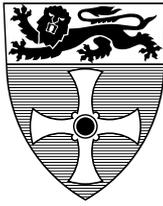


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# COMPUTING SCIENCE

VDMTools: advances in support for formal modeling in VDM

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VDMTools: advances in support for formal modeling in VDM

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**Abstract**

We describe the current status of “VDMTools”, a group of tools supporting the analysis of system models expressed in the formal language of the Vienna Development Method. Three dialects of the language are supported: the ISO standard VDM specification language with support for modular structuring, the extension VDM++ which supports object-oriented structuring and concurrency, and a version extending VDM++ with features for modeling and analysing distributed embedded real-time systems. VDMTools provides extensive static semantics checking, automatic code generation, round-trip mapping to UML class diagrams, documentation support, test coverage analysis and debugging support. The tools’ focus is on supporting the cost-effective development and exploitation of formal models in industrial settings. The paper presents the components of VDMTools and reports experience using them for the development of large models.

## Bibliographical details

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### Abstract

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### About the author

John Fitzgerald is Reader in Computing Science at Newcastle University. His research crosses the academic-industry divide and concerns the use of formal methods to support the design of trustworthy, resilient computing systems. He is most closely associated with the Vienna Development method (VDM) and particularly its proof theory. He is co-Investigator in the Trustworthy Ambient Systems project, the ReSIST Network of Excellence on Resilience in IST and the BAESYSTEMS Dependable Computing Systems Centre. He is Chairman of Formal Methods Europe.

Peter Gorm Larsen is Professor of Computer Technology and Embedded Systems at The Engineering College of Aarhus, Denmark and an independent consultant. An authority on system modelling, particularly the Vienna Development Method, he has pioneered the development of industrial-strength tool support for model-oriented specification languages, heading the group that initially developed VDMTools(R).

Shin Sahara is with CSK Systems in Japan. He has been closely involved with the strategy for the use and development of VDMTools since they were acquired by CSK. He has many years of experience in promoting the transfer of formal techniques and tools into industrial use in several application domains.

### Suggested keywords

FORMAL METHODS,  
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VDM,  
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SOFTWARE ENGINEERING TOOLS

# VDMTools: advances in support for formal modeling in VDM

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## Abstract

We describe the current status of “VDMTools”, a group of tools supporting the analysis of system models expressed in the formal language of the Vienna Development Method. Three dialects of the language are supported: the ISO standard VDM specification language with support for modular structuring, the extension VDM++ which supports object-oriented structuring and concurrency, and a version extending VDM++ with features for modeling and analysing distributed embedded real-time systems. VDMTools provides extensive static semantics checking, automatic code generation, round-trip mapping to UML class diagrams, documentation support, test coverage analysis and debugging support. The tools’ focus is on supporting the cost-effective development and exploitation of formal models in industrial settings. The paper presents the components of VDMTools and reports experience using them for the development of large models.

**Keywords:** Formal Methods, Vienna Development Method, VDM, Validation, Tool support.

## 1 Background

Formal methods are mathematically-based techniques for the modeling, analysis and development of software and systems [22, 12, 9, 11]. Their use is motivated by the expectation that, as in other engineering disciplines, performing an appropriate mathematical analysis can contribute to the reliability and robustness of a design. Formal methods can be used at various levels of rigour and, in industrial applications, it is paramount to be able to strike a proper balance between the effort spent on the use of formal techniques and the insight gained [14].

The Vienna Development Method (VDM) is one of the most mature formal methods, primarily intended for the modeling and subsequent development of functional aspects of software systems [36]. Applying VDM involves developing a system model expressed in a (formal) modeling language. The language’s formality means that the full range of analytic techniques, from testing to formal mathematical proof, can be applied to validate the model, or to verify the correctness of the model with respect to an existing statement of requirements or design. Three dialects of the VDM modeling language are in use, each supporting different forms of system:

1. VDM-SL [17] provides facilities for the functional specification of sequential systems with basic support for modular structuring. It has been standardised under the auspices of the International Organization for Standardization (ISO) [37].
2. VDM++ [16] extends VDM-SL with features for object-oriented modeling and concurrency [38].
3. VICE (VDM++ In Constrained Environments) further extends VDM++ with features for describing real-time computations [34] and distributed systems [46].

VDM modelling techniques have been used in a variety of ways within software development processes. One very pragmatic approach is to develop VDM-SL system models and analyse them by prototyping in a programming language. For example Kans and Hayton [25] report on the use of ABC+ to prototype VDM-SL specifications for educational purposes; Borba and Meira [6, 7] describe a prototype semi-automatic translation system producing Lazy ML code from VDM-SL models. These approaches have the drawback that another formalism (ABC+ or Lazy ML) must be introduced to cope with the semantics of the VDM-SL specifications. Furthermore the support provided for prototyping in these tools is not tailored for VDM-SL but rather depends on the programming language in use. Similar features have been found for other formal specification notations [21, 44, 10] and, more generally, there has been debate around the value of executable specifications have caused a debate [23, 20, 2, 18]. Liu’s work based on the SOFL language [31] contains elements derived from VDM and supports direct animation of models from systematically derived execution scenarios.

A more formal approach to the use of VDM-SL is through mathematical proof of essential properties. Many text books cover this area e.g. [5] provides a sound constructive approach to proof in VDM. Much of the mathematical foundation has been laid to support fully formal development in which the design steps from an abstract model to an implementation are formally verified [24]. However, it is rarely cost-effective to undertake such a development. Even with state-of-the-art tools, carrying out formal proofs on the industrial scale is still expensive, although success stories have begun to appear, such as those surrounding B [1, 3].

VDMTools are a development of the IFAD VDM Toolbox [13] to support the three dialects of VDM listed above

and intended to support a pragmatic approach [33] to the construction and analysis of formal models. The tools provide syntax checking, extensive static semantics checking and documentation support. Furthermore they support the validation of specifications written in a (large) executable subset of VDM-SL using testing and debugging techniques. We have applied VDMTools successfully to models up to 100k lines of VDM code in size.

## 2 Main Characteristics of VDM Modeling Notations

In this section we review the more distinctive features of the VDM modeling notations which pose challenges for tool support.

VDM models center on data type definitions built from a repertoire of abstract base types and type constructors union and record types, sets, sequences and mappings. Any type definition in VDM can be augmented with an *invariant*, a Boolean formula describing a property that must be respected by all elements of the newly defined type. Consider, for example, the following type definition in VDM-SL:

```
PosReal = real
inv r == r >= 0
```

This defines a new type `PosReal` containing all real numbers satisfying the invariant property (in this case that they are larger than or equal to zero). Such a type could then, for example, be used in the definition of a function, such as the following, which defines a function `ImplSort`:

```
functions

ImplSort (l: seq of PosReal)
         r: seq of PosReal
post IsPermutation(r,l) and
      IsOrdered(r);
```

The input `l` of the function `ImplSort` is a sequence of `PosReal`, so the function body can rely on the fact that the elements of `l` respect the invariant on that type. Note also that this function definition does not contain an expression or algorithm for calculating the result `r` from the input. Instead a postcondition characterizes the result in terms of the properties that are required of the result, namely that it should be a permutation of the input and that it should be ordered. This property is stated using two Boolean auxiliary functions: `IsPermutation` and `IsOrdered`.

Functions may also be defined explicitly. For example, the `IsOrdered` auxiliary function might be defined as follows:

```
IsOrdered: seq of real -> bool
IsOrdered(l) ==
  forall i, j in set inds l &
    i > j => l(i) >= l(j);
```

Here the body of the function is a Boolean expression stating that, for any indices in the sequence, the value at the high index is itself at least as large as the value at the lower index. As this example shows, because of the importance of data type invariants and the possibility of implicit definition, logic is a cornerstone of VDM.

In addition to the forms of construct introduced here, VDM also has a built-in notion of persistent state variables that can be modified by operations which may themselves be specified implicitly or explicitly.

The VDM++ modeling language also supports the description of object-oriented and concurrent systems, with persistent state modeled as instance variables. Logic expressions are used to describe the synchronisation constraints on threads. The VICE extension further supports the modeling of time and the deployment of functionality to resources in a distributed system architecture.

## 3 Working with VDMTools

Figure 1 gives an overview of the structure of VDMTools. Figure 2 is a screen dump showing the graphical user interface through which the major tool functions can be applied to a model. We will present the tool components by describing the way in which they are typically used during the development of VDM models. The underlying principle in the tools' development has been to support industrial use. At various points, we have emphasized robustness over the provision of advanced functionality.

VDMTools support concurrent development and allow models to be split among several files. Models can be written in an ASCII representation, Unicode (if, for example, Japanese characters are desired), or a literate programming mix of source code and comment using with  $\LaTeX$  macros. This allows standard version control system such as CVS to be readily applied to the model files. Alternatively VDM models can be produced directly using Microsoft Word, provided they are stored in Rich Text Format (`rtf`) and use special styles.

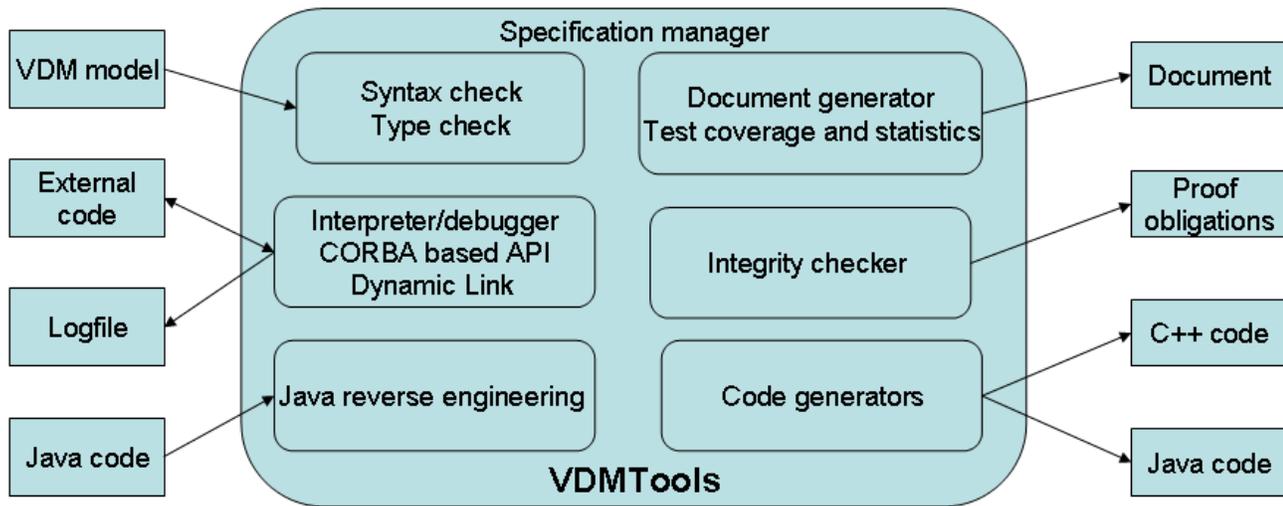


Fig. 1. VDMTools Overview

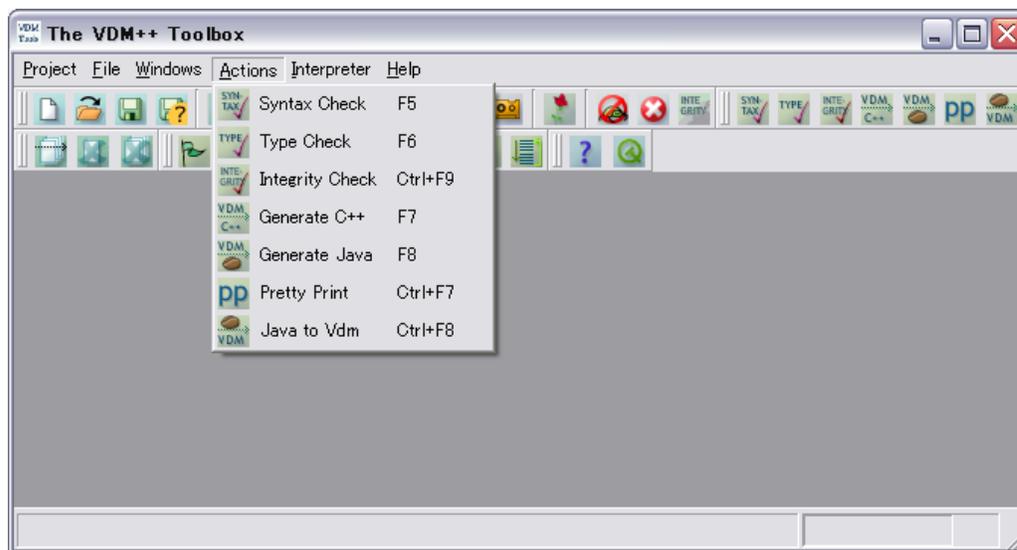


Fig. 2. VDMTools Actions Menu

### 3.1 Producing Documents

Since a formal model provides an unambiguous system description, it can serve as the basis for technical documentation of the specification and the implemented system. We see VDM models as an integral part of a system's documentation which also includes such material as informal specifications, graphical structural models and model annotations. VDMTools supports this idea, not only by allowing models to be composed from multiple source files, but also by including a pretty-printing facility whereby ASCII or Unicode models can be translated to  $\text{\LaTeX}$  source that renders

the model in the mathematical syntax preferred by some users. This also supports the automatic generation of  $\text{\LaTeX}$  indexes for models. We have found these facilities to be essential when handling large specification documents.

### 3.2 Syntax Checking

VDMTools supports syntax checking of VDM models with positional error reporting supported by an indication of error points in a source window. VDMTools may be config-

ured so that a user's favorite external editor can then be invoked with the file shown in a source window.

### 3.3 Type Checking

Having established a VDM model as syntactically correct, the next step is to check its static semantics (type errors, scope errors, etc.). VDM has a powerful type system supporting constructors that are complex from a traditional type-checking perspective. These include union types and recursively defined types. VDMTools includes a static semantics analyser that is able to check for a large number of static semantic errors well-known from normal programming language type checkers, for example incorrect values applied to function calls, badly typed assignments, use of undefined variables and module imports/exports. Since the VDM modelling languages have formal static semantics, it is also possible to provide extended checks. In all these cases the types involved can be arbitrarily complex compositions of any of the standard VDM types.

For large models it is important to be able to check smaller parts of the specification in isolation before they are integrated. The static semantics analyser can check VDM-SL modules and VDM++ classes in isolation but when checking several modules/classes will also check the consistency of the module/class interfaces.

### 3.4 Integrity Checking

In addition to static type checking, in VDM it is possible to define *proof obligations* that represent semantic inconsistencies and potential sources of run-time errors. For example, a proof obligation (known as the *satisfiability* obligation) requires that all functions and operations respect the data type invariants on their outputs and persistent state values. Run-time error checking includes the obligation to show that partial operators are applied safely, for example avoiding division by zero or an array bounds violation. The integrity checker in VDMTools [4] detects all places where proof obligations may be violated and generates a description of the obligation. This may subsequently be checked by inspection, or taken over to an external proof tool and formally verified [47].

### 3.5 Executing VDM Models

To aid the understanding of complex models VDMTools supports execution and debugging. The debugger supports many of the facilities known from debuggers of programming languages such as setting breakpoints (at functions and operations), stepping (performed at expression and

statement level) and inspecting the current calling stack. Furthermore the interpreter supports VDM-specific facilities such as dynamic checking of type invariants and checking pre- and post-conditions on function and operation calls.

The interpreter also supports the incorporation of external (legacy) code in C++ using *dynamic link libraries* [19]. The external code is compiled into a `.ddl` and the interface of that code is described at the VDM level so that the user can access its functionality directly. In addition, standard libraries for mathematical functionality and input/output are directly built in to VDMTools so the user does not need to define these.

One of the advantages of VDMTools compared to other prototype-based approaches is the large subset of VDM that is supported for execution. All the VDM constructs supported in other prototype-based approaches (e.g., [6, 25]) may be executed directly in VDMTools. Furthermore more advanced constructs are supported, including higher order functions, polymorphic functions, complex (loose) pattern matching, comprehension expressions for mappings, sets and sequences, lambda expressions and exception handling [30]. VDM being a modeling rather than a programming language, contains several constructs that are not executable, so VDMTools does not support execution of expressions in which local variables range over entire data types (which are unbounded in VDM) and purely implicitly defined functions and operations. In fact, research indicates that larger parts of the language could be supported by the interpreter [18].

### 3.6 External Access via an API

When models have been checked for internal consistency, it is important that they should be *validated*. By validation, we mean the process of increasing confidence that a model is faithful to the stakeholders' expectations (e.g. that it embodies critical properties and does indeed describe the behaviour of the system under consideration). Stakeholders are rarely expert formal modellers, and so VDMTools includes a CORBA-based Application Programmer Interface (API) that can be accessed by either external C++ or Java, allowing the full functionality of VDMTools to be accessed by an external application such as a graphical user interface designed for domain experts unfamiliar with the modeling notations. Feedback from scenarios performed with such domain experts can be incorporated immediately and updated without the need for new compilation of the application.

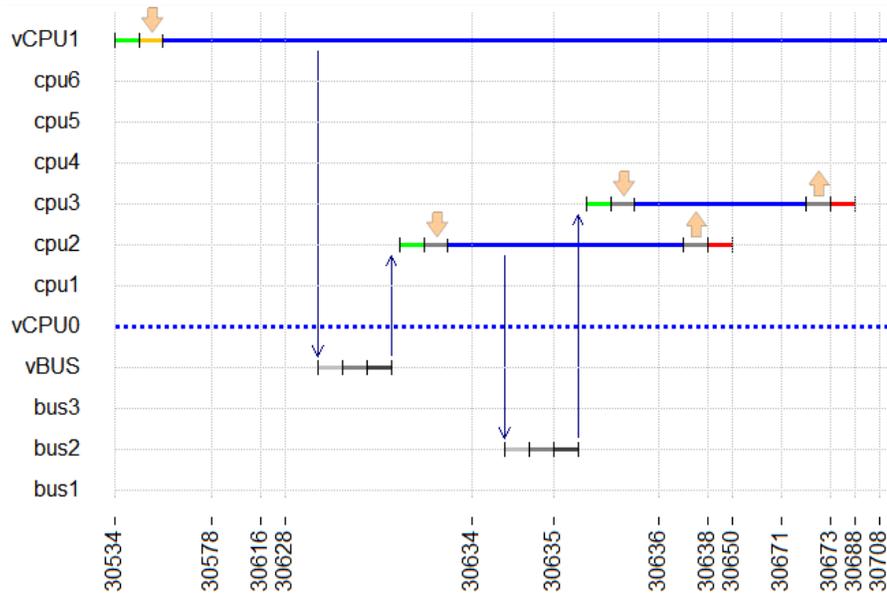


Fig. 3. Graphical overview of the system model activity

### 3.7 Support for Validating Distributed Models

The VICE version of VDMTools has an interpreter that automatically produces an external logfile containing all the events observed during an execution of a model. Each event in this logfile is tagged by the time at which it occurs and, in case of a distributed system model, also the resource on which the event appeared [45]. This information can then be displayed graphically so potential bottlenecks in a proposed system architecture can be discovered at a very early stage in development. See Figure 3 for an example of such a graphical overview. Time is shown on the x-axis; the computing resources in the distributed system are listed on the y-axis. Thick lines indicate that the resource is busy and thin lines between resources indicate messages that are passed over a communication medium. The large arrows indicate swapping in and out of task on a specific resource.

A further extension in this direction permits the formulation of validation conjectures (system-level timing requirements) and automated checking that a system logfile respects them. Violations can then be identified graphically to the user on the trace display [15]. This feature has been experimentally evaluated but is not yet integrated into VDMTools.

### 3.8 Systematic Testing

In practice, systematic testing is the most widely-used important technique for gaining confidence in the correctness

of a large formal model in VDM. The interpreter supports interactive testing of models, and has an additional test support mode. This facility allows a test suite to be set up for the specification using standard shell scripts, allowing thorough batch-mode testing of reasonably large models and the provision of test coverage statistics.

### 3.9 Code Generators

The VDMTools contain code generators for a large subset of the VDM modeling language (around 95%), producing C++ and Java code. Applying the code generator to a type correct VDM model yields an implementation rapidly although the generated code will most likely be slower than manually crafted code. Thus, the utility of this feature depends on the nature of the application and its performance requirements. As explained in Section 3.11 below the VDMTools features are themselves developed from VDM models; for parts of these models, the code generators have actually been used to produce the VDMTools production code itself. Note also that the code generators enable the user to update parts of the generated code manually and take that new code into account next time code is generated.

### 3.10 Reverse Engineering Support for Java

VDMTools incorporates a beta-version of a feature that allows code in a Java subset to be reverse engineered to low-level VDM++ models. The subset does not support the GUI

libraries because those parts can better be used with the CORBA-based API instead. The current beta-version here is expected to be most useful for research and experimentation.

### 3.11 Implementation

Once a formal model has been suitably validated (using proof obligation generation, reviews and testing), implementation is the next step. In our own work we have found that implementing a formal model is an almost mechanical, but mainly manual, effort once an implementation strategy has been adopted. In the development of VDMTools themselves, the data handled by an application are implemented using C++ classes representing the common VDM data types (sets, maps, sequences etc.). In some cases the formal models for features of VDMTools have been used to generate the production code implementing the features. Furthermore the tests developed for the specification are reused to test the implementation. This provides a certain degree of confidence that no more errors are introduced during the implementation phase.

## 4 Industrial Usage

VDM and VDMTools have been applied in a wide variety of application domains. Here we list some of the best documented applications that are in the public domain:

**ConForm:** An experiment at British Aerospace comparing the conventional development of a trusted gateway with a development using VDM [28, 42].

**Dust-Expert:** A project carried out by Adelard in the UK for a safety related application determining that the safety is appropriate in the layout of industrial plants [41, 43].

**The development of VDMTools:** Most components of the VDMTools tool suite are themselves developed using VDM. This development has been made at IFAD in Denmark and CSK in Japan [27].

**SIC2000:** A project carried out by GAO in Germany for integrating sensor software and hardware in a banknote processing machine [40].

**ISEPUMS:** In a project from the space systems domain, VDM was used in processing the messages communicated to the SPOT4 satellite [39].

**TradeOne:** Key components of the TradeOne back-office system developed by CSK systems for the Japanese stock exchange were developed using VDM. Comparative measurements exist for developer productivity and defect density of the VDM-developed components versus the conventionally developed code [16].

**FeliCa Networks:** This is the development of an operating system for an integrated circuit for cellular telephone applications [26].

A large number of other applications, mainly from safety critical sectors, can not be publicly reported in any detail.

## 5 Availability and Platforms

VDMTools are available for several different platforms including Windows, Linux, Solaris (for Intel PC) and MacOS. Executables and manuals can be downloaded after registration at <http://www.vdmttools.jp/en/>. Free academic licenses can be obtained for bona fide institutions completing a license agreement. In addition, free industrial license agreements can be obtained from CSK Systems.

## 6 Future Plans

Any tool that is used actively is extended in order to enhance its usability. For VDMTools the most important extensions currently are as follows:

- Because of the importance placed on documentation using formal VDM models, it is planned that a “VDMdoc” feature inspired by JavaDoc [32] will be incorporated as one of the new features.
- Additional standard libraries are desired by existing users and so new extensions in this direction are expected.
- Test automation is an important issue. Here it is expected that VDMTools will be enhanced with new capabilities. Initially the target here is the UniTesK approach [8] for ensuring easy test sequencing automation. However, different test automation possibilities exist and these are currently under investigation.
- Proof support enhancements have been developed for the Overture project [35] and it is envisaged that in the future this will also be incorporated into VDMTools [47].

Significant industrial take-up, for example in Japan, is likely to remain a significant driver for future tools work in VDM. The Overture open-source initiative is more geared towards providing a vehicle for applications and tools research, especially in areas such as proof. Alongside this, new academic courses are being developed that emphasise the transferable skills of abstraction and rigorous reasoning through formal modelling technology [29]. Our hope is that, with a strong record of industry application, formalisms such as VDM will continue to contribute to the wider adoption of advanced software development technologies in many application domains.

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Features of CML: a formal modelling language for systems of systems. J Woodcock, A Cavalcanti, J Fitzgerald, P Larsen, A Miyazawa, S Perry. System of Systems Engineering (SoSE), 2012 7th International Conference on, 1-6, 2012. Formal Modelling in VDM. Contribute to nickbattle/vdmj development by creating an account on GitHub.Â VDMJ provides basic tool support for the VDM-SL, VDM++ and VDM-RT specification languages, written in Java. It includes a parser, a type checker, an interpreter (with arbitrary precision arithmetic), a debugger, a proof obligation generator and a combinatorial test generator with coverage recording, as well as JUnit support for automatic testing and user definable annotations. VDMJ is a command line tool, but it is used by the project, which adds a graphical Eclipse IDE interface as well as features like code generation (see screen shots below). Features. Parses, type checks, executes and debu