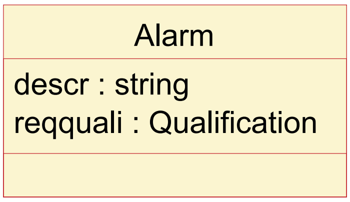


Figure 1: The Alarm Class.

Expert is a class with *qualifications* as an attribute. The requirements state that there is a list of qualifications. The word list implicitly implies some kind of ordering but we do not know from the requirements anything about how this ordering should be. We need to have this clarified with our “customer”, but for the time being we will assume that there is no specific ordering which has importance for the desired functionality. This is shown in Figure 2.

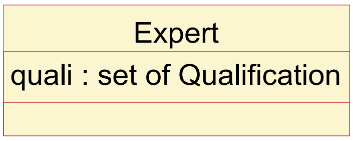


Figure 2: The Expert Class.

Somehow we need to make some connection to associate alarms and a schedule of experts. In order to be able to express the *precise limitations* in the UML/VDM++ methodology for such connections we typically recommend creating a main class, containing associations to the other classes.

Guideline 2: Create a “main” class to represent the entire system such that the precise limitations between the different classes and their associations can be expressed here.

In our example the main class will be **Plant**. Recall that the purpose of our model is to clarify the rules concerning the duty schedule and the calling out of experts to deal with alarms. We choose Plant as a class to model an abstract perspective focusing on this purpose. Hence, two aspects of the “plant” are important: the *schedule* of experts on duty and the collection of (registered) possible *alarms*. Let us consider the alarms first. We need to have an association from the Plant class to the Alarm class and since we may have more than one alarm in our system we need to use a multiplicity with this association. We call this association *alarms* (see figure below).

Guideline 3: Whenever an association is introduced one should consider the multiplicity of it and give it a role name in the direction in which one wishes to use the association.

Let us now consider the schedule that must hold a number of experts allocated to periods. For each period we can have zero or more experts on duty. Thus we need to use an association which is qualified with period and has a multiplicity of zero or more. We call this association *schedule*.

Guideline 4: If an association depends on some value a qualifier should be introduced for the association. The name of the qualifier must be a VDM++ type.

We are not told much about periods in the requirements, and we don't need to know much with the chosen focus of the model. We can model period as a type because it does not contain any "real" functionality.

At this point in time the class diagram for our system can be drawn with three classes as shown in Figure 3.

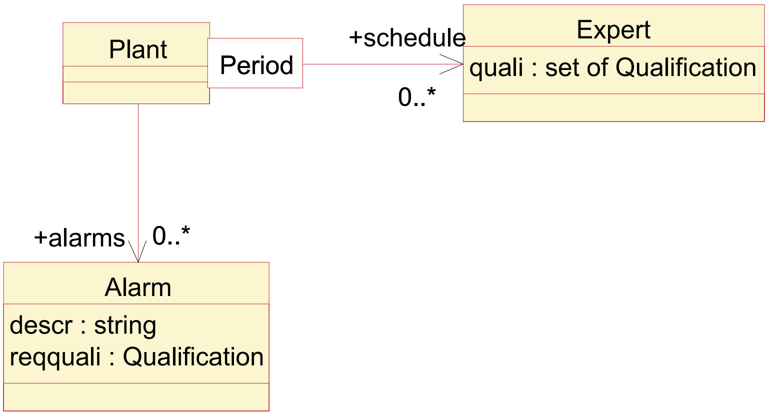


Figure 3: Initial Class Diagram.

Here we have used Rose, adding attributes and establishing relationships between the classes. We enter attributes and their types according to the templates provided by Rose. The types are VDM++ types, e.g. the set type constructor "set of" and class names and other type identifiers. All of this could equally well have been done directly in VDM++, and sometimes developers find it faster to write the textual model first and produce the graphical visualization using the Rose-VDM++ Link.

There is no such thing as the right model. For example, if we wanted to clarify the business processes concerning the use of this alarm subsystem, perhaps as part of a larger computer system, then our model would probably be different. We might want to focus more on how schedules are constructed and maintained.

Next we map the UML model to VDM++ skeletons automatically, using the Rose-VDM++ Link. These are included below.

The class Plant

```
--
-- THIS FILE IS AUTOMATICALLY GENERATED!!
--
-- Generated at Mon 09-Aug-99 by the Rose VDM++ Link
--
class Plant

instance variables
 alarms : set of Alarm;
 schedule : map Period to set of Expert;

end Plant
```

Note that *schedule*, which is a qualified association in UML, is translated to a mapping in VDM++. A mapping is like a table, where it is possible to look up with a key (in the domain) to get the associated value (in the range). Above, the key is a period and the value is a set of experts. Also note that the VDM++ set type is used to represent unordered "zero-or-many" associations, as in the *alarms* instance variable.

The class Expert

```
--
-- THIS FILE IS AUTOMATICALLY GENERATED!!
--
-- Generated at Mon 09-Aug-99 by the Rose VDM++ Link
--
class Expert

instance variables
 quali : set of Qualification;

end Expert
```

Note again that the VDM++ set type is used to represent the UML association with a “zero-or-many” multiplicity for the *quali* instance variable.

The class Alarm

```
--
-- THIS FILE IS AUTOMATICALLY GENERATED!!
--
-- Generated at Mon 09-Aug-99 by the Rose VDM++ Link
--
class Alarm

instance variables
 descr : string;
 reqquali : Qualification;

end Alarm
```

Note that attributes of UML classes become instance variables of VDM++ classes, just like UML associations. The difference is that the type of an attribute is not a class.

Type checking the classes

Guideline 5: Use **VDMTools** to check internal consistency as soon as class skeletons have been completed (before any functionality has been introduced).

Using **VDMTools** we can try to type check the model in order to ensure its internal consistency, i.e. that all identifiers are well-defined. The three classes above are not type correct, as there are three identifiers that are not defined: *Period*, *Qualification* and *string* (not built-in in VDM++). Therefore the following three type definitions are inserted into the three VDM++ classes respectively.

```
class Plant

types
 public Period = token;

instance variables
...
end Plant
```

The type *token* contains an infinite set of unspecified values with equality as the only operator. It is used because we do not care what representation for periods that will be chosen in the final implementation at this point of time. We abstract away from this. The type *Period* needs to be declared `public` because it must be available outside the *Plant* class.

```
class Expert

types

 public Qualification = <Mech> | <Chem> | <Bio> | <Elec>;

instance variables
...
end Expert
```

Qualification is an enumeration type defined as unions (vertical bars) of quote types in VDM++. A quote type has the same name as the single value that it holds, which must be written in “<” and “>” signs.

```
class Alarm

types
 public string = seq of char;

instance variables
 descr : string;
 reqquali : Expert`Qualification;

end Alarm
```

Note that the type of the instance variable *reqquali* has been prefixed with the class name *Expert* since *Qualification* is defined there. Using the Rose-VDM++ Link, this change is updated at the Rose UML level automatically as shown in Figure 4.

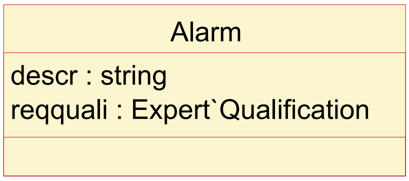


Figure 4: The Updated Alarm Class.

The type definitions do not have a counter part in the UML model and are therefore not translated. However they are kept in the VDM++ model files and cannot be deleted (or changed) by updates in the UML model.

3.3 Sketching Signatures for operations

We continue the development by adding operation signatures in UML. All three operations listed in the directory above belong naturally in the class Plant, because they are dependent on the schedule which is allocated there. The updated class diagrams for Plant is shown in Figure 5.

The signatures of the operations are straightforward. For example, the *ExpertToPage* operation takes an alarm and a period as input and returns an expert as a result.

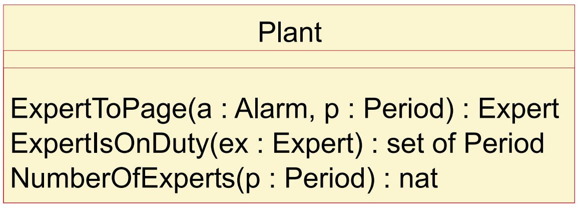

Plant
ExpertToPage(a : Alarm, p : Period) : Expert
ExpertIsOnDuty(ex : Expert) : set of Period
NumberOfExperts(p : Period) : nat

Figure 5: The Updated Plant Class.

Guideline 6: Think carefully about the parameter types and the result type as this activity often is able to identify missing connections in the class diagram.

The updated skeleton VDM++ class is produced automatically.

```
class Plant

types
 public Period = token;

instance variables
 alarms : set of Alarm;
 schedule : map Period to set of Expert;

operations
 ExpertToPage : Alarm * Period ==> Expert
 ExpertToPage(a, p) ==
   is not yet specified;

 ExpertIsOnDuty : Expert ==> set of Period
 ExpertIsOnDuty(ex) ==
   is not yet specified;

 NumberOfExperts : Period ==> nat
 NumberOfExperts(p) ==
   is not yet specified;

end Plant
```

It is possible to syntax and type check the model we have developed above but it is too vague to be of much use for validation purposes. Our next step is to add more precision to this model using VDM++. Note that traditionally most UML developers would stop at this step and as we shall see below the most important analysis and design discoveries are still to come.

4 Making the Model More Precise

At this stage it is a good idea to review the requirements to see that our model covers the individual ones satisfactorily. Clearly we have not yet considered the operations in detail, so **R6**—**R8** are not fully covered. Otherwise the requirements seem covered reasonably well, except that we have not documented requirement **R3** anywhere:

R3 There must be experts on duty during all periods allocated in the system.

However, the graphical and the type checked VDM++ model above has some further hidden assumptions and unclear aspects as we shall see below.

Typically a person implementing a model will not, and should not, do this from the original requirements directly, but using analysis and design models with accompanying comments. That is one purpose of models. Hence, the more precise, yet abstract, we can make such models the lower is the risk of an erroneous implementation, without prejudice to choice of implementation.

4.1 Adding Invariant Properties

We can formulate requirement **R3** in a precise way in the VDM++ model. First, what does it mean that a period is allocated in the system? This is when it is in the schedule for experts on duty, i.e. in the domain of the instance variable schedule, which is a mapping from periods to sets of experts.

```
forall p in set dom schedule &
  there are experts on duty in p
```

Next, what does it mean that there are experts on duty for a period? It means that the range value associated with the period, namely a set of experts, is non-empty.

```
  forall p in set dom schedule & schedule(p) <> {};
```

In VDM++, this predicate is added as an invariant (abbreviated `inv`) in the instance variables section of the class *Plant*:

```
class Plant
...

instance variables
 alarms : set of Alarm;
 schedule : map Period to set of Expert;
 inv
   forall p in set dom schedule & schedule(p) <> {};

...
end Plant
```

An invariant is a condition that must hold always of an object state.

Guideline 7: You should try to document important properties or limitations as invariants because some part of a system may implicitly assume some invariant property to hold that other parts should be aware of.

4.2 Completing Operation Definitions

Next we consider conditions associated with operations, pre-conditions and post-conditions respectively. A pre-condition formalises assumptions made by an operation, i.e. what must hold of the parameters and object state before an operation is executed. A post-condition states what an operation provides, i.e. what holds after it has been executed. Thus the post-condition is a relation between the initial object state and parameters on one side, and the final state and the result on the other. For example, the operation *ExpertToPage* takes an alarm and a period as inputs and returns an expert to handle the alarm. Will it accept an arbitrary alarm or period (pre-condition)? And what must hold of the expert (post-condition)?

`ExpertToPage` has the following signature:

```
ExpertToPage : Alarm * Period ==> Expert
```

However, as indicated above, it cannot treat any alarm and period. First, the period must be known about in the schedule, in order to ensure that there are experts on duty. It also seems obvious to require that the alarm has been registered in the system, i.e. that it is among the possible alarms contained in the instance variable alarms:

```
ExpertToPage : Alarm * Period ==> Expert
ExpertToPage(a, p) ==
  is not yet specified
pre a in set alarms and
    p in set dom schedule
```

Moreover, the operation should not return any expert on duty. The expert should have the right qualification to cope with the alarm. This is documented in the post-condition:

```
post let ex = RESULT in
       ex in set schedule(p) and
       a.GetReqquali() in set ex.GetQuali();
```

The let-expression just binds the result of the operation to an identifier. The first conjunct says that the result expert is on duty, the second that the qualification requirement is met. Here we have assumed that access operations `GetReqquali` and `GetQuali` are defined for the `Alarm` and `Expert` classes respectively. Because of information exchange these kind of access operations must often be defined in OO developments, but they are trivial to define. We do not need to specify a body of the operation at this stage, but this is introduced later in order to make the operation executable.

Note that the definition given here does not state which of the experts should be chosen if more than one expert with the right qualification is on duty in the given period. The requirements have not given us any way to see what the most desirable choice is and therefore this implicit definition leaves freedom to decide on this issue later in the development process.

Guideline 8: When several choices are possible you should try to use implicit ways of describing the desired functionality.

Now we can ask ourselves whether it is always possible to return such an expert with the right qualification? We cannot be sure in the current model as there is no limitation on the schedule of experts on duty in relation to the registered alarms. However, we can introduce this dependency by adding an invariant property:

```
instance variables
 alarms : set of Alarm;
 schedule : map Period to set of Expert;
 inv forall p in set dom schedule & schedule(p) <> {};
 inv forall a in set alarms &
        forall p in set dom schedule &
           exists ex in set schedule(p) &
              a.GetReqquali() in set ex.GetQuali();
```

The new invariant says that for any alarms and periods registered in the system there must be an expert on duty in the period who has the right qualification to handle the alarm. This ensures that the specification of `ExpertToPage` makes sense and is implementable, i.e. a desired expert can always be found. Note that because of the precision of the VDM++ model we have been forced to ask ourselves such detailed questions related to the desired functionality of the system. For example, the above invariant would also be important if the system was extended to support that experts could change their shifts. The invariant identifies a property which is a dominant design parameter for the system, but which is not identified using the conventional OO approach.

Guideline 9: You should try to identify additional invariant properties when operations are being described.

`NumberOfExperts` has the following signature:

```
 NumberOfExperts : Period ==> nat
```

It must return the number of experts on duty in a given period. Probably we want the period to be a known one in the schedule. This is the pre-condition. The result should just be the cardinality of the set of experts on duty in the period. This is the body of the operation:

```
NumberOfExperts : Period ==> nat
NumberOfExperts(p) ==
  return card schedule(p)
pre p in set dom schedule;
```

We do not need a post-condition in this case, as it would just copy the body, which is already described in a fairly high-level way.

`ExpertIsOnDuty` has the following signature:

```
ExpertIsOnDuty : Expert ==> set of Period
```

It must be possible to ask when any expert is on duty so we do not need to specify a pre-condition for this operation. Again a post-condition is not necessary because the body of the operation can be described in a high-level and natural way:

```
ExpertIsOnDuty : Expert ==> set of Period
ExpertIsOnDuty(ex) ==
  return {p | p in set dom schedule &
              ex in set schedule(p)};
```

The body returns the set of periods in the domain of the schedule such that the given expert is on duty in the periods. Precise, clear and yet abstract! Such a statement could take up several lines of code in a programming language. In Java this would look something like:

```
import java.util.*;

class Alarm {

  Map schedule;

    Set ExpertIsOnDuty(Integer ex) {
      TreeSet resset = new TreeSet();
      Set keys = schedule.keySet();
      Iterator iterator = keys.iterator();

      while(iterator.hasNext()) {
        Object p = iterator.next();
        if ( ( (Set) schedule.get(p)).contains(ex))
            resset.add(p);
      }

      return resset;
   }
}
```

Guideline 10: Try to make explicit operation definitions in VDM++ precise and clear, and yet abstract compared to code written in a programming language.

To summarise, let us map our changes in the (type checked and consistent) VDM++ model to the UML model, using the Rose-VDM++ Link. The resulting diagram is:

This gives a nice overview of the model, but has no detailed information about the requirements. The VDM++ model holds essential information for the implementation of the system. In this way the two models, or the two views of the same model, are complementary.

5 Validating the VDM++ Model

In the previous sections we have gone through the first steps of the construction of a model. We have seen how type checking facilities of **VDMTools** can be used to check its internal consistency. Such facilities are useful but they do not allow us to detect all errors. In addition, validation can be used to get confidence that the model describes

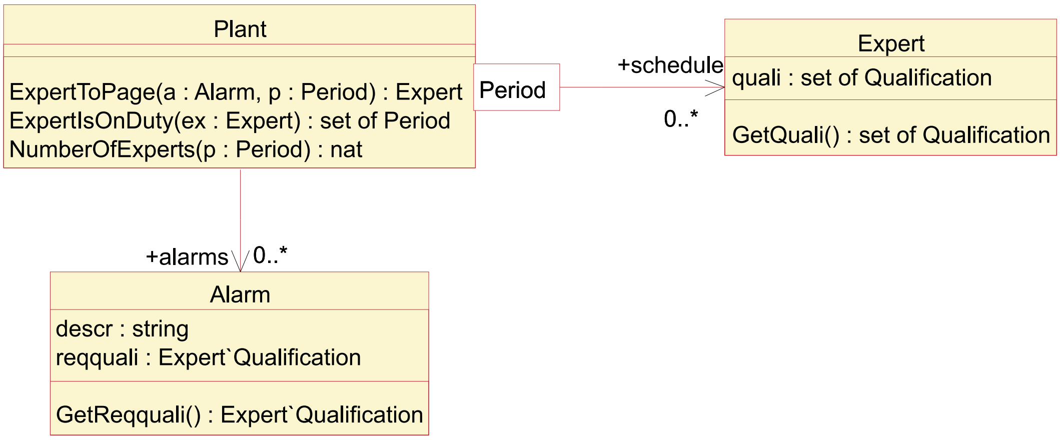

Plant
ExpertToPage(a : Alarm, p : Period) : Expert
ExpertIsOnDuty(ex : Expert) : set of Period
NumberOfExperts(p : Period) : nat
Period
+schedule
0..*
Expert
quali : set of Qualification
GetQuali() : set of Qualification
+alarms
0..*
Alarm
descr : string
reqquali : Expert`Qualification
GetReqquali() : Expert`Qualification

Figure 6: The Updated UML Class Diagram.

what the customer wanted, and to clarify what the customer thought was wanted.

Essentially there are two approaches to validating models which are based on systematic testing and rapid prototyping, respectively. Therefore **VDMTools** supports the ability to validate models using conventional testing techniques and to execute models together with other code, e.g. a graphical front end. Hence, the interpreter of the VDM++ Toolbox is able to execute specifications symbolically, before they are implemented. During execution it automatically checks annotations, i.e. invariants and pre- and post-conditions. If some condition does not hold the user is notified with specific information about the violated condition and where the violation occurred. The stronger the conditions are and the more comprehensive the testing is, the higher the confidence in a model will be as a result of the validation.

5.1 Automated Validation Using Systematic Testing

Models are tested in a traditional way, so we shall not go into the details of testing theory in this document. However, it is worth noting that the interpreter supports two modes of working. It is possible to test models interactively, where test expressions are given to the interpreter manually and evaluated immediately. The other mode is a batch mode, where the interpreter is executed automatically on a potentially large test suite. In this mode, it is possible to produce test coverage coloring of non-executed parts of a model as well as statistics about the execution.

In order to carry out testing it is often necessary to introduce operations for setting the values of the different instance variables, like the `SetReqquali` and `SetDescr` operations used above. Moreover, the operation `ExpertToPage` defined above cannot be executed in its current form. It is what we call an implicit operation because it does not have an operation body. However it is easy to turn the post-condition into a body and make the operation executable:

```
public
ExpertToPage : Alarm * Period ==> Expert
ExpertToPage(a, p) ==
  let ex in set schedule(p) be st
      a.GetReqquali() in set ex.GetQuali()
  in return ex
pre a in set alarms and
    p in set dom schedule
post let ex = RESULT in
       ex in set schedule(p) and
       a.GetReqquali() in set ex.GetQuali();
```

This uses a high-level VDM++ expression, called the let-be-such-that expression, which selects an arbitrary expert such that the predicate after “be st” holds, and then returns this expert.

The interpreter can execute commands like:

```
create a1 := new Alarm()
print a1.SetReqquali(<Mech>)
print a1.SetDescr("Mechanical fault")
```

The command `create` is used to make an instance of a class. The command `print` evaluates an expression, e.g. a method invocation as above. Each line can be typed to the interpreter manually or entire test scenarios can be set up in script files containing such commands. A script file is executed using the command script. Script files can call other script files as well. The following file is called test1, and is executed by typing `script test1` in the interpreter window.

```
init
script testing/alarm1
script testing/expert1
create plant := new Plant()
print plant.SetSchedule({plant.p1 |-> {ex1}})
print plant.SetAlarms({a1})
print plant.ExpertIsOnDuty(ex1)
print plant.ExpertToPage(a1,plant.p1)
```

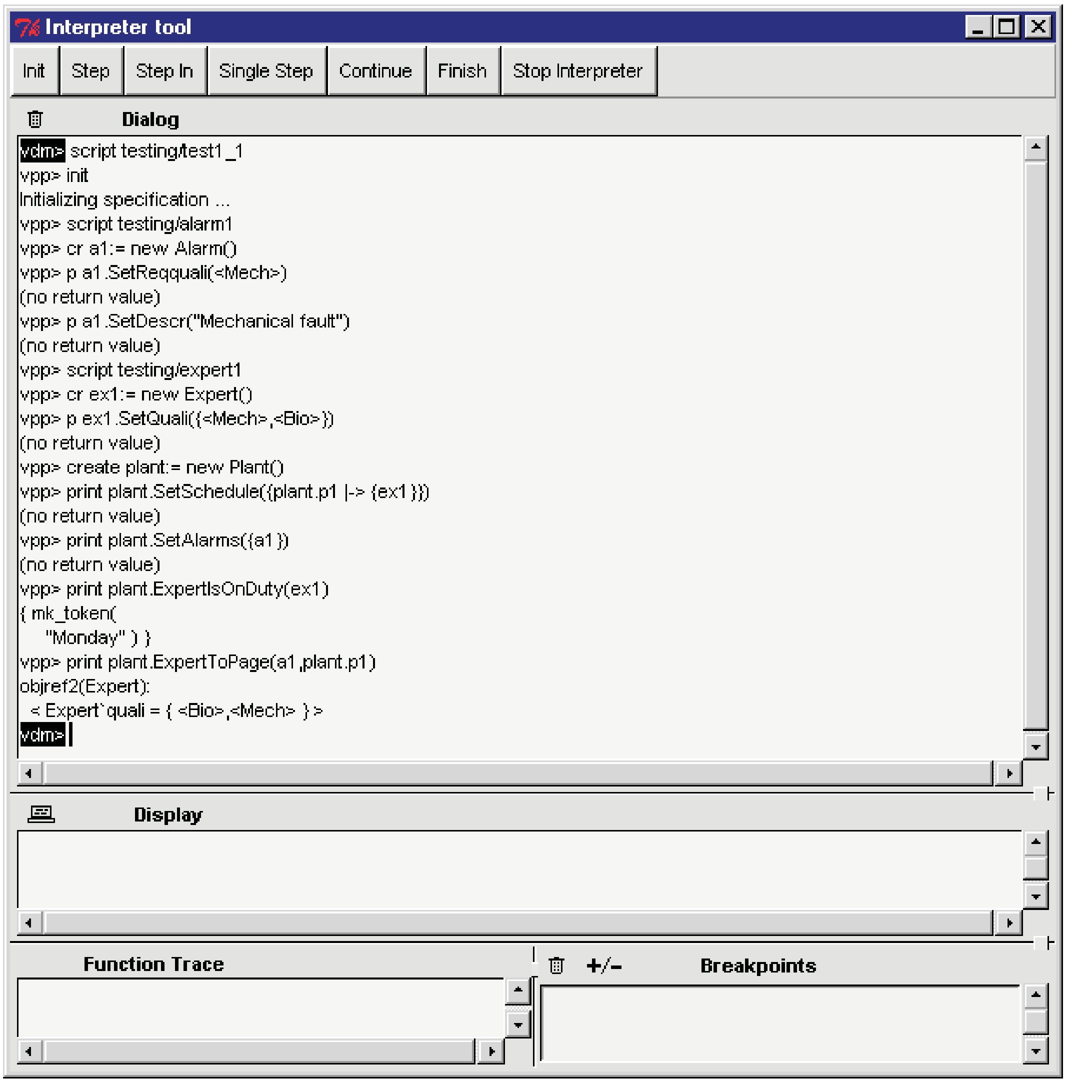
It calls two other scripts, the file `alarm1` which defines a new alarm object `a1`:

```
create a1 := new Alarm()
print a1.SetReqquali(<Mech>)
print a1.SetDescr("Mechanical fault")
```

And the file `expert1`, which defines a new expert object `ex1`:

```
create ex1 := new Expert()
print ex1.SetQuali({<Mech>,<Bio>})
```

The test script updates the schedule and set of alarms. At the same time, it checks invariants and other properties automatically.



```
vdm> script testing/test1_1
vpp> init
Initializing specification ...
vpp> script testing/alarm1
vpp> cr a1:= new Alarm()
vpp> p a1.SetReqquali(<Mech>)
(no return value)
vpp> p a1.SetDescr("Mechanical fault")
(no return value)
vpp> script testing/expert1
vpp> cr ex1:= new Expert()
vpp> p ex1.SetQuali({<Mech>,<Bio>})
(no return value)
vpp> create plant:= new Plant()
vpp> print plant.SetSchedule({plant.p1 |-> {ex1}})
(no return value)
vpp> print plant.SetAlarms({a1})
(no return value)
vpp> print plant.ExpertIsOnDuty(ex1)
{ mk_token(
    "Monday" ) }
vpp> print plant.ExpertToPage(a1,plant.p1)
objref2(Expert):
  < Expert`quali = { <Bio>,<Mech> } >
vdm>
```

Figure 7: Using the Interpreter.

The identifier `p1` is a constant token value, defined in the class `Plant`. The version of the classes used during testing can be found in Appendix A. The figure above shows a screen dump of the Toolbox interpreter after executing the above `test1` script as shown in Figure 7.

The following test script executes `test1` above and then attempts to add a new alarm `a2` which requires the electrical qualification:

```
script test1
script alarm2
print plant.SetAlarms({a1,a2})
```

Here the script `alarm2` contains the following commands:

```
create a2 := new Alarm()
print a2.SetReqquali(<Elec>)
print a2.SetDescr("Electrical fault")
```

Note that the expert does not have the electrical qualification. Therefore this breaks the invariant as the screen dump from Figure 8 shows.

Note that the interpreter provides specific location information of the runtime error, and the error message says what is wrong. The display window shows in the specification source file where the problem was and the function trace gives the call stack, which in this case is only one deep. By clicking on the three dots in the function trace window, the argument of the listed operation call can be expanded.

The interpreter can also be used to debug specifications. It is possible to set breakpoints on functions and then interactively step through an execution and inspect variables in scope.

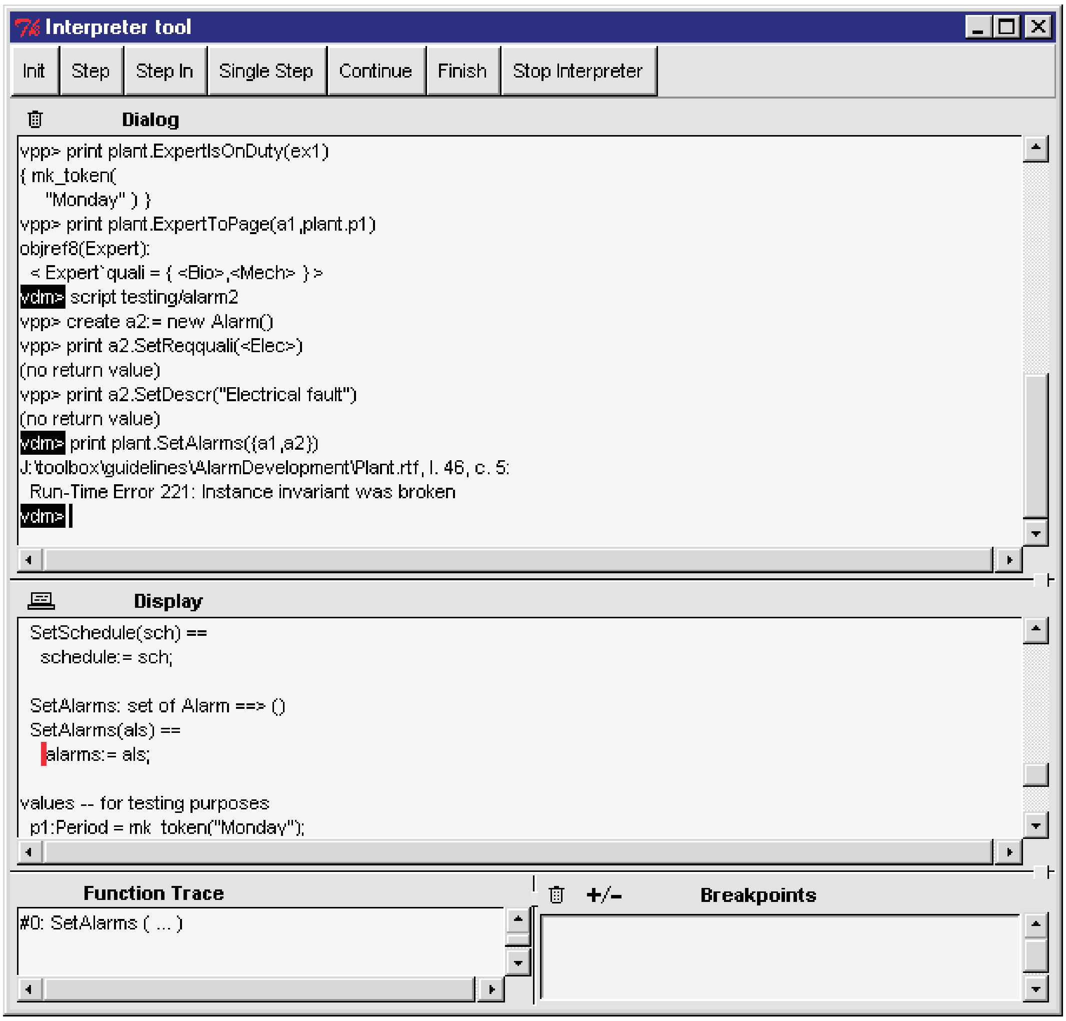
As part of the pretty-printing facility, it is possible to print test coverage information using colours in specifications. The VDM++ Toolbox is executed by typing vppde (VDM++ development environment) in a DOS or UNIX shell. This command takes various options, for example, "`-t`" activates the type checker and "`-i`" activates the interpreter. Hence, the specification above is type checked by typing

```
vppde -t Plant.rtf Alarm.rtf Expert.rtf
```

The command line interpreter requires that we develop a so-called test argument file. This can contain a list of expressions to be evaluated by the interpreter. An example could be the following file which is called `test1.arg` and runs a version of the above test script:

```
new Test1().run()
```

This uses a new class Test1:



```
vpp> print plant.ExpertIsOnDuty(ex1)
{ mk_token(
    "Monday" ) }
vpp> print plant.ExpertToPage(a1,plant.p1)
objref8(Expert):
  < Expert`quali = { <Bio>,<Mech> } >
vdm> script testing/alarm2
vpp> create a2:= new Alarm()
vpp> print a2.SetReqquali(<Elec>)
(no return value)
vpp> print a2.SetDescr("Electrical fault")
(no return value)
vdm> print plant.SetAlarms({a1,a2})
J:\toolbox\guidelines\AlarmDevelopment\Plant.rtf, l. 46, c. 5:
  Run-Time Error 221: Instance invariant was broken
vdm>
```

```
  SetSchedule(sch) ==
    schedule:= sch;

  SetAlarms: set of Alarm ==> ()
  SetAlarms(als) ==
    alarms:= als;

values -- for testing purposes
  p1:Period = mk_token("Monday");
```

```
#0: SetAlarms ( ... )
```

Figure 8: Breaking an Invariant in the Interpreter.

```
class Test1

instance variables
 a1 : Alarm;
 ex1 : Expert;
 plant : Plant;

operations
 public run: () ==> set of Plant`Period * Expert
 run() == test1();

 test1: () ==> set of Plant`Period * Expert
 test1() ==
   (alarm1();
    expert1();
    plant:= new Plant();
    plant.SetSchedule({plant.p1 |-> {ex1}});
    plant.SetAlarms({a1});
    let periods = plant.ExpertIsOnDuty(ex1),
        expert = plant.ExpertToPage(a1,plant.p1)
    in
      return mk_(periods,expert));

 alarm1: () ==> ()
 alarm1() ==
   (a1:= new Alarm();
    a1.SetReqquali(<Mech>);
    a1.SetDescr("Mechanical fault"));

 expert1: () ==> ()
 expert1() ==
   (ex1:= new Expert();
    ex1.SetQuali({<Mech>,<Bio>}))

end Test1
```

Then the following command is executed:

```
vppde -iDIPQ test1.arg Plant.rtf Alarm.rtf Expert.rtf Test1.rtf
```

While testing from the command line, the interpreter can collect test coverage information. This requires that we first produce a test coverage file as follows

```
vppde -p -R vdm.tc Plant.rtf Alarm.rtf Expert.rtf Test1.rtf
```

and then execute a test case based on the argument file above

```
vppde -iDIPQ -R vdm.tc test1.arg Plant.rtf
                       Alarm.rtf Expert.rtf Test1.rtf
```

The produced output file contains the expected result:

```
mk_( { mk_token(
 "Monday" ) },
 objref4(Expert):
 < Expert`quali = { <Bio>,<Mech> } > )
```

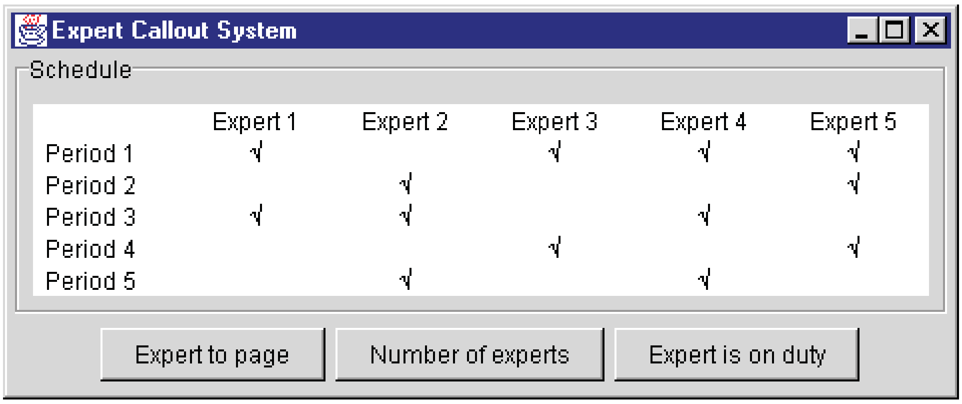
The resulting test coverage information is displayed in the pretty-printed specification in Appendix A.

Of course the vppde commands above can be called from batch or shell script files under Windows and Unix. This approach is recommended for systematic testing and is illustrated on a sorting example in the Toolbox User Manual [SCSc].

5.2 Visual Validation Using Rapid Prototyping

Testing is an excellent approach to validating a model and engineers master testing techniques well. However, the kind of relatively low-level testing introduced above is suitable mainly for engineers and less for customers, non-technical staff and management, who might not be familiar with VDM (or UML) and the details of a model. The VDM++ Toolbox provides an API to facilitate the need for presenting models to such an audience through a graphical front-end. The front-end can then work as graphical user interface to the model, so that customers can test the model directly via the GUI. An example of a simple front-end for the alarm example could look like in Figure 9

Obviously better GUIs could be developed but this is not the essential point here, rather that users can easily use this to test the developer's understanding of the requirements of the system. In this way, the VDM++ model is used as an early prototype of the



	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Period 1	√		√	√	√
Period 2		√			√
Period 3	√	√		√	
Period 4			√		√
Period 5		√		√	

Figure 9: A Prototype GUI for the Alarm System.

system. The front-end can be built using an engineer's favourite tool independent of VDM++. The one above was developed in Java/Swing.

The API can also be used to test models together with legacy systems, in fact, any other code independent of programming language, due to its general nature. This is because the API uses the Common Object Request Broker Architecture (CORBA), allowing communication with code written in any language for which an object request broker (ORB) exists. Currently free and commercial ORBs exist for all major languages. As CORBA is a network based architecture, this also means that multiple external clients located on a network can communicate with a single VDM++ Toolbox. Therefore this validation approach can also be used for distributed models.

6 Code Generating the VDM++ Model

Though the VDM++ model is an abstract model of the alarm system it is concrete enough to be code generated to Java or C++, compiled and run. The VDM++ Toolbox provides automatic code generators to accomplish this, which produce directly compilable, production quality code. Typically abstract models as the one above need more work before they can be code generated and delivered to a customer. Models for code generation are typically more design and implementation oriented, in particular, if there are strong efficiency requirements. However, even high-level expressions like the let-be-such-that expression introduced in the previous section can be code generated, compiled and run in Java and C++.

In addition to the obviously drastic reduction in the time to construct an implementation, automatic code generation offers a number of benefits. Principle amongst these is the strong correspondence between the abstract model and the generated code. This simplifies understanding of the code and its architectures. This also opens up the possibility of reusing test data originally used for testing the model. Of course it may be that the algorithm used in the generated code is inappropriate in a particular instance, so in this case it is possible to generate code skeletons which may then be hand implemented.

7 Conclusions

This document has presented some method guidelines for the construction of software models using VDM++. The methodology was applied to a simple example, an alarm system for a chemical plant. We would like to note that for brevity the model presented was abstract omitting many details. However, VDM++ can equally well support more concrete and substantially larger models e.g models corresponding to hundreds of pages of UML and thousands of lines of VDM++. The key to the approach described is the combination of UML and VDM++, so we conclude by summarising the complementary benefits of UML and VDM++.

7.1 Who Should Use the Rose-VDM++ Link

We believe that the following two groups of users can benefit from **VDMTools** and its Rose-VDM++ Link:

1. Those who apply or wish to apply a graphical modelling notation like UML in their software development process and want to improve and automate the reviewing and validation of models. Their motivation for doing this can be that their software is critical in some way or they want to reduce risk, and therefore they wish to obtain early and high confidence in their models by clarifying requirements and uncovering bugs as early as possible using the VDM technology.

2. Those who apply or wish to apply a formal object-oriented specification language like VDM++ in their development process and want to get access to graphical visualisation capabilities for documentation purposes.

Both groups will probably use the link in more or less the same fashion. The first group may wish to do more modelling in UML while the second group will do more modelling in VDM++, but the round trip engineering capabilities of the link will be central to both groups. Hence, the users can benefit from starting the modelling at UML level because the graphical notation is better for obtaining an overview of the problem. Once, this model has reached a relatively fixed state it will be appropriate to translate the model to VDM++ and continue the analysis there, or switch back and forth between the two representations as desired.

7.2 Graphical Modelling in UML

We believe that UML and Rose are more suitable for

- making the first sketches of an object-oriented model of a software system (in part supported by a piece of paper),
- defining graphically visible aspects of a model such as class names, names of attributes and operations, signatures of operations and relations between classes (inheritance, associations, role names, etc.),
- visual and efficient presentation of a model, e.g. through different diagram views, and
- documentation of abstract and high-level aspects of a software model.

An example of such a use of UML and Rose has been shown in this document.

7.3 Analysing a Model using VDMTools

We believe that VDM++ and the **VDMTools**are more suitable for

- precise description of desired functionality, e.g. by formalising requirements properties as VDM++ invariants on instance variables and pre- and post-conditions on operations,
- checking internal consistency of models using type checking, e.g. checking signatures of operations and types in declarations (attributes and associations in UML)
- defining and checking concrete aspects of models such as what operations should do, which would normally be expressed in natural language which is not checkable by tools,

- gaining confidence in models through a systematic and repeatable reviewing process based on executing and testing models while consistency checking documented properties, and
- rapid prototyping where the model is executed together with a graphical front-end, or existing software for which a new component is being specified.

The beneficial use of the VDM technology to analyse a version of the SAFER model is described in the papers [AL97, AS99]. SAFER is a backpack module for astronauts to wear when they are outside a space shuttle to do a repair. Other papers on the VDM technology in the safety critical and security critical domains may also be of interest [ALR98, LFB96].

References

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A The UML and VDM++ Models

This appendix lists the pretty-printed VDM++ classes of the model of the chemical plant example, plus a test class. For each class a test coverage table has been inserted by the **VDMTools** pretty-printer. Non-executed parts of the model are coloured in red (or gray), see the operation NumberOfExperts in the class Plant.

The UML class diagram in Figure 10 gives an overview of the model.

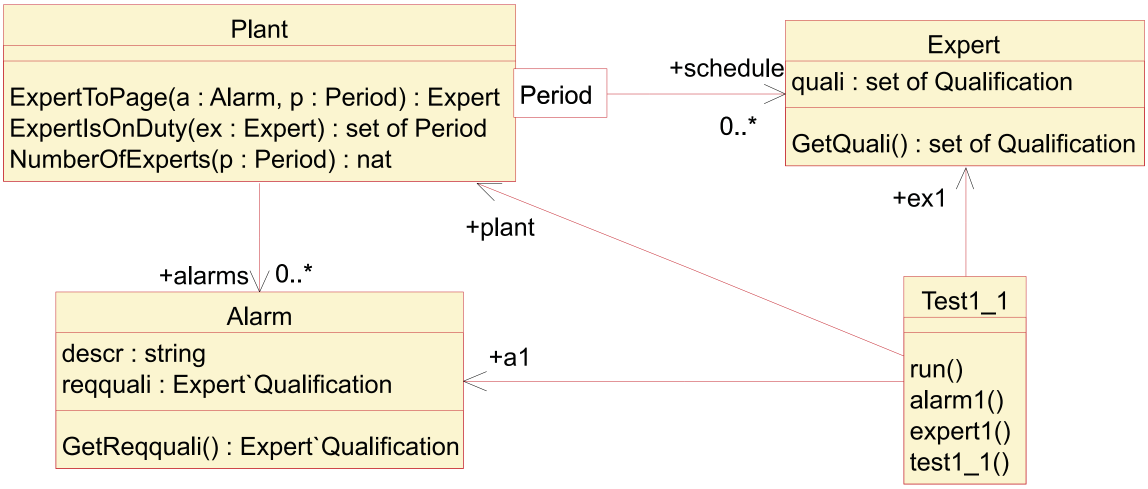
Plant
ExpertToPage(a : Alarm, p : Period) : Expert
ExpertIsOnDuty(ex : Expert) : set of Period
NumberOfExperts(p : Period) : nat
Period
+schedule
0..*
Expert
quali : set of Qualification
GetQuali() : set of Qualification
+ex1
+plant
+alarms
0..*
Alarm
descr : string
reqquali : Expert`Qualification
GetReqquali() : Expert`Qualification
+a1
Test1_1
run()
alarm1()
expert1()
test1_1()

Figure 10: The Full UML Class Diagram Model.

A.1 The Class Plant

```
class Plant

types
 public Period = token;

instance variables
 alarms : set of Alarm := {};
 schedule : map Period to set of Expert := {|->};
 inv
   forall p in set dom schedule & schedule(p) <> {};
 inv
   forall a in set alarms &
      forall p in set dom schedule &
         exists ex in set schedule(p) &
            a.GetReqquali() in set ex.GetQuali();

operations
 public
 ExpertToPage : Alarm * Period ==> Expert
 ExpertToPage(a, p) ==
   let ex in set schedule(p) be st
       a.GetReqquali() in set ex.GetQuali()
   in return ex
 pre a in set alarms and
     p in set dom schedule
 post let ex = RESULT in
       ex in set schedule(p) and
       a.GetReqquali() in set ex.GetQuali();

 public
 ExpertIsOnDuty : Expert ==> set of Period
 ExpertIsOnDuty(ex) ==
   return {p | p in set dom schedule
             & ex in set schedule(p)};

 public
 NumberOfExperts : Period ==> nat
 NumberOfExperts(p) ==
   return  card  schedule ( p )
 pre  p  in set  dom  schedule;
```

```
  public
  SetSchedule: map Period to set of Expert ==> ()
  SetSchedule(sch) ==
    schedule:= sch;

  public
  SetAlarms: set of Alarm ==> ()
  SetAlarms(als) ==
    alarms:= als;

values -- for testing purposes
  public p1:Period = mk_token("Monday");
  public p2:Period = mk_token("Tuesday");
  public p3:Period = mk_token("Wednesday");
  public p4:Period = mk_token("Thursday");
  public p5:Period = mk_token("Friday");

end Plant
```

name	*#calls*	*coverage*
Plant`ExpertIsOnDuty	1	100%
Plant`ExpertToPage	1	100%
Plant`NumberOfExperts	0	0%
Plant`SetAlarms	1	100%
Plant`SetSchedule	1	100%
total		***84%***

A.2 The Class Expert

```
class Expert

types
 public Qualification = <Mech> | <Chem> | <Bio> | <Elec>;

instance variables
 quali : set of Qualification;

operations
 public
 GetQuali: () ==> set of Qualification
 GetQuali() == return quali;

 public
 SetQuali: set of Qualification ==> ()
 SetQuali(qs) ==
   quali:= qs;

end Expert
```

name	***#calls***	***coverage***
Expert`GetQuali	3	100%
Expert`SetQuali	1	100%
total		***100%***

A.3 The Class Test1

```
class Test1

instance variables
 a1 : Alarm;
 ex1 : Expert;
 plant : Plant;

operations
 public
 run: () ==> set of Plant`Period * Expert
 run() == test1();

 public
 test1: () ==> set of Plant`Period * Expert
 test1() ==
   (alarm1();
    expert1();
    plant:= new Plant();
    plant.SetSchedule({plant.p1 |-> {ex1}});
    plant.SetAlarms({a1});
    let periods = plant.ExpertIsOnDuty(ex1),
        expert = plant.ExpertToPage(a1,plant.p1)
    in
      return mk_(periods,expert)
  );

 public
 alarm1: () ==> ()
 alarm1() ==
   (a1:= new Alarm();
    a1.SetReqquali(<Mech>);
    a1.SetDescr("Mechanical fault"));

 public
 expert1: () ==> ()
 expert1() ==
   (ex1:= new Expert();
    ex1.SetQuali({<Mech>,<Bio>}))

end Test1
```

name	***#calls***	***coverage***
Test1`alarm1	1	100%
Test1`expert1	1	100%
Test1`run	1	100%
Test1`test1	1	100%
total		***100%***