Concepts and an Implementation for Product Data Management

Doctorate Thesis

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Abstract

Shorter product life-cycles, growing product complexity and the need for a large number of product variants have made Product Data Management (PDM) increasingly important for many manufacturing companies. This thesis provides a survey of the most important concepts of PDM technology and illustrates the concepts by describing the design and implementation of an advanced document management system.

The survey in the first part of the thesis illustrates the relations between different concepts and can be used as a framework for evaluating PDM systems. This part includes summaries of the STEP standards for product models and the IEC 6130 and ISO 13584 standards for component management. The STEP standards are particularly difficult to read, and these sections of the thesis provide accessible introductions to these very complex standards.

The document management system described in the second part of the thesis has been developed in close co-operation with a large manufacturing company, which now stores all engineering documents in the system and accesses the system through a global intranet. The main strengths of the system are its versatile document model and the flexible customisation properties of the system, including dynamic schema manipulation operations and a programmable authorisation mechanism.

One particular topic in the thesis is product configuration. The first part introduces a framework for configurable products in terms of an explicit structure and constraints. The second part discusses different ways to add product family structures to the implemented system.

Preface

The work reported in this thesis was completed between 1991 and 1999 within the Product Data Management Group (PDMG) at the TAI Research Centre at the Helsinki University of Technology. The work was done in multiple projects, which were mainly financed by the National Technology Agency of Finland (Tekes) and KONE Elevators. Some projects were part of the Rapid programme co-ordinated by the Federation of Finnish Metal, Engineering and Electrotechnical Industries (MET).

My first thanks go to professor Reijo Sulonen, who has supervised the preparation of this thesis and has guided the research group. I also thank Kim Gunell, Asko Martio, Tomi Männistö, Kati Sarinko, Timo Soininen and Juha Tiihonen for giving me the opportunity to work in a stimulating and pleasant research environment. It has been wunderful to know you and all the other people at our office in Spektri Duo. I hope we shall work together, and occasionally also meet outside the office, for many more years.

I would also like to thank Dr. Peter van den Hamer for important comments that improved the thesis crucially in its last stages.

I have designed and implemented most of the server of the EDMS document management system. The original model for generic product structures in EDMS was developed by Asko Martio. Timo Nyyssönen has implemented the object filters in the server. Kari Alho implemented the X/Motif user interface of the EDMS. The original object manager was implemented by Kari Alho, Tomi Männistö and myself. The Java user interface was originally implemented as a student project by Janne Kontkanen, Sami Vaarala, Phuoc Tran Minh, Janne Huttunen, Pekka Salmia, Kim Gunell and Teppo Peltonen. Kim Gunell has joined our research group and continues the development of the interface. Fredrik Nyberg at KONE Elevators has also written some parts of the user interface. The object manager of the Java user interface is now being developed by Kim Gunell and myself.

The success of EDMS has depended on the support of people at KONE Elevators. Asko Martio was in charge of the EDMS project at KONE before joining our research group. Without his faith in the project there would be no system to write a thesis about. Asko's work at KONE has been continued by Matti Eskola, who has been the best possible promoter for the system both within and outside the company. Heikki Karhunen and Jorma Heimonen have been responsible for actually making the system run at KONE. Jorma Heimonen has also written the Web tools, which have been crucial for the success of the whole project.

I have written the Application Programming Interface of EDMS, which has been used by Jarmo Ukkola and Kalevi Turkia at Vertex Systems Oy to implement a link between EDMS and the Vertex CAD program. At KONE Elevators, the Vertex link has been managed by Jussi Nissi.

The English language of the thesis has been checked by Ms Kathleen Tipton.
Finally, I would like to thank my wife Marja for the most important things in life: love and companionship.

Helsinki, May 2000

Hannu Peltonen

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1 Introduction

Shorter product life cycles, growing product complexity and the need for a large number of product variants have made Product Data Management (PDM) increasingly important for many manufacturing companies. The growth of the PDM market is illustrated by the large number of PDM software products; a leading survey describes 52 products and estimates that in 1996, companies invested over USD 800 million in PDM worldwide (Miller, MacKrell and Mendel 1997: 55).

This thesis analyses the most important concepts of PDM technology and illustrates the concepts by describing the design and implementation of an advanced document management system. This introductory chapter includes the history of the thesis, a summary of its methods and contributions, and an outline of its structure.

In addition to being an academic dissertation, this thesis can be read by engineers and software developers in companies that use and develop PDM systems. However, as the thesis concentrates on PDM systems and largely ignores the processes that should be supported with the systems, it is not an overall guide for a company that wants to learn about PDM and possibly launch a PDM project.

There are other terms more or less synonymous with Product Data Management, such as Engineering Data Management, Engineering Document Management, Product Information Management and Technical Data Management (Miller, MacKrell and Mendel 1997: 1). Nevertheless, this thesis only uses the term ‘PDM’, which is now the established generic term for this field.

1.1 History of the Thesis

This thesis is based on my work in the Product Data Management Group at the Helsinki University of Technology. The group has had many joint projects with Finnish industry, investigating the present state of PDM at each company and making suggestions for future actions. I have been especially involved with KONE Elevators. The co-operation with KONE started in 1991 and eventually resulted in the document management system described in the second part of the thesis.

After an intensive period of development, the system was roughly in its present form around 1995 when KONE started the operational use of the system. Although the system has been developed thereafter, with the Java user interface as the most important change, I had more time for other activities. I have mainly been occupied with PDM in general and with configurable products and component management in particular. Some results of this work are reported in this thesis, which has configurable products in PDM systems as one important theme.

Over the years the topic of the thesis has alternated between configurable products and what it is now. The ideas of configurable products presented in this thesis are being developed further by other members of the research group and by me, and could certainly be a topic for a separate thesis.

After the topic of the thesis was determined, it was originally intended to consist of separate papers and a summary. Nevertheless, it gradually became evident that the thesis should be written as a monograph. Many of the separate papers had to introduce the same basic concepts repeatedly, and a collection of papers would not have served the goal of presenting an overview of PDM technology and a quite detailed description of the implemented system. In all honesty, I must also say that my present publications, which can be found in the reference list, would not constitute a thesis without a "summary" that would include much additional material.

1.2 Contributions of the Thesis

This thesis makes two contributions to PDM: it presents a comprehensive overview of the most important PDM concepts and industry standards, and it documents the data model, implementation and usage experiences of a large document management system together with an outline for extending the system to accommodate configurable products.

The first contribution consists of a survey of the fundamental concepts and functions that should be found in a PDM system. The survey does not cover all possible aspects of PDM systems but provides a balanced treatment of the most important ones. Although most of the material comes from literature and is as such "old stuff", a contribution is made by the survey, which illustrates the relations between different concepts, and can be used, among other things, as a framework for evaluating PDM systems.

The overview includes summaries of the STEP standards for product models and the IEC 6130 and ISO 13584 standards for component management. The STEP standards in particular are very difficult to read, and these sections of the thesis provide accessible introductions to these quite complex standards.

The second main contribution is a detailed description of a document management system. The system has been developed in close co-operation with a large manufacturing company, which now stores all engineering documents in the system and accesses the system through a global intranet. The main strengths of the system are its versatile document model and the flexible customisation properties of the system, including dynamic schema manipulation operations and a programmable authorisation mechanism.

The literature contains few case studies of companies with PDM, and although the system does not implement all concepts discussed in the thesis, it is a good example of the issues to be considered in document management systems—and in PDM systems in general. At the moment the system mainly deals with documents, but the thesis discusses different ways to add product structures and configurable products to the system.

1.3 Methods

A doctoral thesis is supposed to present new knowledge that has been acquired through scientific methods. The requirement on a proper methodology is a problem in this thesis because results cannot be "proved" by formal means and it is also difficult to achieve "empirical" results.

In the first part of the thesis I present a number of concepts and claim that PDM systems should be analysed and built using these concepts. This claim is based on literature and the experiences I have gained from my colleagues at the university and from people in industry.

The second part of the thesis describes an advanced document management system with its data model. The quality of the model is shown by the success of the system as a core for a company-wide document management solution. Nevertheless, the basic claim of the second part of the thesis is that the data model is in general suitable for engineering documents. It is again very difficult to validate this claim as the system has not yet been used in other companies. However, it would be possible to compare the system described in this thesis with similar commercial systems. This has not been done because it is hard to find detailed information about commercial products, and this kind of survey would have extended the thesis beyond its planned scope. Moreover, commercial products evolve quickly, and the results of a product survey would soon become obsolete.

I am a software engineer at heart and have implemented a large part of the system described in the second part of the thesis. Accordingly, the thesis is written from the point of view of a system builder, who looks at PDM systems in a different way than, for example, a manager who is responsible for the processes that use the PDM system, or a product designer to whom a PDM system is at best a supporting tool and at worst only a hindrance to his or her "real" work.

1.4 Structure of the Thesis

As there are few well-established concepts and terms in this field, the thesis starts from the basics and can be read as a tutorial. This approach and the wide scope mean that the thesis is rather long and mentions many topics that could be treated with much more detail in a more specialised thesis. This also probably means that some readers may find the presentation "unscientific" in style.

The thesis is divided into two main parts. The first part provides a summary of the concepts and functions of PDM systems. Among other things, the information in this part should help prospective buyers of PDM systems to evaluate different systems, which typically have identical terms on their feature lists but actually have quite different notions of the concepts.

Chapter 2 delineates the scope of the thesis by analysing what kind of data in a company is related to products and what part of this data is actually handled by a typical PDM system. The chapter also includes a summary of the basic functions usually found in PDM systems and a very brief section on PDM projects.

Chapter 3 is the core of this part because it describes the basic concepts and corresponding data models, such as versioning and product structures, which serve as the foundation of any PDM system.

After the data concepts have been introduced, chapter 4 deals with the processes that manipulate the data. The fundamental term in this chapter is 'design transaction'.

Chapter 5 discusses some system aspects, such as the integration between a PDM system and other information systems within a company. The first part ends with chapter 6, which describes two important standardisation efforts in the PDM field: the STEP standard for general product data, and the IEC 6130 and ISO 13584 standards for component management.

The second part of the thesis describes a document management system called EDMS, which has been built by the Product Data Management Group in a joint project with KONE Elevators. Chapter 7 provides general background on the project. The data model of EDMS is described in chapter 8.

At the moment EDMS does not support product structures. A simple model for product structures has been implemented, but this model has never actually been used. Chapter 9 describes the implemented model and future plans for product structures that can also represent configurable products.

Chapters 10 to 12 describe the architecture of EDMS, which consists of a relational database accessed through a server program from multiple client programs.

Much of the value EDMS at KONE comes from additional applications that have been built on top of the basic system as described in chapter 13. Finally, chapter 14 tells how EDMS is used at KONE and discusses possibilities to further improve the system.

The whole thesis ends with conclusions and ideas for further work on many topics, which deserve a much more thorough treatment than was possible within the confines of this thesis.

Part I: Product Data Management Concepts

This first part of the thesis provides an overview of the main concepts in product data management. At least with the current knowledge and experience on PDM systems, it is very difficult to present a comprehensive "integrated model", which would neatly combine all the relevant concepts. Although the individual issues seem relatively straightforward, their interaction raises problems. For example, it is by no means clear how versioning and product structures should be combined.

2 Product Data and Product Data Management

2.1 Product Data

As the subject of this thesis is product data management, it is appropriate to start with an analysis of the term ‘product data’.

Consider a company in discrete manufacturing industry. The operations of the company are divided into a number of functions, which are typically organised in separate departments. Most of these functions involve the products manufactured by the company. The following list is by no means complete; it only illustrates the variety of data connected to a product.

Product development is the primary source of new product data. For each product there are market analyses, requirements specifications, 3D models, drawings, test reports, etc.

Marketing prepares brochures, product catalogues and other additional product material.

Sales uses product data during the preparation of tenders. Often the sales function also needs information on the inventory levels and production schedules. In the case of a configurable product, which is adapted to the requirements of a particular customer, an individual product description is created for each customer order.

Process planning attaches production instructions to the product. These instructions include more detailed drawings, NC programs, quality inspection procedures, etc.

Manufacturing makes the actual products using the data that has been associated with the products in process planning. Manufacturing may add its own data to the descriptions of the manufactured products. For example, if each manufactured product instance is tested separately, the test reports are attached to the products.

Invoicing has data on sold products, their prices, customers, terms of payment, outstanding invoices, etc.

After-sales services, such as maintenance and product modernisation, are increasingly important in many industries. Often the life cycle of each manufactured product instance must be followed separately. For example, the manufacturer may record all maintenance operations and component replacements with the product.

2.2 Product Data Management

If product data is understood to encompass all data connected with products, much of the data managed inside a manufacturing company can be regarded as product data. Corporate functions that deal with data other than product data include financing and human resources, and possibly also manufacturing resources.

Nevertheless, the term ‘product data management’ usually has a much more restricted scope. Typically PDM systems have their roots in the engineering aspects of product development, and accordingly the systems mainly deal with engineering data. Most PDM systems are less concerned with operative manufacturing or sales and delivery processes. Often a PDM system does not deal with costs, prices and other financial issues at all.

Product data outside a PDM system must be managed with other systems. Instead of using a large number of separate systems, it is becoming increasingly popular to manage this data in large integrated Enterprise Resource Planning (ERP) systems, such as SAP R/3, Baan IV and Oracle Applications.

As the goal of ERP systems is to manage comprehensively almost all data within a company, the functions typically included in a PDM system should logically be found as part of ERP systems. In fact, ERP systems are beginning to include PDM functions, sometimes as separate modules. Nevertheless, at least at the moment the PDM functionality in ERP systems is rather limited, and an ERP system is seldom a substitute for a PDM system. However, there is obviously overlap between these two kinds of systems and a strong need to share common data. The co-operation between PDM and ERP systems is discussed later in the thesis.

Product data management should not be confused with *product management*. The latter term includes business aspects, such as marketing, product policy and the introduction of new products.

2.3 Basic Functions of a PDM System

There is a rough general agreement on the basic functions that a PDM system should provide (Katz 1990; van den Hamer and Lepoeter 1996). The terminology and details vary considerably.

A list of the basic functions is given below. The term 'object' in the list refers to an entity, such as a product or a document, managed by a PDM system.

- *Secure storage of documents and other objects in a database with controlled access.* In many companies the first motivation for considering PDM comes from people frustrated from not being able to find documents they are looking for. The people may only know that the needed documents are located somewhere in a network of file servers. There may even be many copies of a document at different locations, and in the worst case two people can make conflicting changes in two copies of the same document.

- *Mechanism for associating objects with attributes.* The properties of documents and other objects are described by means of attributes. The attributes provide necessary information about an object, and they can also be used for finding objects.

- *Management of the temporal evolution of an object through sequential revisions.* Many PDM systems were originally built for design and development environments. In these environments the users typically spend more time modifying existing designs than creating completely new designs. The evolution of drawings and other design objects is usually captured in the form of successive revisions.

- *Management of alternative variants of an object.* Many products and documents have alternative variants. For example, a user's guide for a particular product can be available in different languages.
- *Management of the inspection and release procedures associated with the objects.* Documents and other objects with engineering data must typically be checked and approved with more or less elaborate procedures before the objects are released for general use.
- *Management of the recursive division of an object into smaller components.* Almost any product has a hierarchical breakdown structure, which divides the product into components, which are further divided into smaller subcomponents, etc.
- *Management of changes that affect multiple related objects.* One of the primary functions of a PDM system is to support change management. In their basic form the revisions and variants represent the changes of separate objects. Nevertheless, it is often also necessary to view a set of related objects as a single unit with respect to change management.
- *Management of multiple views of an object.* A PDM system should make it possible to have different views of an object. For example, a product can be divided into components in more than one way.
- *Management of multiple document representations.* A PDM system should also make it possible to store a document in multiple different presentations. For example, a drawing created with a CAD tool can be available both in the native file format of the tool and in a neutral file format for viewing and printing.
- *Viewing tools.* In addition to simply displaying the read-only representations, some viewing tools allow users to insert textual and graphical annotations on top of the documents without modifying the original data.
- *Tool integration.* From an ordinary user's point of view, the usability of a PDM system depends very much on how well the system is integrated with other tools that he or she needs in his or her daily work.
- *Component and Supplier Management.* The management of standard components bought by a company from external suppliers is a rapidly growing field within PDM.

The functions are not independent of each other. It is, for example, difficult to discuss sequential revisions without the idea that an object under development is released for use after it becomes "ready".

Many of the items on the above list can be seen as part of *configuration management*, which is an engineering discipline and a process for maintaining the integrity of products while they evolve through development and production cycles (Buckley 1996). The term 'configuration management' should not be confused with the terms 'product configuration' and 'configurable products', which refer to the concept of a generic product that can be customised for each order according to the particular requirements of the customer.

2.4 PDM Projects

This thesis concentrates on the technical aspects of PDM systems. Nevertheless, they are not the only, or even the most important, issues to be considered in a company that wants to investigate PDM. This chapter therefore ends with a brief discussion on PDM projects.

The introduction of a PDM system in a company is a large undertaking. Although at some level most PDM systems seem to provide similar functions, such as a document vault and versioning, there are considerable differences between the available systems. Although there seems to be a general agreement on the growing importance of PDM, it seems difficult to define and measure the exact benefits of PDM and to relate PDM to the overall business strategy of a company (Harris 1996). Of course, to a large extent the same comment applies to information systems in general.

Before evaluating various PDM systems and their features in any detail, a company should analyse thoroughly the processes that are going to be supported by the system (Peltonen, Pitkänen and Sulonen 1996).

The result of an analysis can even be that no expensive PDM system is needed or that the introduction of a PDM system must wait till the company has dealt with the necessary prerequisites, such as establishing an identification and classification scheme for documents and items.

However, if the analysis shows that the company should continue investigating PDM technology, the actual PDM project should start with a feasibility study, which identifies processes and needs, establishes a target specification, performs a pilot test, and refines the specification for further implementation if the results are positive (Hakelius and Sellgren 1996).

A pilot implementation includes not only a system pilot with the appropriate hardware and software but also an organisational pilot, which considers any changes that must be made in the organisation to accommodate PDM, and a process pilot, which reviews and changes any necessary processes (McIntosh 1995: sec. 8.3).

Grudin (1994) has analysed psychological and social issues related to the introduction of groupware software in organisations. Many of the problems and suggestions for addressing them apply to PDM systems as well. Typical problems include disparity between work and benefit (i.e., the fact that a system may require additional work from users who do not gain direct benefits), lack of a "critical mass" of users, missing commitment from management, and overly rigid descriptions of office procedures without necessary consideration for exceptions.

3 Data Models

In this thesis a data model is regarded as a definition of the basic concepts of an information system by means of objects and relationships between objects. A data model is static in the sense that it describes what kind of a data exists in a system without describing in detail the operations and processes that manipulate the data. Nevertheless, the data model defines on a more general level what kind of operations can be available.

The description of an information system begins with its data model. As pointed out by Cook (1996: 78), during the development and operation of an information system, the data models are more stable and thus more important than the processes that manipulate the data.

This thesis uses the well-established object-oriented concepts as the general approach to data models (Rumbaugh et al. 1991). The graphical notation in figures is that of the Unified Modelling Language (UML) (Fowler 1997). Constraints in UML diagrams are written in the Object Constraint Language (Warmer and Kleppe 1999). Some constraints use an extension of the Object Constraint Language, which is described in appendix A.

3.1 Metamodels and Company Models

When the data models for PDM are discussed, it is necessary to distinguish between two levels of models, which are called here *metamodels* and *company models*.

A company model defines concepts for products, components, documents and other items in a particular company. The concepts are defined by means of item types arranged in a class hierarchy, attributes for the types, relationships between items, etc.

A metamodel defines the general concepts that can be used for constructing individual company models. This thesis mainly deals with metamodels in the sense that the goal is not so much to specify, for example, what document types should be defined in a PDM system, but what general mechanisms are needed for defining the document types.

The metamodel of a PDM system should be explicitly available to a company that uses the system. This means that the metamodel is not only used for describing a particular company model that the maker of a PDM system has implemented. Instead, the company that uses the PDM system should be able to define its own company model with the concepts of the metamodel. The company model should also be dynamic so that the model can be modified according to the changing requirements of the company.

Figure 1 illustrates the relationships between metamodels and company models. The metamodel defines the concept of an object type. Company model 1 defines the object types 'drawing' and 'manual', which are instances of the type 'object type', defined in the metamodel. The PDM system of company 1 stores objects, such as individual drawings and manuals, which are in turn instances of the object types defined in company model 1. Company 2 defines its own object types in its company model, again as instances of type 'object type' of the metamodel, and the PDM system of company 2 stores instances of these types.

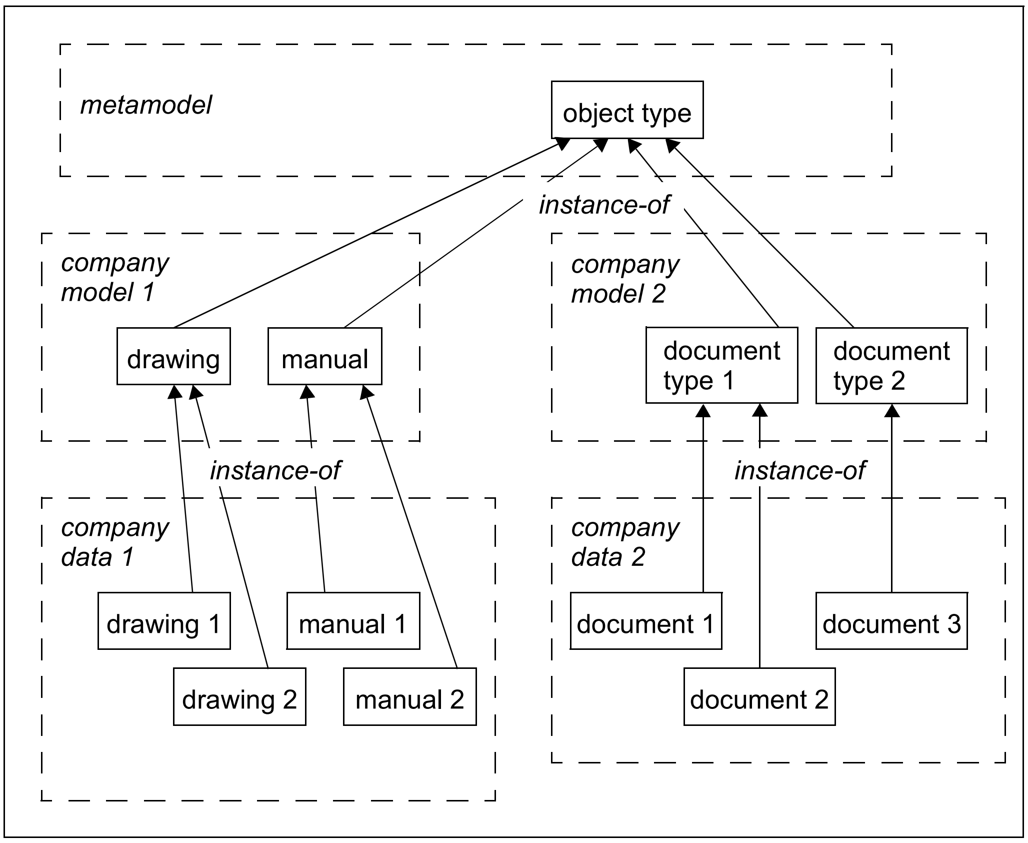


Figure 1. Metamodel and company models

There are thus three kinds of entities: (1) instances of the types of the company model, (2) types of the company model, which are at the same time instances of the types of the metamodel, and (3) types of the metamodel. Different ways to represent these entities in a relational database are discussed in section 5.2.

In practice, figure 1 would typically be complicated by classification relations between object types (section 3.2.1.2). For example, the object types 'drawing' and 'manual' would be subtypes of the object type 'document'. In fact all object types in different company models could ultimately be subtypes of an object type 'object', which could be a "built-in" object type in a PDM system.

3.2 Basic Data Modelling Concepts

The data model of a PDM system can be described with the basic object-oriented modelling concepts discussed in this section. For example, the concept of an object type (discussed in detail shortly) can be used for describing the different kinds of data, such as 'product' or 'document', that the developer of a PDM system has included in the system. Moreover, it should also be possible to use the same concepts for extending the system according to the requirements of a particular organisation that wants to use the system. For example, the different kinds of documents needed by the particular organisation should be represented as new object types that are subtypes of the predefined object types defined by the developer of the PDM system. (The predefined object types are in turn instances of types in the metamodel.)

3.2.1 Objects and Types

Typical data managed by a PDMS includes, among other things, documents, products, components, parts lists, users and projects. It is convenient to refer to the various kinds of product data with a generic term.

Often one says that product data is represented as *objects*. In this context the term 'object' does not necessarily imply that the objects should exhibit all properties familiar from object-oriented programming and data modelling, such as object classes or inheritance (Stefik and Bobrow 1986). The term 'entity' would perhaps be more neutral in this respect. Nevertheless, in this thesis objects are treated very much according to ordinary object-oriented concepts.

The various kinds of objects are stored in a PDM database. This does not entail that the PDM system should be implemented by means of an object-oriented database (Cattell 1994; Mattos, Meyer-Wegener and Mitschang 1993). The objects can, for example, be stored in relational databases.

3.2.1.1 Types and Instances

Products, documents and other objects are often organised in *object types*. For example, consider documents. There can be a number of different document types, such as 'drawing' and 'manual', and whenever a new document is created, one specifies its type.

Individual objects are often called *instances*. For example, if a PDM system has different document types, each document is an instance of a particular document type. Usually an object is an instance of exactly one object type. The term *multiple classification* is sometimes used for referring to the property that a single object can be an instance of more than one type at the same time (Fowler 1997: 77).

Each object type specifies various common properties of all objects of that type. For example, the type of a document determines what attributes the document has; each document of this type has its own values for the attributes (attributes will be discussed in detail in section 3.2.2).

Although most object models are based on object types and their instances, this distinction is not absolutely necessary. In the *prototype object* approach, there are only objects and no object types (Ungar and Smith 1991). All operations are represented as messages between objects. If an object cannot handle a message it receives from an object, it can re-send, or delegate, the message to another object. The common properties of a group of objects can thus be stored in an object, which handles particular kinds of messages that are sent to any member of the group (Peltonen et al. 1994b).

3.2.1.2 Class Hierarchies

It is useful if a PDM system makes it possible to organise object types in a tree-like type hierarchy. For example, there can be document types for drawings and manuals, and drawings can further be divided into different types of drawings, such as 'manufacturing drawing' and 'maintenance drawing'.

This kind of object type hierarchy is sometimes referred to as a *class hierarchy* (see section 3.2.1.5 for a discussion on the difference between types and classes). Two types related in a class hierarchy are often referred to as *subtype* and *supertype*. For example, 'drawing' and 'manual' can be subtypes of 'document', and accordingly 'document' is a supertype of 'drawing' and 'manual'. Similarly, 'drawing' is in turn a supertype of 'manufacturing drawing'.

There are various graphical notations for class hierarchies. Figure 2 shows an example of the notation of the Unified Modelling Language (UML). Types are represented as boxes and there is an arrow with a hollow head from a type to its supertype.

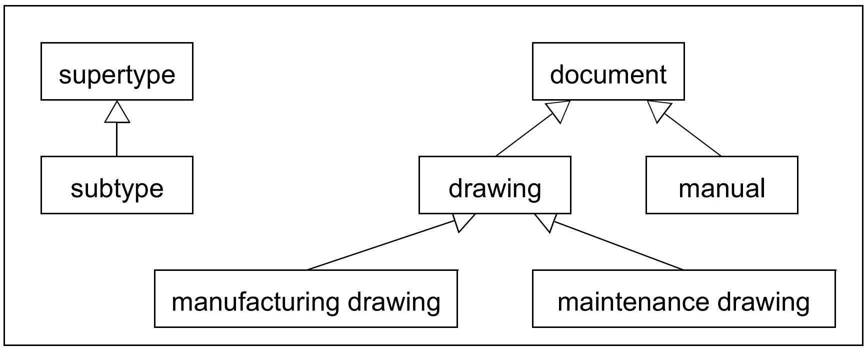


Figure 2. Class hierarchy in UML notation

To be precise, it is necessary to distinguish between subtypes on the "next level" and on "all levels". There does not seem to be established terminology for this distinction. In this thesis 'drawing' and 'manual' are called the *immediate subtypes* of 'document' whereas the subtypes of 'document' include 'manufacturing drawing' and 'maintenance drawing' in addition to 'drawing' and 'manual'. Similarly, both 'drawing' and 'document' are supertypes of 'manufacturing drawing', and only 'drawing' is an *immediate supertype* of 'manufacturing drawing'.

The basic meaning of a class hierarchy is that an instance of an object type is at the same time an instance of the supertypes of the type and can be used wherever an instance of any of the supertypes is expected. For example, if object types are organised according to figure 2, an instance of 'manufacturing drawing' can be used wherever an instance of 'drawing' or 'document' is expected.

This "substitution" property leads to the notion of *inheritance*. For example, suppose that all documents have an attribute that records the name of the person who has last modified the document. If 'drawing' is a subtype of 'document', a drawing can be used wherever a document is expected, and accordingly drawings must also have the attribute that was defined for documents. An object type thus inherits all properties of its supertypes.

Supertypes and subtypes are sometimes called *generalisations* and *specialisations*. For example, 'drawing' and 'manual' are specialisations of 'document', and accordingly 'document' is a generalisation of 'drawing' and 'manual'. One can also say that 'document' is a more general type than 'manual'. In principle, generalisation and specialisation can be seen as different concepts. Specialisation refers to the "top-down" evolution of types: a system first contains the type 'document', and then the designers realise that documents can further be specialised into drawings and manuals, which have their own special properties. Generalisation, on the other hand, corresponds to "bottom-up" evolution: a system first has types for drawings and manuals, and then the designers realise that the common properties these two types can be generalised into the type 'document'. Although usually generalisation and specialisation are simply two symmetrical names for the same relation, some models define them as separate concepts with different semantics (Abiteboul and Hull 1987).

It was said earlier that usually each object is an instance of exactly one object type. Type class hierarchies mean that, in one sense, an object can be an instance of multiple object types. For example, every instance of the object type 'drawing' is also automatically an instance of the object type 'document'. To be precise with the different types that an object can be an instance of, one must therefore define that each object is a *direct instance* of exactly one object type, and that an object that is a direct instance of an object type is an instance of this type and all its supertypes. In other words, an object is a direct instance of type T if the object is an instance of T and not an instance of any subtype of T.

Figure 2 with a class hierarchy looks somewhat similar to figure 1 on page 23, which illustrated different "metalevels" of object types and instances. The important difference is that the 'subtype-of' relation in figure 2 is transitive while the 'instance-of' relation in figure 1 is not. For example, in figure 2 the type 'manufacturing drawing' is a subtype of 'drawing', which is a subtype of 'document'. This means that a manufacturing drawing is also one kind of a drawing, and a drawing is also one kind of document. As a result, a manufacturing drawing is also one kind of a document.

Figure 1 contains a similar chain of related entities: 'drawing 1' is an instance of 'drawing', which is an instance of 'object type'. Nevertheless, the entities are on "different metalevels" as 'drawing 1' is *not* an instance of 'object type'.

All object types in figure 2 are on the same "metalevel" because they all are instances of the 'object type' of figure 1. Moreover, the class hierarchy in figure 2 can contain an arbitrary number of levels whereas the hierarchy in figure 1 has a fixed number of levels.

3.2.1.3 Multiple Inheritance

In the class hierarchy of figure 2 each object type except the root type 'document' has exactly one immediate supertype. This arrangement of object types, which results in a tree-like hierarchy, is called *single inheritance*. Accordingly, *multiple inheritance* means that an object can have multiple immediate supertypes.

Multiple inheritance makes it possible to represent more complex relations between object types. For example, figure 3 shows how a maintenance drawing is at the same time one kind of drawing and one kind of maintenance document.

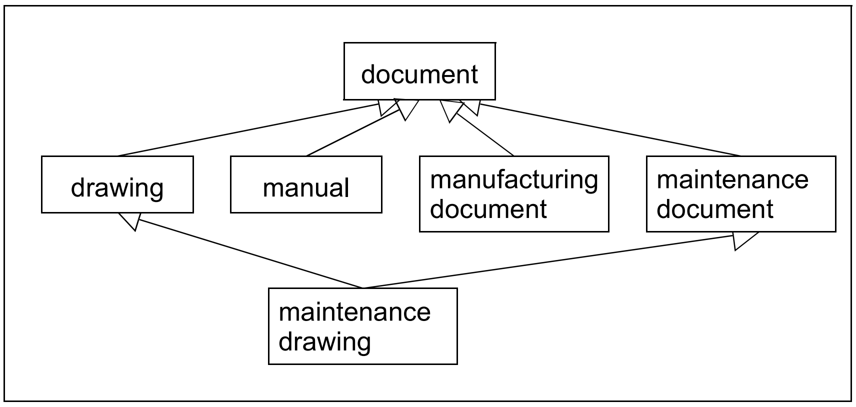


Figure 3. Multiple inheritance

3.2.1.4 Abstract and Concrete Types

Consider again the object types in figure 2. Suppose that it does not make sense to create an object that is simply a document or a drawing. Instead, each drawing must be a manufacturing drawing or a maintenance drawing. To represent this distinction between different kinds of object types, an object type can be designated as *abstract* (Fowler 1997: 85). There does not seem to be any established term for a non-abstract type; this thesis refers to such a type as a *concrete* type.

All objects must be direct instances of concrete types. Abstract types cannot be used directly to create instances; these types only serve as supertypes for other types. In figure 2, the types 'manufacturing drawing' and 'maintenance drawing' are thus concrete while ‘drawing’ and ‘document’ are abstract. The rule against instances of abstract types will, however, be relaxed for configurable products in section 3.3.2.7.

Usually the leaves of a class hierarchy (i.e., types without subtypes) are concrete. An abstract type without subtypes does not make much sense because it is impossible to create any instances of the type.

Moreover, if a type with subtypes is concrete, usually all the subtypes are concrete, too. Nevertheless, there is no technical reason for this rule. As an example, which may be somewhat artificial, consider again figure 2 and suppose that it should be possible to create a document without specifying its type more precisely. In other words, it is not necessary to classify each document as a drawing or as a manual. On the other hand, it should be impossible to create an object that is simply a drawing without specifying whether it is a manufacturing drawing or a maintenance drawing. This behaviour of different kinds of documents is achieved by designating the object types ‘document’, ‘manufacturing drawing’ and ‘maintenance drawing’ as concrete, and the object type ‘drawing’ as abstract.

3.2.1.5 Types and Classes

Some object-oriented programming languages distinguish between types and classes. For example, in the Eiffel language, a type defines a set of operations that can be applied to the instances of the type. Type T2 is subtype of type T1 if every operation that can be applied to an instance of T1 can be applied to an instance of T2. An Eiffel program consists of classes, and each class defines a type. A class can be defined to be a subclass of other classes, and the subclass inherits the properties of the superclasses.[1] The type defined by a subclass is thus usually a subtype of the type defined by a superclass. Nevertheless, a class can hide inherited properties, in which case a subclass no longer defines a subtype (Meyer 1992: sec. 22). In the Java language, a type defines an interface, i.e., again a set of operations, and a class implements one or more types (Arnold and Gosling 1996: 21–22). In PDM systems, however, this kind of distinction between types and classes is usually irrelevant because an object type only defines the data to be stored for objects of a particular type, and there are no separate interfaces and implementations.

3.2.2 Attributes

Database objects, such as products and documents, are associated with data that describes the object. This data is recorded as *attributes*. For example, a document can include attributes for the name and creation time of the document.

In principle attributes could be handled so that any object could directly specify a value to any attribute. Each object could then have a different set of attributes. Nevertheless, usually this approach is too unsystematic because users would have to decide separately for each object what data should be recorded about the particular

1. Actually, the Eiffel language does not use the terms ‘subclass’ and ‘superclass’.

object. Therefore, normally object types define attributes, and instances of a particular object type can assign values to attributes defined by the object type.[2]

3.2.2.1 Attribute Definitions

Usually each object is a direct instance of a particular object type. One of the functions of an object type is to record *attribute definitions*. An attribute definition specifies at least the name and value type of the attribute. The name is used for referring to the attribute, and the value type of an attribute specifies the possible values of the attribute. The value type can, for example, be 'positive integer', 'string of at most 20 characters' or 'date'.

In addition to name and value type, it should be possible to record other information about attributes. For example, in addition to a unique identifying name, an attribute can have multiple display names in different languages. The set of properties that must be recorded in an attribute definition varies between organisations and should accordingly not be fixed by the PDM system. Moreover, within a single organisation it may be necessary to record different things about different attributes.

In a very general model, attribute definitions should therefore be instances of attribute types, which can be created by a system administrator. An attribute type specifies what information is stored in an attribute definition of this attribute type. Moreover, it should be possible to arrange attribute types in a class hierarchy so that all attribute types have the properties specified in the root attribute type, and other attribute types can add other properties. In this approach, the root attribute type would thus specify the properties 'name' and 'value type' because all attribute definitions must include this information.

3.2.2.2 Attribute Assignments

An object is associated with a set of *attribute assignments*, which specify values for attributes in the particular object. Each attribute assignment specifies an attribute name and an attribute value, which is typically a character string or a number.

An instance of a particular object type can only assign values to attributes that are defined by the object type. Initial values are assigned to the attributes when the object is created, and existing attribute values can be later modified. If object types are arranged in a class hierarchy, attribute definitions are inherited from a type to its subtypes. For example, if there is the object type 'document' with a subtype 'drawing', drawings (more precisely, objects of the type 'drawing') can assign values to all

2. In PDM literature, attributes are often called 'metadata' (Miller, MacKrell and Mendel 1997). Nevertheless, in this thesis, the term 'metadata' refers to the data that tells what data is available about objects, i.e., to a "data dictionary" (Korth and Silberschatz 1986: 11). In other words, attribute definitions—not the attributes themselves—are metadata. For example, metadata is manipulated when a new attribute is added to a database, but not when the value of an attribute is modified.

attributes that are defined for all objects and documents in addition to the attributes defined specifically for drawings.

If the attribute definition in an object type specifies the attribute as *compulsory*, all instances of the type must assign a value to the attribute; if the attribute is *optional*, an object can leave the attribute unassigned (or assign a null value, which usually means the same).

3.2.2.3 Attribute Value Types

The *value type* of an attribute specifies what kind of values can be assigned to the attribute. Simple value types include integers, character strings and dates. It is often necessary to specify the allowed values for an attribute more precisely than by saying that the value must be any number or any string of at most a particular number of characters. In many systems it is possible to create value lists and specify that a particular attribute can only be assigned values from a particular value list.

Sometimes the value of an attribute must be of a particular form, such as two letters followed by a hyphen and three digits. This kind of constraint on attribute values can for example be described by means of a regular expression (Aho and Ullman 1977: sec. 3.3). In more complex cases it is necessary to a write a piece of program code to check the attribute value. Section 11.4 shows an example of this kind of mechanism.

It is useful if an attribute can also record a *set* or *list* of individual values instead of a single value. For example, a document can have an attribute that records the names of users who should be notified when new versions of the document are available, or a product can have a list of market areas as an attribute. Moreover, it should be possible to define attributes that store much larger pieces of data than a single integer or a relatively short character string. For example, it may be useful to have an attribute that stores a bitmap picture or even moving video data.

The allowed values of an attribute in an object may also depend on the values of other attributes in the object and other data in the database. In this case the routines that check attribute values are not necessarily associated with individual attributes. Instead, a single routine may check the values of a group of mutually dependent attributes. Whether an attribute is compulsory or optional may also depend on the values of other attributes.

If relations are represented by means of attributes, there are also attributes that have references to other objects as values. Relations and alternative possibilities for their representation are discussed in section 3.2.3.

3.2.2.4 Default Values

It should be possible to specify a default value in an attribute definition. The default value is assigned to the attribute when a user creates a new object without assigning any value to the attribute.[3] If the attribute definition in an object type definition simply includes a specific default value, all objects of this type have the same default value for the attribute. In more elaborate cases the default value again depends on the values of other attributes. The default value may also depend on the user who is creating the object. For example, suppose that each document is assigned to a particular department of the company. The default value for the corresponding document attribute could be the department of the user who creates the document.

3.2.2.5 Derived Attributes

If there is a mechanism for computing a default value for an attribute from other attribute values and other data, the same mechanism can also be used for derived attributes. The value of a derived attribute is computed from other data in the database. To ensure the correct value of a derived attribute, users are typically not allowed to assign values directly to the attribute.

There are basically two ways to handle derived attributes. One possibility is to compute the value each time the value is needed; the attribute value is not stored in the database at all. The view mechanism of relational databases is an example of this approach (Korth and Silberschatz 1986: sec. 3.5). The other alternative is to store the attribute value in the database and assign a new value to the attribute whenever the contents of the database change so that the value of the derived attribute needs to be changed, too. The latter method is usually more efficient (at least assuming that the value of the derived attribute is read more than once before the value changes). Nevertheless, if the value of the derived attribute is computed in a complex way, it may be difficult to ensure that the attribute is updated properly by all database operations that affect the attribute. Section 11.5 shows an example of a stored derived attribute.

Attributes in a PDM system may correspond to data in other systems. At worst, data from one system must be manually re-entered in another system. For example, some attributes that a PDM system stores for drawings may directly correspond to data stored in the drawings by the CAD tool. In this case the CAD tool must be integrated with the PDM system so that attribute values are automatically transferred between the systems.

3.2.2.6 Read-only Attributes

Attributes can be used for representing data that cannot be modified by users, or at least not with explicit attribute assignments. For example, suppose each object records its creation time. The creation time can be represented as an attribute that can be read by users in the same way as other attributes but cannot be assigned a new value. As another example, suppose that objects also record their last modification times. This data could be stored as an attribute that can again be read by users but can be assigned by the system only.

3. Alternatively, one can say that an attribute has a default in an object that does not assign a value to the attribute.

3.2.2.7 Attribute Refinements

If an object type inherits an attribute from a supertype, it should be possible to refine the attribute in the subtype. Typically an attribute refinement changes the value type or the default value of an attribute.

An object type can refine the value type of an attribute defined in a supertype. For example, suppose the object type 'document' defines an attribute with a list of allowed values. The object type 'drawing', which is a subtype of 'document', can refine the attribute value type by further restricting the list of allowed values. A subtype cannot extend the attribute value type; for example, the attribute in a drawing cannot be assigned a value that would not be allowed in a document.

If an object type inherits multiple refinements for an attribute, the "effective" value type of the attribute in the object type is the "intersection" of all value types. For example, figure 4 shows object type A, which defines attribute 'i' with the value type 'integer'. Subtypes B and C refine the value type as 'integer greater than 100' and 'even integer'. Object type D, which is an immediate subtype of both B and C, has 'even integer greater than 100' as the "effective" value type for the attribute.

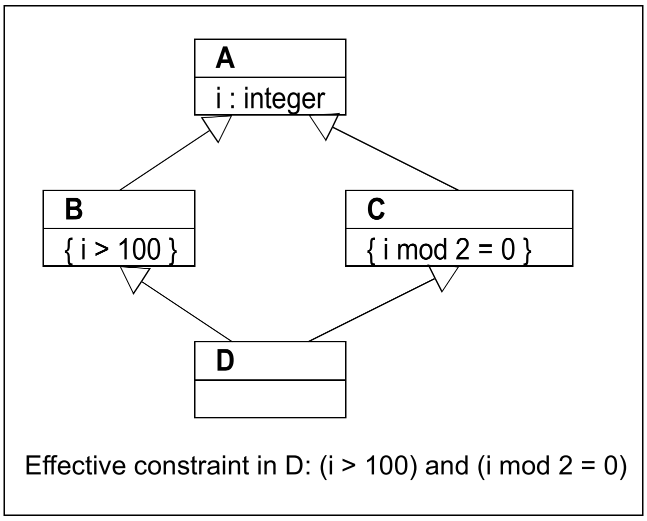


Figure 4. Attribute refinement

An attribute refinement can also specify a new default for an inherited attribute. For example, if both the object type 'document' and the object type 'drawing' define a default value for an attribute, the default value defined by the object type 'drawing' is used for all drawings. Multiple inheritance obviously poses a problem if conflicting default values are inherited from two immediate supertypes. One possibility is to specify that in this case the subtype itself must define a default value for the attribute.

3.2.3 Relations

So far the discussion has mainly concerned data that is attached to individual objects. For example, products and documents have attributes. Nevertheless, there are also *relations* between objects. Below are some examples, which are discussed in more detail in other sections.

- Relations between a product and its components (section 3.3.1).
- Relations between products and connected documents (section 3.4).
- Relations between an object and its versions, and between versions (section 3.5).
- Relations between interdependent objects (section 4.5).

In the same way that a PDM system should make it possible to create new object types (e.g., a new document type), the system should allow the creation of new relations. The definition of a new relation must at least specify the name of the relation, the types of objects that can participate in the relation, and the cardinality of the relation. For example, if a particular relation between products and documents has the cardinality '[0..1]-[0..*]', each product can be related to many documents, and each document can be related to at most one product.

There are various ways to represent relations between objects. As an example, suppose there is a relation between documents and products.[4]

One possibility is that objects have reference attributes. The definition of a reference attribute specifies an object type, and the value of the attribute is a reference to an object of this type or a set of references to objects. In the previous example, documents could include an attribute of the type 'reference to a product', and correspondingly products could include an attribute of the type 'set of references to documents'. This representation of relations is simple because reference attributes can be treated in much the same way as other attributes.

Nevertheless, there are also good reasons for representing relations as "first-class entities" instead of using reference attributes (Rumbaugh 1987). This approach uses two kinds of entities: objects and relationships. Each relationship entity is an instance of a relation type in the same way that objects are instances of object types. Each relationship records references to the related objects. In the case of a relation between products and documents, each related ⟨product, document⟩ pair would thus be represented as a relationship that contains a reference to one product and one document.

To some extent the choice between representing relations with attributes or relationship entities is only a matter of implementation techniques. Nevertheless, only relationship entities make it possible to add attributes to the relationships. For exam-

4. Note that the term 'relation' is defined in mathematics as a subset of the Cartesian product of the related sets. In the example, the relation would thus consist of all related ⟨product, document⟩-pairs. An individual pair of a relation is here called a 'relationship'.

ple, consider the 'has-part' relation between components. An individual relationship could for example tell that component X has component Y as a part. The position and orientation of Y with respect to X could be stored as an attribute of the relationship because this data is associated with the particular combination of two components, not with either of the components.

3.3 Products

The term 'product' is ambiguous in more than one way. Firstly, consider the hierarchical breakdown structure of product, such as a car and its engine. From a customer's point of view the car is a product whereas the engine is only a component of the product. On the other hand, typically similar PDM functions are needed for both "top-level products" (e.g., the car) and "components" (e.g., the engine). It is therefore rather irrelevant whether items at all levels are called products or components. This thesis mainly uses the term 'component'. When a component is said to consist of subcomponents, the component with subcomponents can also be a complete product. It is possible to make another choice. For example, Part 41 of the STEP standard (section 6.1.3.1) only uses the term 'product', and consequently a product can be composed of other products (ISO 1994d: sec. 2.3.4.1).

Secondly, suppose I have bought a car of the same make and model as my friend. Have we bought the same product? The answer is positive if the term 'product' is understood to refer to the product design which can be manufactured in multiple copies. On the other hand, my car and my friend's car are two separate products if the term refers to the actual physical products.

One area where this distinction becomes obvious is the life cycle of a product. The life cycle of a physical product extends from manufacture to demolition and recycling whereas the life cycle of a product design begins with some initial concept for a new product and ends when the design is taken away from production and the existing physical products can in effect be "forgotten". The last comment refers to the fact that the manufacturer must often provide spare parts and other after-sales services even when the product is no longer manufactured.

Thirdly, consider a configurable product, which allows some degree of customer-specific variation (section 3.3.2). Again, 'product' can mean either a generic product with all the allowed variation, or a specific product that has been configured for a particular customer order.

The differences between a car design and an individual car, and between a configurable product and its variants are similar because they both deal with the distinction between a product type and its instances. A physical product is an instance of a product design, and a product configuration is an instance of a configurable product. Depending on the context, the term product can refer either to a type or one of its instances.

The term 'product' is so generic that one should not try to reserve one of its possible meanings as the "correct" one. When products are discussed in a more specific context, such as in a particular data model or PDM system, the term must be defined more precisely. Even then it may be better not to select arbitrarily a particular restricted meaning for the term. Instead, other terms, such as 'product family' and 'product variant' in chapter 9, should be defined with more precise meaning.

This thesis mainly deals with physical, manufactured products. To some extent the concepts are also applicable to non-physical products. For example, most of the issues discussed by Cagan (1995) in connection with software configuration management are valid for PDM, too.

3.3.1 Product Structures

One of the fundamental properties of virtually any product is a hierarchical product breakdown structure, which describes how the product is divided into components, which are in turn divided into subcomponents, etc. In this thesis, the term 'product structure' refers to this hierarchical arrangement of the components of a product. Another commonly used term is bill-of-material (BOM). The STEP standard discussed in section 6.1 further distinguishes between the BOM structure and the parts list structure of a product. This distinction, however, is not in general use.

The important question of component versions in product structures is addressed together with versioning in section 3.5.6.

3.3.1.1 Parts and Components

This thesis refers to the hierarchical connection between components by saying that a component has another component as a part. Moreover, a component is said to *realise* a part in another component. For example, a bicycle can have the parts 'front wheel' and 'back wheel', both of which can be realised with the same kind of component. The distinction between components and parts becomes especially important in section 3.3.2 in connection with configuration models. A configuration model can, for example, specify that a particular part can be realised with either of two alternative components.

To illustrate the difference between a part and a component that realises the part, one can also regard a part as a "slot" that can be "filled" with an appropriate component. The name of the part is an identification for the "slot", and the name of a component is an identification for the component that "fills" a particular slot in a particular component. One can also say that a part, such as the front wheel of a bicycle, defines a role, which is played by the component that realises the part.

The product structure is sometimes also referred to as the *has-part* relation. If component X has component Y as a part, one can say that X and Y are related through the 'has-part' relation.

Note that sometimes the term 'part' is used quite differently. For example, in the draft ISO standard on Part Libraries, discussed in section 6.2, a part corresponds to what is called a component in this thesis, and a component in the standard is a part on the "lowest" level of a product structure, i.e., a component cannot be decomposed into further components.

Some models define a fixed number of product structure levels with different names. For example, the American military standard MIL-STD-280A defines the following eight item levels: system, subsystem, set, group, unit, assembly, subassembly and part (Buckley 1996: 10, 270). Each level is given a different definition, but the definitions are so vague that one wonders whether it is really possible to assign the components of a product to these levels. The fixed number of levels also seems arbitrary; why not seven or nine levels instead of eight?

Components, like all objects, are instances of object types. One important question is how parts relate to component types and instances. A component type defines attributes, and an instance of the component type assigns values to the attributes. Should parts be treated in a similar way so that a component type defines parts, and an instance of the component type realises the part with other component instances?

This approach is taken for configurable products in section 3.3.2. A single configurable product is represented with a component type. The instances of the type are similar in the sense that all instances have the same parts but different in the sense that in different instances of the type the parts are realised by different component instances. As a result there is a large number of component types because every component with different parts requires its own component type.

Nevertheless, it is not always necessary to represent parts in such detail. Alternatively, a component type does not define any parts. A component instance can then have any parts regardless of the component type. This approach is typically used in systems that do not support configurable products or generic product structures.

3.3.1.2 Multiple Structures and Views

Thus far the discussion has referred to *the* product structure of a product, implying that each product would have a single breakdown structure. Nevertheless, this is not necessarily true. For example, a product can have separate manufacturing and maintenance structures. These different structures are sometimes referred to as views (van den Hamer and Lepoeter 1996).

A simple approach to multiple views is that a product has a single breakdown structure, and each component in this structure can be associated with multiple views of the component (Cleetus 1995). The problem with this approach is that all views of a single product have the same breakdown structure.

If different views of a product should have different structures, a simply solution is to assume that a product has a single "complete" structure. The different views only display different parts of this structure by filtering out unwanted data.

In general, however, a product can have multiple "truly" different structures, which cannot be created with filters from any single "master" structure. As all the structures still represent different aspects of the same product, there must be a mechanism for saying that particular components in two views are related in a particular way, for example by corresponding to the same physical component. The model described by Katz (1990) represents this information with structural objects called *equivalencies*.

3.3.1.3 Shared Components

One issue with product structures is the question of shared components, i.e., the question whether a single component can realise multiple parts. Here it is important to understand the level on which things are shared.

It is clearly possible to share component descriptions. A physical product consists of physical components, which are described by some kind of component objects in the PDM system. A component object can be shared so that two physical components are described by the same component object. This means that the physical components are identical with respect to the properties that are represented with the component objects in the PDM system.

Consider a product with "identical" components. While the components are being designed, they are described by a single component object. However, when the product is manufactured, it may be necessary to give the components their own "identities" by describing them with two separate component objects. These objects can store data that is applicable to individual components, such as maintenance histories.

What is not so clear is whether there is ever the need for truly shared components. In other words, can a single physical component realise two parts at the same time? If the parts of a product represent functions that must be fulfilled by physical components, a single component can fulfil two functions and thus realise two parts. Nevertheless, in this case it may be more appropriate to introduce functions and their relations with components as altogether new concepts.

3.3.2 Configurable Products

Companies are becoming increasingly interested in *configurable products*, which can be adapted individually for customer requirements (Tiihonen et al. 1996). A configurable product represents a set of different but closely related *product variants*. All variants of a configurable product can also be called a *product family*. All possible variants of a configurable product are described with a *configuration model* or a *generic product structure* (Erens 1996: sec. 4.3), which mean more or less the same.

Figure 5 illustrates two paths that can lead a company towards configurable products. First, a company can originally be making non-configurable standard products. The company has a fixed range of products that are first designed and then manufactured in large numbers. The production can be made efficient because all "instances" of the product are identical. Many companies, however, want to increase their competitiveness with configurable products, which means that the customers can buy products that have been adapted individually, within some limits, to their needs.

The second path to configurable products starts from individually designed one-of-a-kind products. These products cater very well for the needs of customers, but

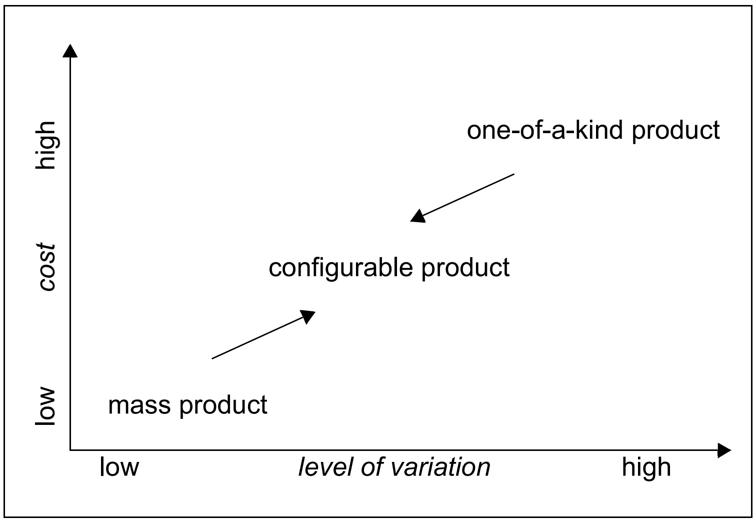


Figure 5. Two paths to configurable products

the individual design and engineering work involved in each product order is expensive. Companies with these products want to reduce costs by eliminating some of the creative, and expensive, engineering needed for individual product deliveries.

Few of the current PDM systems can manage configurable products. Although there are many separate configurator tools (Haag 1998; Richardson 1997), the additional functionality needed for configurable products is so closely connected with the other functions of PDM systems that support for configurable products should be included directly in a PDM system.

Although a PDM system should provide support in the management of configurable products, it is important to understand that the configurability of a product is based on the product itself, not on any information system. Usually this means that the product must have a modular structure so that a particular variant of the product can be created by combining a suitable subset of the available modules.

This section defines fundamental concepts for configurable products. The concepts and terms are based on the work in the Product Data Management Group (Peltonen et al. 1998).

3.3.2.1 Configuration Process

Although this chapter of the thesis deals with data models, the presentation of the data model for configurable products must begin with a brief description of the processes that provide the context for the data model.

The variants of a configurable product are constructed individually for each customer order from predefined components on the basis of an order specification and a predefined configuration model.

As noted earlier, the distinction between products and components is not important in this thesis. In the definition above, a product is not necessarily an end-product sold to customers. The product can also be a component within a larger product, and the customer can for example be a manufacturing or assembly unit within the same or in another company. Although this section, like most of the thesis, is written in terms of physical, manufactured products, a configurable product can also be a service or other immaterial good, such as an insurance policy.

Figure 6 illustrates the sales-delivery process that is carried out for each customer order, leading from customer requirements to the physical products that are manufactured for the customer. This section mainly deals with the configuration process, which is one part of the whole sales-delivery process.

The input to the configuration process is an *order specification*, which is a formal representation of customer requirements. The specification is created by sales personnel, possibly in a computer-assisted sales configuration process, which may be similar to the configuration process described here.

The configuration process is controlled by a *configuration model*. The configuration model of a configurable product describes all the possible variants of the product and specifies how to create an appropriate variant for a given order specification or at least how to check whether a given variant conforms to a given specification.

The configuration process generates a *configuration*, which is a description of the specific product variant that will be manufactured for the particular order. The configuration is said to be based on the configuration model that controls the configuration process. As illustrated in the figure and explained later in the text, it is assumed here that the order specification is actually stored as part of the configuration.

A configuration does not only represent the final outcome of the configuration process but also its intermediate stages (Peltonen et al. 1994b). A configuration is created at the beginning of the process, and during the process the configuration records what is known about the product variant. In general a configuration thus represents many possible product variants. During the configuration process, which is often iterative, the configuration becomes more and more detailed representing fewer and fewer variants. Finally the configuration becomes a *specific configuration*, which represents a single variant.

Before the product is actually manufactured, one creates an *individual description* of it. Each individual description corresponds to a single physical product and contains additional information that is needed and created during the manufacturing process. An individual description can for example record the serial number and the maintenance history of a physical product.

Later a configuration may become subject to *reconfiguration*. This refers to a situation in which an individual configuration must be modified to satisfy new customer requirements. In general, reconfiguration is more difficult than configuration because one must not only consider the desired outcome of a configuration process but also find the most suitable (least expensive, fastest, etc.) way to reach this state by modifying the existing configuration.

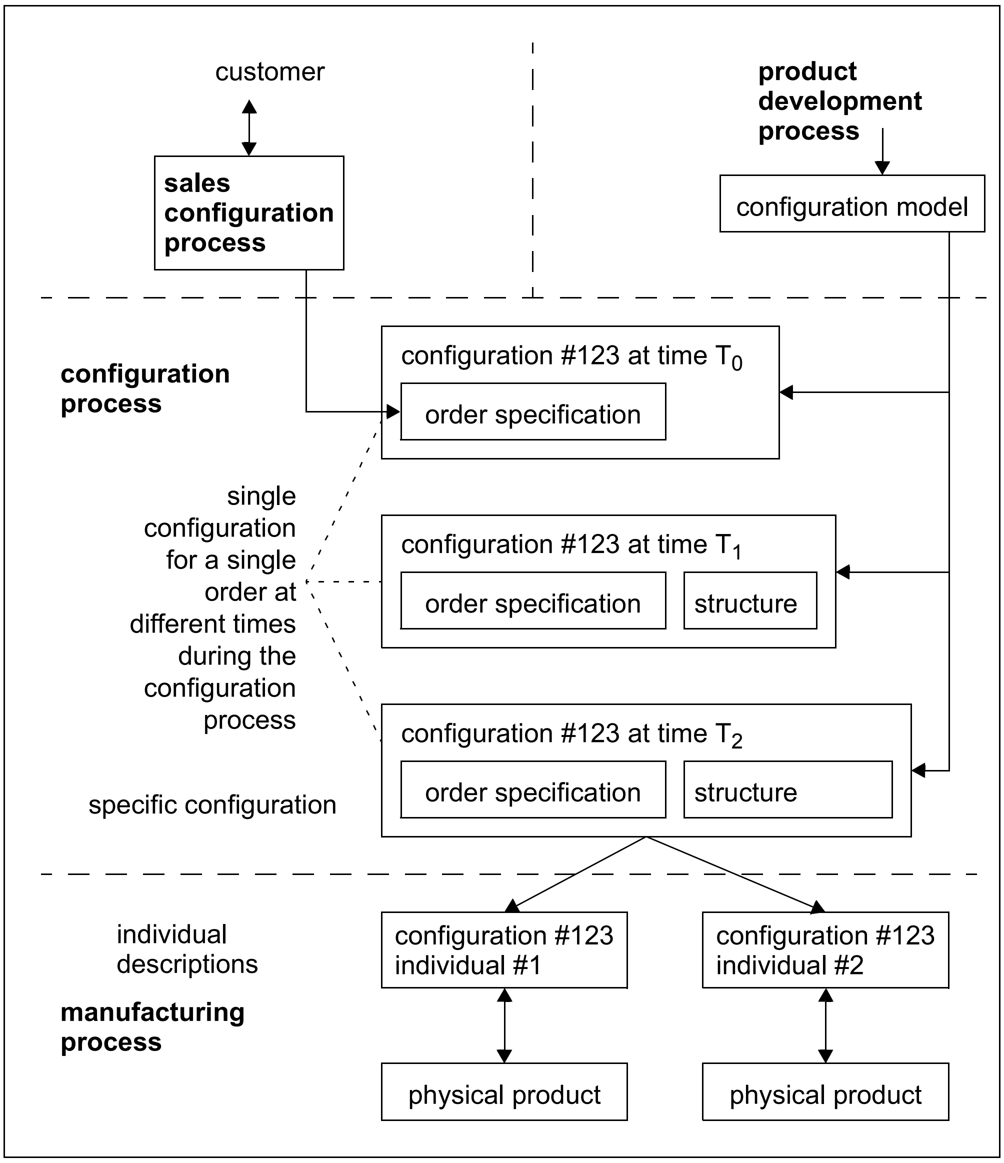

customer
product development process
sales configuration process
configuration model
configuration process
configuration #123 at time T_0
order specification
single configuration for a single order at different times during the configuration process
configuration #123 at time T_1
order specification
structure
configuration #123 at time T_2
order specification
structure
specific configuration
individual descriptions
configuration #123 individual #1
configuration #123 individual #2
manufacturing process
physical product
physical product

Figure 6. Configuration process

3.3.2.2 Explicit Structure

There are many different approaches to configurable products (Sabin and Weigel 1998). When configurable products are included in a PDM system, it seems best to use a conventional hierarchical product structure as the basis for the description of a configurable product. A configuration model is therefore divided into an *explicit structure* and constraints (Männistö, Peltonen and Sulonen 1996). Explicit structures are discussed here, and constraints in section 3.3.2.4.

To represent configurable products, product structures must be extended with concepts like optional and alternative parts and parametric components. A part is optional if the part need not be realised by any component. An alternative part does not need to be realised with a particular kind of component. Instead, the part has multiple alternatives for its realisation. A parametric component has parameters, which must be given values during the configuration process. Typical parameters include the colour or physical dimensions of a component.

So far it has been assumed that there are relatively few component types. For example, there could be a type for standard components bought from outside the company, another type for components manufactured by the company itself, etc. There can be a class hierarchy of component types, but in any case the number of component types is assumed to be in the order of tens rather than hundreds. The set of component types is quite static. Although new instances of the component types are created constantly, a new component type is created only when there is a need to represent components that have attributes different from other components and that must be processed somehow differently.

Accordingly, in the discussion on product structures in section 3.3.1, the 'has-part' relation was established between component instances. In other words, a component instance has other component instances as parts. The difference between a reference to a component (instance) and a reference to a component version is ignored here but will be brought up later.

In configurable products, however, component types play a more important role. For example, a parametric component is represented with a component type that defines attributes for the parameters of the component. Whereas an ordinary product structure records 'has-part' relationships between component instances, a component type in a configuration model has other component types as parts. More precisely, a component type can specify that a valid instance of the type has a part that must be realised with an instance of a particular component type.

The explicit structure of a configuration model can, for example, be built with the following concepts:

- A configuration model defines component types, which are arranged in a class hierarchy. It should be possible to use multiple inheritance.
- A component type can define attributes.
- A component type can define parts. A part definition specifies the following properties:
    - *Part name.* Part name makes it possible to refer to a part independently of the component type or types that can realise the part.
    - *Allowed component types.* The part can be realised with instances of any of the allowed types.

    - *Cardinality.* The cardinality of a part tells the allowed number of instances that can realise the part. The can be specified, for example, as an integer range or a set of ranges. A part is optional if its cardinality includes zero, in other words, if "no components" is an allowed realisation for the part.

- One of the component types is designated as a *configuration type*. The configuration as a whole is represented as a configuration instance, which is an instance of the configuration type or its subtype. Other components of the configuration are direct and indirect parts of the configuration instances.

If the cardinality of the part makes it possible to realise the part with multiple component instances, and there are multiple allowed component types, it is further necessary to specify whether all components in the realisation of the part must be of the same type or whether it is possible to mix instances of different allowed component types in a realisation of the part.

In addition to the explicit structure, configurable products can also be described with other constructs, such as components with ports that must be connected to other ports (Mittal and Frayman 1989). This approach, which is not discussed further in this thesis, emphasises the physical and other connections between components; the hierarchical breakdown structure of the product is more or less implicit.

3.3.2.3 Configuration Questions and Completeness

This section introduces the concept of configuration completeness, which is one necessary condition for a specific configuration. One way to illustrate completeness and other properties of configurations is to think of the explicit structure of a configuration model as "asking questions" that must be answered during a configuration process. For example, an optional part in the explicit structure asks if the component is included in the configuration; an alternative part asks which alternative is chosen; and a parametric component asks what values are given to the parameters.

The explicit structure of a configuration model asks questions, and the answers are recorded in a configuration that is based on the configuration model. As the configuration gradually becomes more detailed during a configuration process, in terms of questions and answers this means that the configuration answers an increasing number of questions. A configuration that answers all the questions asked by the configuration model is a *complete* configuration.

Note that all questions of an explicit structure do not necessarily have to be answered during each configuration process. Some questions are "activated" only if other questions are answered in a particular way.

The questions and answers must only be understood as a metaphor for explaining completeness and other concepts related to configuration models and configurations. The explicit structure is still represented as an extended bill-of-material, not as a set of questions.

3.3.2.4 Constraints

The explicit structure of a configuration model defines a large number of different possible complete configurations. Typically not all of them can be accepted as specific configurations resulting from a configuration process. A complete configuration can, for example, be disallowed because it represents a product variant that cannot be built for technical reasons. The marketing policy of a company may also dictate that certain variants are not sold although there are no technical reasons against it. For example, a car may not be available with a leather interior in combination with a small engine.

Since all complete configurations are not acceptable as specific configurations, a specific configuration must be both complete and *valid*. A configuration model defines the validity criteria as *constraints*. Constraints are conditions that can be evaluated in a configuration and none of which is false in a valid configuration.

The result of evaluating an individual constraint in a configuration is true, false or unknown. The result can be unknown in an incomplete configuration that does not yet answer a question that the constraint refers to. If a constraint evaluates to true or false in a particular configuration, the configuration is said to satisfy or to violate the constraint, respectively. If the value is unknown, the configuration neither satisfies nor violates the constraint.

These definitions allow all combinations of completeness and validity. For example, if a configuration is incomplete and valid, all questions of the explicit structure have not yet been answered, but the answers given so far violate no constraints.

3.3.2.5 Order Specifications

In this section it is assumed that it is possible to distinguish between an order specification, which serves as input to a configuration process, and the structure of a configuration, which represents the output from the process. This distinction is meaningless for products that are configured without a formal order specification. Their structure is built gradually during the configuration process, and the inclusion of a particular component, for example, can sometimes be "input data" and sometimes "output data" determined by other "input data".

If, however, the product has an order specification, the relations between the specification and the configuration are also defined with constraints, which are here called *implementation constraints* because they specify how different specifications should be "implemented" by means of different configurations. For example, a computer could be associated with an implementation constraint saying that if the customer wants to run a particular application on the computer, the computer must have at least a particular amount of memory.

To write formal implementation constraints, the description of a configurable product must specify the allowed form for an order specification that can be used as input to a configuration process. For example, a configurable computer could be associated with a set of applications and the order specification could contain some subset of this set.

One way to organise configuration models and order specifications is to include the implementation constraints and the description of the order specification in the configuration model. The order specification itself is part of a configuration, as was illustrated in figure 6.

Earlier a configuration was said to contain information for the manufacture of a product variant. If the configuration also contains the order specification, a specific configuration based on a particular configuration model represents an acceptable variant of the configurable product that also conforms to the order specification included in the configuration.

There can be many specific configurations for a given configuration model and a given order specification. In this case one of the specific configurations is selected for manufacturing on the basis of some criterion, such as an optimality criterion on price or delivery time. If possible, the criterion should of course be included in the configuration model so that the model does not accept multiple specific configurations for any order specification.

3.3.2.6 Constraint Classes

It is now necessary to elaborate on the division of a configuration model into an explicit structure and constraints. A configuration model consists of an order specification description, an explicit structure and constraints. The constraints are further divided into three classes according to whether they refer to the order specification, to the explicit structure or to both.

- *Specification constraints* refer to the order specification only. In other words, specification constraints define the criteria for checking the validity of an order specification that is going to be used as input in a configuration process. It is useful if the product, its configuration model and the configuration process can be designed so that a valid order specification always leads to a specific configuration.

- *Implementation constraints* refer to both the order specification and the explicit structure. They thus define the criteria for checking whether the structure of a given configuration implements the specification of the configuration.

- *Structural constraints* refer to the explicit structure only. They define the criteria for checking whether the configuration as such represents a product that the company is able or willing to manufacture without considering any order specification.

The completeness and validity of a configuration must be redefined similarly. A configuration can thus be separately complete with respect to the order specification and the structure. It is also possible to check separately whether a configuration is valid with respect to each of the three constraint groups.

3.3.2.7 Abstract Component Types in Configuration Models

When the distinction between abstract and concrete component types was introduced in section 3.2.1.4 it was said that all component instances must be instances of concrete component types. An instance of an abstract type does not make sense in an ordinary product structure, which does not involve any notion of configuration. Nevertheless, a configuration of a configurable product can reasonably contain an instance of an abstract component type during a configuration process.

For example, consider figure 7, which shows component types that represent different kinds of computers. In this figure the "leaf" component types, i.e., 'business computer', 'entertainment computer' and 'educational computer' are concrete, and the component types without subtypes are abstract.

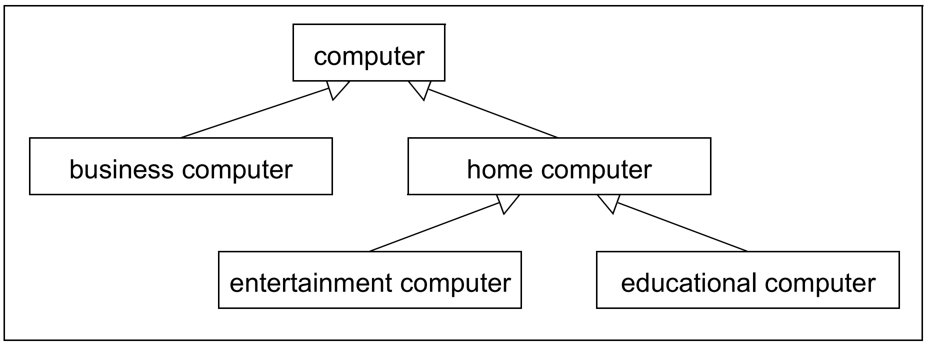


Figure 7. Component type hierarchy

This means that a product delivered to a customer must be a business computer or either of the home computer models. One cannot simply order a computer or a home computer without specifying a particular kind of computer. The component types 'computer' and 'home computer' thus describe the general properties of all computers and of all home computers, respectively. They do not specify a product in "sufficient detail" in the same way as the component type for the business computer and the component types for the two specific home computer models.

In terms of questions asked by an explicit structure one can say that the component type 'entertainment computer' is concrete because the component type (together with its supertypes) asks all questions that need to be answered in a configuration process to make a specific product variant. A concrete component type also contains all necessary constraints for checking the validity of the answers. The abstract component type 'home computer' on the other hand asks "too few" questions; even when all questions have been answered, there is not enough information to serve as output from a configuration process.

A configuration can contain instances of abstract component types during a configuration process. For example, suppose a computer is being configured. The configuration can first contain an instance of the abstract component type 'home computer', which tells that the computer is going to be some kind of home computer. Later during the configuration process the component instance must be changed to be an instance of a concrete component type, such as 'entertainment computer'.

A specific configuration, which is the output from a configuration process, was earlier required to be both complete and valid. The third and final requirement for a specific configuration is that all its components are instances of concrete component types.

3.3.2.8 Part Refinement

Section 3.2.2.7 already showed how a component type can refine attributes defined in its supertypes. Similarly, a component type can refine parts. As an example, consider figure 8, which shows the component types 'car', 'bus', 'engine' and 'diesel engine'. The component types 'bus' and 'diesel engine' are subtypes of 'car' and 'engine', respectively. The component type 'car' specifies that it has a part 'engine' of the component type 'engine'. The component type 'bus' is a subtype of 'car', and accordingly can refine the part by specifying that the part must be of the type 'diesel engine', which is a subtype of 'engine'. In summary, each car has some kind of engine, a bus is one kind of a car, a diesel engine is one kind of an engine, and a bus has a diesel engine.

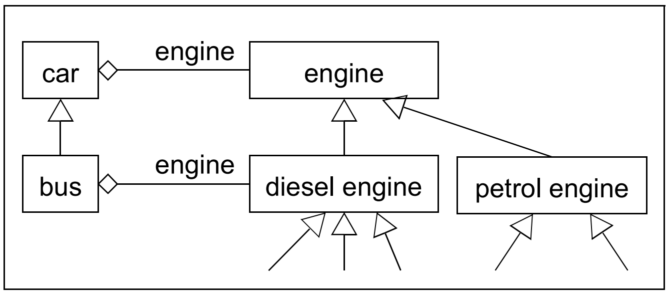


Figure 8. Part refinement

In the previous example the component type of the engine part was refined when one moved from component type 'car' to its subtype 'bus'. Parts can also be refined during a configuration process. For example, the configuration for a bus may originally specify the engine to be simply a diesel engine. Later during the configuration process the part is refined to a subtype of the diesel engine. Typically both 'engine' and 'diesel engine' would be abstract component types. In a specific configuration the part must have been refined to a concrete component type.

The configuration instance, which represents the configuration as a whole, can be refined in the same way as any of its parts. This means that a configuration that is originally an instance of one component type can change during a configuration process to be an instance of a subtype of the original component type.

The discussion above dealt with the refinement of a part from a component type to one of the subtypes. A part can also be replaced with an instance of a supertype, which is an example of "backtracking" during a configuration process.

3.3.2.9 Validation and Generation

The constraints are a mechanism for specifying the validity conditions for a configuration. Nevertheless, a PDM system that supports configurable products should obviously do more than just check the validity of a configuration that the user has somehow created.

Some constraints can be solved automatically. In other words, given a set of constraints, one can automatically derive a procedure that generates a configuration that satisfies the constraints (Shah and Mäntylä 1995: sec. 8.3.3). Nevertheless, many constraints in actual configurable products are too complex to make constraint programming a general solution to product configuration.

It is therefore necessary to draw a distinction between the *validation* and *generation* of a configuration. A configuration is validated with constraints, and generated with procedures. A procedure can employ various techniques, including conventional procedural language, logic programming and, in some cases, constraint programming. A procedure can also be an external program, which is started by the configuration tool with input values derived from the answers already available in the configuration and which adds new answers to the configuration.

Sometimes it is difficult to separate validation and generation. For example, suppose part of the configuration is generated with an external stress analysis program. It seems impossible to associate this procedure with a more meaningful validation constraint than with one that checks that the current output values have been computed from the current input values with the correct program.

3.4 Documents

To a large extent product data is represented as documents, which are created and manipulated with specific tools. Although document management is one of the most important functions of a PDM system, this section on document management is rather short because document versioning in discussed separately in the next section and document management is the main topic of the second part of the thesis.

Most documents in a manufacturing company are connected to products. Typical examples of documents include drawings manipulated with a CAD tool and manuals manipulated with text processors and desktop publishing tools. A document may not have any direct representation on paper. For example, a 3-D solid model can also be regarded as a document related to a product.

The connection between products and documents is many-to-many. A single product can have many connected documents, and a single document can be connected to many products. For instance, a number of similar related products can share a common service manual. There can also be documents that are not connected to any product. For example, quality handbooks and other documents that describe general procedures within a company are not connected to products.

Sometimes one distinguishes between drawings and other documents (Buckley 1996: sec. 8.2). This distinction seems to be motivated by the convention that each product is closely associated with a "main drawing", which can include other information in addition to a graphical description of the product. For example, the parts list of a product with a particular identification may be found on a drawing with the same identification as the product. In this thesis, however, drawings are not distinguished from other documents. Other information, such as the parts list, is assumed to be associated directly with the product.

In everyday speech, a document is usually understood as a file that can be opened and manipulated with a document tool, such as a word processor. Nevertheless, in a PDM system, a document is a more abstract object. For example, in the system described in the second part of the thesis, a document is a hierarchical structure of document versions, subdocuments and other entities. Moreover, a document, its version, etc., have attributes, which are typically managed by the PDM system only and are not seen by the document tools. In this thesis the "actual document", which is manipulated with a document tool, is called a *document file*.

Today virtually all documents are available in digital form. The actual document (i.e., a document file) is thus also stored in a PDM system. Companies often also have old drawings and other documents on paper only. These documents can be scanned into digital form and stored in the database, or the database can contain only a reference to the paper copy.

A PDM system typically treats a document file simply as a binary file, i.e., as an arbitrary sequence of bytes. This means that the system can store any kind of document, which must be manipulated with a separate document tool (see tool integration in section 5.5.1).

Usually a document file is the smallest unit manipulated with a PDM system. Nevertheless, a document file can have a further internal structure. A text file, for example, can consist of chapters, subsection, paragraphs, figures, etc. Similarly, a drawing can consist of assemblies, components, lines, points, etc. The fact that the PDM system does not "understand" the contents of a document file at this level is not a serious problem if the document files are self-contained in the sense that the relations between different components of a document file are always within a single document file. For example, consider a text file that contains a figure. There is no problem if the figure is embedded in the file so that the figure is stored as part of a single file.

Nevertheless, it is also possible that the figure is stored as a separate document or as a separate document file within the same document, and the text file only contains a link to the figure file. Moreover, the same figure can be used in many documents, all which contain a link to the same document. These links between documents (or document files) should also be known by the PDM system. For example, the system should prevent a user from deleting the figure as long as there are other documents with a link to it.

It is difficult for a PDM system to determine these kinds of relations between documents, especially if the documents are stored in the proprietary formats of the tool programs. The problem becomes somewhat easier if documents are stored in a structured and standardised format, such as SGML or XML (Light 1997).

It is usually assumed that products and other "abstract" entities serve as the main "access points" to product data in a PDM system. The products can then provide links to associated drawings and other "concrete" documents. However, Dong and Agogino (1998) describe an alternative approach, in which a CAD program and CAD drawings are the primary interface to engineering data. In their system, the graphical entities in a CAD drawing can contain links to data in a relational database system and to other documents stored in a document management system. The system thus relies heavily on documents, or "smart drawings" as they are called in the system.

The use of CAD drawings as a basis for an engineering data system may make the system easier to use because of its concreteness and the familiarity to engineers who mainly work with drawings. On the other hand, one wonders how convenient the document-based approach is, for example, for describing product structures, in which the primary relation seems to be between components and other "abstract" entities rather than between concrete documents.

In general, structural relations among documents should be used only when it is really a question of document structure. For example, a chapter can be a part of a document. Otherwise, 'has-part' relations should be between components, and components should be associated with documents (figure 9). It has been said that "The more there is structure in a document rather than there are documents in a structure, the more inconsistency of views can be the consequence" (Erens 1996: 53).

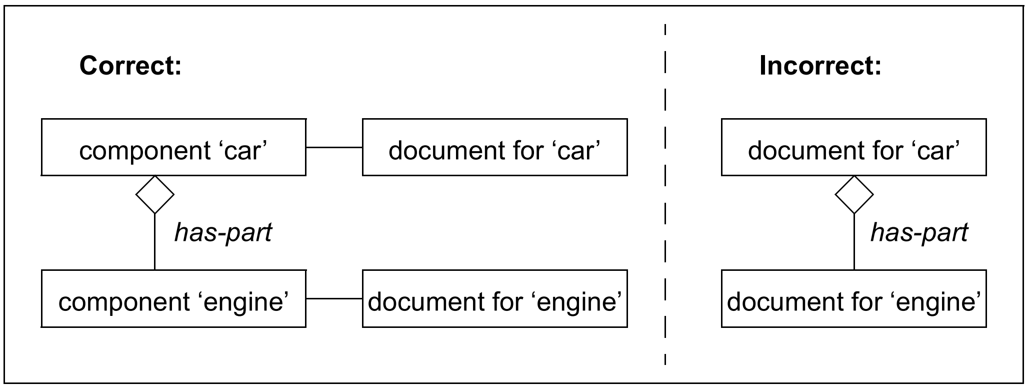


Figure 9. Structure between components instead of documents

3.5 Versioning

All PDM systems allow an object to have many separate *versions*. The term version, however, has many meanings in different systems.

Versions are mainly used for two basic concepts. Firstly, versions can represent the evolution of an object through successive stages. These versions are often called *revisions*. Secondly, an object can have a number of parallel alternatives. Versions of this type are often known as *variants*.

This section first discusses revisions and then variants as well as the interplay between revisions and variants. To make the discussion more concrete, versions are introduced in the context of engineering documents. Nevertheless, the same concepts are applicable to many other objects. Moreover, this section only deals with the versions of a single atomic object. The versioning of components and composite objects is discussed in section 3.5.6.

3.5.1 Revisions

An engineering document is typically produced by a single person or a small team of people. After the document becomes ready, it is released for use by a large number of people. The modification of a released document is very likely to disturb the work of many people and should therefore be avoided.

Nevertheless, usually an engineering document, unlike for example a novel, must be modified even after the document has been released. A document typically describes some aspect of a product manufactured by a company, and no company remains competitive without constantly improving its products through new versions.

When a released document must be modified, the users of the document should be exposed to the modifications in a controlled manner to minimise the inevitable disruptions. This is usually done by representing the evolution of a document with consecutive revisions.

During the lifetime of a document the revisions represent milestones that have been made available to a group of people. The release of a new document revision is typically associated with procedures that ensure the quality of the revision (e.g., inspections, reviews, approval procedures).

Controlled release of documents is by no means the only reason for a revision mechanism. When a product and related documents are modified, it is necessary to save the old revisions of the documents so that the manufacturer knows what the earlier manufactured products were like. This information is essential for after-sales operations such as maintenance and modernisation. During the development of a new product or product version it is also useful to have older revisions of the design available for reference. For example, the developers of computer software are often faced with the problem "My program no longer works after the changes I made yesterday. What did I actually change?".

3.5.1.1 Successors and Derivations

The basic meaning of revisions is that the new revision of a document replaces the old revisions. Normally the revisions of a document thus form a linear sequence in which the latest revision represents the "current state" of the document and the old revisions are kept for reference. Each revision of a document, except the first one, is therefore a *successor* to an earlier revision. (Non-sequential arrangement of versions will be discussed later.)

To create a new revision of a document, a user usually makes a copy of the latest old revision of the document and makes the necessary modifications. The new revision is said to be *derived* from the old revision that was used as a basis for the new revision.

Usually the two relations, 'revision B is a successor to revision A' and 'revision B has been derived from revision A', coincide, and some discussions on versioning make no distinction between them (Conradi and Westfechtel 1998). Nevertheless, the relations are different because 'successor' refers to the "logical reason" why a new revision was made, and 'derivation' refers to the "physical way" a revision was made.

Usually it is a more or less implicit assumption that a document revision with a successor cannot be modified because the successor is created on the basis of the earlier revision. Nevertheless, sometimes this assumption does not necessarily hold. It is possible that while changes are still being made to revision n, the designers already want to start to develop revision $n+1$. This kind of parallel development of successive product revisions is typical of products with fast technological development and short life cycles, such as mobile phones.

3.5.1.2 Revision Deltas

As revisions represent the incremental evolution of a document, typically two consecutive revisions are quite similar to each other. For some kinds of documents, such as text files, it is possible to store revisions by means of *deltas*. This means that instead of storing each revision in its entirety, the system only stores a base revision completely, and other revisions are stored as sequences of differences, or deltas, between the base revision and the particular revision.

One well-known example of the use of deltas is the RCS system, which maintains revision histories of computer program source files and other plain text files (Tichy 1985). RCS uses backward deltas, i.e., the latest revision is stored as such, and old revisions are stored as differences to the latest revision. The unit of change is a line of text; a delta thus records the modified, deleted and inserted lines.

Deltas are feasible for documents in which a "small" change by a user results in a correspondingly "small" change in the internal representation of the document. For example, modifications of program source files typically affect individual lines. However, the 3D geometric models manipulated by CAD tools do not necessarily have this property, and accordingly deltas are not useful for all geometric models.

3.5.1.3 Multi-level Revisions

Sometimes it is useful to be able to distinguish between *major* and *minor* revisions, which represent "large" and "small" changes in a document. In general, it is impossible to define the line between major and minor revisions, but in an abstract sense a minor revision is created when the contents of a document only change "superficially". For example, in the case of a user's manual, a minor revision could be created to correct a misspelling whereas a new major revision would be created to record the changes caused by a new product revision with new features.

Consecutive revisions are typically identified with numbers or letters. If major and minor revisions are used, a revision number can for example be '7.2' where '7' is the major revision and '2' is the minor revision.

Some systems automatically create a new minor revision (e.g., revision 2.4 after revision 2.3) whenever a modified document is stored in the database, and a user explicitly creates a new major revision when the document has reached a stable state that needs to be released (e.g., revision 3.0 after revision 2.4).

If new document revisions are created automatically, the database will typically accumulate a large number of revisions, all of which are not necessarily interesting for future reference. The PDM system must therefore allow users to remove unnecessary revisions in the middle of the revision history.

The terminology is by no means well-established. For example, in some systems minor revisions are called simply revisions, and major revisions are called versions, whereas other systems use the same terms with opposite meanings.

3.5.2 Version Trees and Graphs

If each version of a document has at most one successor, the versions form a linear sequence of revisions that represent a single line of development. However, the result is a version tree if branches are allowed, in other words, if a version can have multiple successors (it is still assumed that each version is a successor to at most one version).

A branch can, for example, represent a parallel line of development that will co-exist with the original line as a new variant (figure 10a). Branching can also be used for creating multiple tentative alternatives, one of which is eventually chosen for further development (figure 10b). Versions that were originally created as tentative alternatives can of course later change to become variants and vice versa.

So far each version has been assumed to be a successor to at most one version. A *merge* operation, however, creates a new version as a successor to multiple existing versions (figure 10c). In other words, the new version is formed by combining two or more old versions. In some cases the operation can be assisted by merge tools, which have been investigated especially in the context of computer program source files (Buffenbarger 1995). Merging can, for example, be used when two designers want to modify different parts of a single document at the same time. First two parallel "temporary" versions are derived from the common base version, then the two

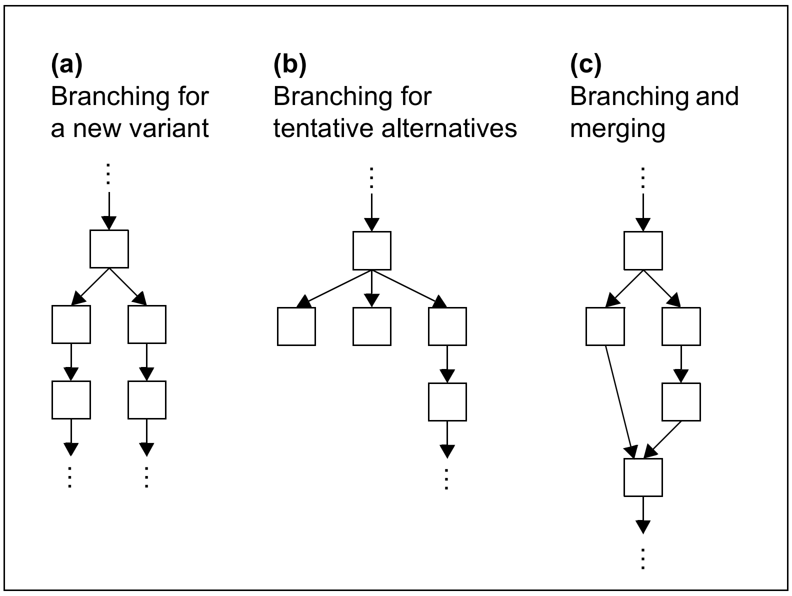

(a)
Branching for a new variant
(b)
Branching for tentative alternatives
(c)
Branching and merging

Figure 10. Version branching

designers modify their own versions, which are finally merged into the next "permanent" version.

With branching and merging the versions form a directed acyclic graph (DAG). This is the most general way to arrange versions according to the successor relation between pairs of versions. However, the rest of this section shows that even in this general form the successor relation alone is insufficient for representing all relevant information about revisions and variants.

3.5.3 Variants

In addition to sequential revisions, an object can have a number of parallel variants. The variants can, for example, represent different customer groups and marketing areas. For instance, a manual can be available in different languages or an electric appliance can be manufactured for different voltages. The basic difference between revisions and variants is that a new revision of a document replaces older revisions whereas all variants of a document are available at the same time as alternatives.

A document can have variants along multiple dimensions. For example, consider a product that has three variants with different features. Suppose further that a user's guide for the product is available in four languages. As a result, the guide has altogether twelve variants, such as 'user guide for product variant 2 in language 3'.

In addition to the variants with different contents, a digital document may have multiple alternative representations. For example, a CAD drawing can be stored in the "native format", i.e., as a file that can be directly manipulated with the CAD tool. At the same time the drawing can also have read-only representations in generally available standard formats that make it possible to display and print the document without the original tool. Popular examples of these formats include PostScript and Portable Document Format (PDF).

Moreover, a document can be stored in a format suitable for printing on paper (e.g., as a PostScript or PDF file) and in a format suitable for viewing with a Web browser (i.e., as an HTML file). These formats can be regarded either as different representations or as different variants of a document.

3.5.4 Configurable Documents

Variation within documents can also be achieved with *configurable documents*. The idea is similar to configurable products. A configurable document is described by means of a generic document, which specifies the rules for constructing different document variants from a specification.

Configurable documents are especially useful in connection with configurable products. Consider a product with alternative and optional components. When a particular variant of the product with particular components is delivered to a customer, the accompanying documentation should correspond to this product variant. For example, the maintenance manual delivered to the customer should mention a particular optional component only if the customer has the component in the product.

3.5.5 Revisions and Variants Combined

The revisions and variants of a document can be represented as a version tree in which each variant is a separate branch. Nevertheless, often particular revisions in different "variant branches" correspond to each other. To properly represent the connections between revisions and variants, the versions must be arranged in a "matrix" or "grid" instead of a tree based on the derivation relation between versions (Conradi and Westfechtel 1997).

Consider a user's manual that has variants in Finnish and English, and major and minor revisions. The major revision identifies the contents of the document for both language variants. Nevertheless, it is not meaningful to relate minor revision numbers between different languages or between different major revisions. For example, all minor revisions in both languages with major revision number 3 have in some sense the same contents; the differences between revisions 3.1 and 3.2 of the Finnish variant are not related to the differences between the corresponding revisions of the English variant; and the differences between revisions 2.1 and 2.2 of the Finnish variant are not related to the differences between revisions 3.1 and 3.2 of the same variant.

In this situation it is possible to recognise a number of meaningful entities, which should have their own identities and for which it should be possible to define attributes. One obvious entity is the document as a whole. As all versions with the same major revision number have the "same contents", this common data should also be presented with its own entity type. An attribute of the entity 'major revision

3 of the document' could for example tell that this major revision of the user manual includes instructions for using a particular new feature of the product. Finally, each individual version, e.g., Finnish revision 3.2, should be a separate entity.

In this example, the derivation relation is meaningful between minor revisions, but not necessarily between major revisions. Suppose the document has Finnish revisions 2.0 and 3.0, and English revision 2.0. There are basically two ways to create English revision 3.0. One possibility is to take a copy of English revision 2.0 and modify it in the "same" way the Finnish variant was modified to derive revision 3.0 from revision 2.0. English revision 3.0 has now been derived from English revision 2.0.

Nevertheless, at least in theory it is also possible for revision 3.0 to be so different from revision 2.0 that it is easier to create English revision 3.0 by translating the complete corresponding Finnish revision. In this case English revision 3.0 is still a successor to English revision 2.0, but the derivation relationship is more problematic. If the derivation between revisions is defined as "modification of a copy of an old revision", English revision 3.0 is not derived from any revision. However, if the derivation of a revision includes the more abstract notion of a new revision being created "on the basis of an old revision", English revision 3.0 can be said to be derived from Finnish revision 2.0 In any case, the derivation history of English revision 3.0 is less important than the fact that this version represents the "combination" of 'English variant' and 'major revision 3'.

Note that it does not make sense to ask whether a particular version is a revision or a variant. Instead, revisions and variants should be seen more as relations between versions. A version can be a revision of one version, and at the same time this version can be a variant of another version.

3.5.6 Component Versions

The versioning concepts can also be applied to products and components, which can have consecutive revisions and alternative variants much the same as documents.

When components have versions, it is necessary to re-analyse relations that involve components. The most important of these relations are the 'has-part' relation between components, and the connection between related documents and components.

3.5.6.1 Parts and Versions

The versioning of components complicates the part-of relationships because it is no longer obvious which kinds of objects have which kinds of objects as parts. If a component is specified to have a particular part, this seems to mean that all versions of the component have the part. This kind of specification, however, is too restrictive because often different versions of the same component differ by having different parts. Therefore, it must be possible to define the parts of each component version separately.

If many parts are included in all versions of a component, it may be useful if one can specify at the component level that all versions of a particular component have particular parts in addition to the parts specified for individual component versions. This mechanism, however, raises the question of what happens when a new version of a component should not have a part that has been specified at the component level because originally the designers assumed all versions to have the part.

The second question is which kinds of objects can be used as parts. One possibility is to use component versions as parts. This kind of reference is called a *fixed reference* because it specifies the part to be a particular version of a particular component.

Fixed references bring up the problem of change propagation. Suppose component X has component Y as a part. Suppose further that all component revisions are "frozen" so that a component revision cannot be modified. The only way to modify a component is to create a new revision of it. The revisions of a component form a linear sequence, and the "current" state of a component is represented by its latest revision.

Suppose the latest revision of component X is 3, which contains a reference to revision 6 of component Y. Now component Y needs to be modified. Revision 7 of Y is thus created. In order to include this revision of Y in component X, it is necessary to create revision 4 of component X and to include a reference to revision 7 of Y in revision 4 of X.

It is easy to see how this leads to a chain reaction. As a new revision of X was created, it is again necessary to create new revisions of all components that have X as a part. The creation of a new component revision thus means that one must create new revisions of all components that have the modified component directly or indirectly as a part. In some cases this may be the desired behaviour, but usually fixed references create too many revisions.

In addition to fixed references, it should therefore be possible to use *generic references* in product structures. A generic reference specifies only the component but leaves the version unspecified. When it is necessary to know the version, for example in order to manufacture the product, all generic references must be *resolved* to specific versions.

In the context of the previous example, the 'has-part' relation could be between component revisions and components. A particular revision of a component would thus have other components as parts. These references from component revisions to components are generic because the revision of the component used as a part is unspecified. When the references are resolved, a generic reference to a component is resolved to some, typically the latest, revision of the component.

The resolution mechanism is simple if a component is always assumed to have a unique "current" version. However, this assumption is not necessarily true. For example, a component can have multiple alternative variants in addition to sequential revisions, and the "latest" revision of a component may be ambiguous between the latest revisions in production and in product development.

3.5.6.2 Product and Document Versions

A number of documents can be connected to a product. This subsection outlines one possible arrangement when the products and connected documents have versions.

Suppose a product is connected to some documents. When the product has multiple versions, each version of the product is connected to appropriate versions of the connected documents. All documents need not be relevant to all versions of the product. In this case some version of the product may not be connected to any version of a particular document although the product as a whole is connected to the document.

The creation of a new product version implies a change in at least one document connected to the product. Accordingly, new versions are created from one or more documents, and these new document versions are connected to the new product version. As for those documents that were not changed, the new product version is connected to the same document versions as the original product version.

On the other hand, a document can be changed without changing the product. For instance, a new version of a user's guide can be written for an old product version. In this case the connection between a product version and the old version of the user's guide is replaced with a connection between the same product version and the new version of the user's guide.

The connections between product and document versions as described above are completely static in the sense that each product version explicitly defines the document versions connected to it. One can also speculate with more dynamic connections. Suppose the versioning model distinguishes between major and minor revisions. A connection between a product version and a document version could then specify only the major revision number of the document version. When the system is asked to find the document versions connected to a particular product version, the system would retrieve the latest minor revision of each connected major revision. In effect, a new minor revision of a document would thus automatically replace the previous minor revision.

Moreover, a document connected to a product can have multiple variants, for example in different languages. To find the specific document variants connected to a particular product version, one must also specify a parameter, such as a language, for selecting the correct document variant. The system will then retrieve the latest minor revision of the selected variant of each major document revision connected to the product.

3.5.7 Larger Versioning Units

Often it is more meaningful to consider a set of related components instead of an individual component as the unit for versioning. Often the mechanisms for larger versioning units define both a "static" data model, which describes the data stored in the system, and a "dynamic" operational mode, which describes how the data is manipulated. These mechanisms will therefore be discussed in chapter 4 in connection with design transactions.

3.5.8 Configurable Products and Versions

This section has dealt with versions, which represent the temporal evolution and parallel alternatives of an object as revisions and variants, respectively. One of the concepts was a generic reference, which refers to an object in general and which can be resolved by various means to select a particular version of the object with multiple revisions and variants.

Section 3.3.2 dealt with configurable products and components. The concept of a variant was fundamental in that section, too. A configurable component corresponds to a set of possible variants, and each configuration of the component represents a particular variant. It is natural to ask how the configurable products discussed earlier relate to the revisions and variants of the present section.

In this section the versions of a generic object are supposed to be separate objects. Each version, which represents one revision and variant of a generic object, is an object of its own. A new variant, or a new version that represents a particular variant and revision, is created explicitly. All variants of an object are thus known and their number is relatively small.

A configurable product also has a number of variants. The set of all variants of a configurable product is defined implicitly by an explicit structure and a set of constraints. Here it is necessary to distinguish between the potential variants of a configurable product and the variants that have actually been generated for customer orders. A product with many alternative and optional parts can have millions of potential variants, of which only a small subset are ever generated.

In general, it is very difficult (and useless) to enumerate all (potential) variants of a configurable product. Given a configuration model with complex constraints, it may be difficult to even know if there are any valid configurations of the product at all.

Individual potential variants of a configurable product are not created explicitly. When a configuration model is modified, the corresponding set of variants changes. If the explicit structure of a configuration model is changed, it is usually rather easy to say how the variants are affected. For example, if an optional part is added to a product, the number of variants is doubled if constraints are ignored. Nevertheless, if the constraints of a configuration model are changed, it may be very difficult to see the actual effect of the change.

The section on configurable products ignored the question of revisions. In other words, the evolution of configuration models and configurations was not discussed. Unfortunately, not much more can be said within the scope of this thesis. Much more work is needed to include the evolution aspect to the present concepts on configurable products. It must be possible to model both the evolution of a configuration model as a result of product development and the evolution of individual configurations as a result of maintenance and upgrading. There are many interesting, and at the moment unanswered, questions. For example, if a configuration model is modified, is it possible to take a specific configuration based on an earlier revision of the model and ask how the configuration should be modified to make it complete and valid with respect to the new revision of the model?

4 Design Management

Many PDM systems support engineering design activities in particular within a company. This chapter briefly deals with those functions of PDM systems that can be grouped under the label Design Management. According to Casotto, Newton and Sangiovanni-Vincentelli (1990) the services required from an automatic design manager include co-ordination within and between design teams, consistency maintenance among data objects, bookkeeping of the design alternatives, policy enforcement, automation of the design flow, documentation of the design process, design estimation, and the verification of design specifications.

This chapter discusses most of the issues of the above list, although not exactly under the same headings. For example, the concepts of most subsections can be seen as supporting the co-ordination of team design.

There is a large array of sophisticated concepts for PDM, especially in the context of design databases (Katz 1990). Nevertheless, it seems that rather few of these concepts have actually been in systems that are used in companies, or even if a system has an advanced feature, the feature is not necessarily used much.

The gap between theory and practice may be even larger in this chapter than in the previous one. Although the details vary between PDM systems, there seems to be some kind of agreement that the data model of a PDM system should include the main concepts discussed in the previous chapter: versions, product structures, links between products and documents, etc. When it comes to the operations that manipulate the data, it is more difficult to identify a set of basic concepts that would be found in some form in all PDM systems.

4.1 Design Transactions

A *transaction* is a fundamental concept in database systems. This concept, however, is not very useful for PDM systems, which must deal with larger "units of work". The term design transaction (or long transaction) has been coined to refer to the general idea of a "transaction" that may last for days or weeks as opposed to the seconds of a traditional transaction and is not based on the "all or nothing" approach of traditional transactions.

This section first briefly describes the properties of traditional transactions. This is followed by a discussion on how these properties could be interpreted and extended in PDM systems. The concepts of this section include document version life cycles and locking. The term 'design transaction' will not be defined in the same precise manner in which traditional transactions are defined in database systems. It may be a matter of taste whether all issues treated in this section should be included under the present heading at all.

4.1.1 Traditional Transactions

A transaction is a sequence of database read and update operations that changes a database from a consistent state to another consistent state (Korth and Silberschatz 1986: sec. 10.2). A classical example is a transaction that transfers money from one bank account to another. The transaction first decreases the amount of money in the first account and then increases the amount in the second.

One property of a transaction is *atomicity*, which means that a transaction is executed on an "all or nothing" basis. Normally a transaction *commits*, which means that the effects of the update operations within the transaction are permanently recorded in the database. If the transaction cannot be completed for any reason, the transaction is *aborted* and the database is not modified at all. A transaction can be aborted for various reasons. For example, the program executing the transaction can explicitly abort the transaction; the program may be terminated abnormally before the transaction has committed; or a hardware failure may prevent the database system from updating the database. No matter what problems occur in software or hardware, the database system thus guarantees that in the bank account example the database can never be left in a state where only one of the accounts would be updated.

Another important property of transactions is *isolation*, which means that the effects of a transaction are not visible to the other users of the database until the transaction is committed.

This "traditional" transaction concept is intended for relatively short and simple transactions, such as the money transfer example, which are executed in large numbers. In a PDM system, this kind of mechanism is still needed for the database operations at the most basic level, but additional concepts are needed to support typical product data processes, especially in product design (Barghouti and Kaiser 1991).

4.1.2 Transactions in PDM

To illustrate how the concept of a transaction should be extended for PDM, consider the creation of a new document revision. It is assumed that the new revision is created in the PDM system immediately when the construction of the revision begins; i.e., not when the finished revision is approved and released for use by everyone. In this discussion, the 'designer' refers to the person who is responsible for the creation of the new revision.

One basic question is, 'who sees the new revision and when?'. In traditional transactions, the answer is simple: The isolation property means that before the transaction has committed, its effects are only seen within the transaction, and after the transaction hass committed, the effects are seen by all users of the database. However, in a PDM system it is necessary to consider different "levels of commitment", which determine the set of people who see the effects of the transaction.

A typical process for the creation of a new document revision with related "commitments" is outlined below.

(1) The transaction is not committed at all. The designer can freely modify the new revision. The question of whether other users see the new revision is discussed shortly.

(2) The transaction is committed by the designer. The designer has in effect said that the new revision is ready as far as he or she is concerned. The revision cannot be modified, and it must next be checked by someone. As a result, the revision is either approved or "decommitted" back to step 1.

(3) The revision has been approved. In effect, the transaction is "fully" and irrevocably committed. The revision can be seen by all users. If the document needs to be modified, a new revision must be created.

One question is whether other users than the designer can see the new revision before it has been approved. If the answer is positive, the other users must be told very clearly that the revision has not been approved. Moreover, the revision itself should contain an indication of this fact. For example, if a non-approved document revision is printed, one should see from the printout that this revision has not been approved.

When discussing the capability of users to see the new revision before its approval, it may be further necessary to distinguish between a user who is only allowed to see that a new revision exists and a user who is also allowed to see the current contents of the revision.

This discussion involved two "levels of visibility": the designer and all other users. There could be additional levels, such as a design team. For example, after a designer has committed a new revision, the revision could first become visible to the rest of a design team before the revision is finally approved and made visible to all users. This topic is further discussed at the end of the next section.

The atomicity of traditional transactions is also completely infeasible in a PDM environment. If the construction of a new document revision were treated as a single traditional transaction, any problem during this operation, which may last several days, could abort the transaction and return the database to the state before the construction of the revision was started causing the loss of work already done.

4.2 Check-out/Check-in

Typically the lowest level transactions for the modification of the contents of a document version are carried out by means of a *check-out/check-in* mechanism. When a user wants to modify a document version, he or she first checks out the document version from the PDM system. Usually this means that the system copies the document version (more precisely, the document file associated with the document version) from the PDM database to the user's workstation. The user then modifies the document version in his or her workstation with a suitable tool (see section 5.5.1 on tool integration). Finally the user checks in the document version, i.e., asks the system to copy the modified document version from the workstation back to the database.

In this section it has been assumed that a single document version can be modified repeatedly with a check-out/check-in cycle during its life cycle. In some systems, however, a check-in operation automatically creates a new document version. In systems that distinguish between major and minor revisions, a check-in operation typically creates a minor revision.

The basic check-out/check-in mechanism has two kinds of "databases" or "workspaces": the common shared database, which stores all documents, and the user's "private" database, to which documents are checked out from the shared database. This two-level model can be extended so that documents are transferred between workspaces, which are arranged in a multilevel hierarchy (Kim et al. 1984).

4.3 Locking

When a user is working on document version, other users must be prevented from modifying the same version without his or her consent. Users must therefore be able to *lock* document versions for their exclusive use with respect to modification.

Suppose revision B is being derived from revision A of a document. If version branching is allowed, it is possible to derive another revision B' from revision A. Unless revision B' is going to be a parallel variant of B, revisions B and B' must eventually be merged to create revision B", which is the final successor of revision A.

The fact that a user has locked a document revision for himself or herself thus means that no one else can unexpectedly interfere with his or her work. Nevertheless, if version branching is allowed and the revision from which the new revision is being derived has not been "locked" against other derivations, the user cannot be certain that he or she alone makes the new revision because his or her "version" of the new revision may have to be merged with other "versions" of the new revision.

The lock and unlock operations can be executed as part of check-out and check-in if the unit to be locked is the same as the unit to be checked out or in. Often, however, there is a set of interdependent objects, and it is necessary to consider the consistency of the set of objects as a whole.

A simple example is provided by the EDMS system, which is discussed in the second part of this thesis. A document version consists of multiple subdocuments, and lock and unlock operations are applied to document versions whereas check-out and check-in are applied to individual subdocuments within a locked document version.

The model presented by Cellary, Vossen and Jomier (1994) groups objects into sets called *constellations*. The objects in a constellation form a meaningful whole from the designers' point of view, and for each constellation there is a designer responsible for the constellation. An object can belong to multiple constellations, and the relationships between constellations correspond to the relationships between designers who are responsible for the constellations. For example, if constellation Y is nested within constellation X (i.e., all objects that belong Y also belong to X), the designer responsible for constellation X as a whole can be seen as having delegated the responsibility for constellation Y within X to a subordinate designer. The division of objects among constellations thus reflects the division of design tasks among designers.

4.4 States

The different "levels of commitment" for a document version that were discussed in section 4.1.2 can be described by means of *states*. One can also say that the states represent different milestones during the life cycle of a document version or other object that begins with the creation of a new object and guides the object through various checking, approval and release procedures.

The states are often called *release levels* or *promote levels* (Miller, MacKrell and Mendel 1997: 14). Although this term may imply that the states are arranged in a linear sequence, in general the states can form more complex graphs with branching and merging.

Usually the current state of an object partly determines the set of operations that can be applied to the object. For example, the contents of a document version should obviously not be modified if it is in the state 'waiting to be approved' or 'approved'.

4.5 Dependencies

The objects in a PDM database have *dependencies* between them. Object Y is said to depend on object X if the modification of X may make it necessary to modify Y, too. In some cases it may be possible to define automatic regeneration rules for a dependent object so that whenever object X is modified, the system automatically regenerates Y by executing a suitable program. In most cases, however, after the modification of X, the system can only mark Y as 'invalid', or more precisely 'potentially invalid'. A user must then check whether Y needs to be modified and carry out the modifications if necessary.

Suppose further that object Z depends on object Y, which in turn depends on object X. When object X is modified, object Y must be checked and possibly modified. It is not immediately necessary to do anything with object Z. Nevertheless, object Z is still in the scope of "potential changes" because it must be checked, and possibly modified, in case Y is modified as a result of the modification of X.

Dependencies were described here as being recorded between documents. In practice this is a rather coarse unit of dependency. For example, consider a specification document and any of the many drawings of a product. There is a dependency between the documents: if the specification is modified, it may be necessary to modify the drawing. Nevertheless, to be useful, the dependency should probably be much more detailed. For example, it should be possible to record a dependency between a particular item in the specification and a particular part in a particular drawing. Obviously the recording and maintenance of dependencies at a useful level requires a considerable amount of work, and the whole concept may be infeasible in practice.

4.6 Workflows

Designers need a wide array of tools for their work. Often the tools must be used in a particular order because the output from one tool serves as input to another tool. A tool can require multiple input files and generate multiple output files, creating complex dependencies between files and the tasks in which the tools are executed. After a set of data has been processed with a tool, the next step in a process may depend on the outcome of the execution of the tool.

In addition to multiple tools, a data object, such as a document, may have to be manipulated by multiple people in a predetermined manner. For example, an organisation can define that a document revision cannot be approved unless it is accepted by all members of a group. As another example, the processing of an engineering change order can involve several steps during which various documents are sent for approval and processing to different people.

For example, the model by Allen, Rosenthal and Fiduk (1991) is based on process tools The description of a tool specifies input and output files, a command line to execute the tool, pre-conditions, which must be met before the tool can be executed, and post-conditions, which determine whether the tool was executed successfully.

Especially in a one-of-a-kind-industry, such as ship building or process plant construction, it seems necessary to have digital means of communication that are less formal than workflow procedures. Many companies that work on large projects have complemented centralised PDM systems with groupware products, such as Lotus Notes (Hameri and Nihtilä 1998).

4.7 Documentation of the Design Process

After the completion of a design task it is obviously important to know the design results. However, often it is also useful to know how the results were reached. For example, when the design of a complex product must be modified, it is useful to know why particular decisions were made, what alternatives were considered, and why they were rejected.

This kind of supplementary information is often called *design rationale*. Designers can record design rationale during the design process or the designers can reconstruct the design rationale afterwards by reasoning from their existing knowledge, conducting interviews and examining the finished design and unstructured records from the design process, such as video tapes from meetings (Lee 1997).

Information on 'why' is difficult to capture in a design process because it can only be provided by the designers. Information on 'what', 'when' and 'by whom', however, is automatically available in a PDM system. If necessary, a PDM system can create a log file, which records for each database update what data was modified, when and by whom. Obviously the automatically collected information on modifications is often rather coarse. For example, if a designer modifies a drawing, a PDM system (or CAD system) cannot typically provide much information about what was actually modified within the drawing.

It may be possible to compute useful statistics from the automatically collected data. For example, a suitable log file allows managers to see how much time typically elapses from the moment a designer submits a modified document for approval until the moment the document is approved or rejected.

Usually a log file only records information about data modifications. Nevertheless, for security reasons a company may want the PDM system to also record information about users who have retrieved data from the system.

5 System Aspects

5.1 System Architecture

A PDM system must be built on top of a database management system that stores at least most of the data handled by the PDM system. This database is usually a relational database system. Of the 52 PDM systems reviewed in a leading survey, 43 systems used a relational database, 2 systems used a commercial object-oriented database, 2 systems used their own "object-oriented" database, and the remaining 5 system used some other database (Miller, MacKrell and Mendel 1997: 99). Although PDM systems have been mentioned as a good application for object-oriented databases (Cattell 1994), object-oriented databases obviously have made very little impact on the commercial PDM field.

When discussing the possible "object-orientedness" of a PDM system it is important to distinguish between the properties of the tool that is used for implementing the system and the properties that the system provides for its users. The fact that a system is written in an object-oriented programming language does not necessarily mean that there would be much "object-orientedness" in the concepts seen by the user, such as inheritance between document types. On the other hand, it is also possible to implement object-oriented concepts with a conventional relational database (Barsalou and Wiederhold 1990).

Most PDM systems are based on a client-server architecture, in which the users execute a client program on their workstations, and the clients communicate with a server program, which in turn accesses the database. The system described in detail in the second part of the thesis is an example of this architecture.

Web technology is important for PDM systems because it allows users to access the system from standard Web browsers. Some systems make all functions of the system available through a Web browser; in other systems only the most common operations can be carried out through the Web while the remaining operations require the specific PDM tool. The system described in the second part of the thesis is an example of the latter approach.

When a company wants to start using a PDM system, almost all systems require at least some company-specific customisation. For example, usually a company wants to define its own document types and attributes. PDM systems differ widely in the amount of customisation that can and must be done. At one extreme there are systems with minimal, if any, needs, and possibilities, for customisation. It is easy for a company to start using this kind of system as long as the predefined properties satisfy the requirements of the company. At the other extreme there are PDM toolkit systems, which only provide a set of building blocks for constructing a working system. Although toolkits make it possible to build a system to the exact requirements of a company, the necessary customisation and programming raises the costs considerably. Some vendors of PDM toolkits have found it necessary to also sell "ready-made" systems, which reduce the need for customisation at the expense of flexibility (CAD/ CAM 1998).

5.2 Metamodels and Company Models in Relational Databases

Section 3.1 introduced the concepts of a metamodel and a company model. This section describes two alternative ways to implement the models on top of a relational database.

A relational database has a schema, which defines a set of tables and a set of columns for each table. The data are stored as rows of the tables, with each row having a value (possibly a null value) for each column of the table. To some extent, the relational model can be described in object-oriented terms. The tables and their columns represent object types and their attributes, respectively. The rows in a particular table represent instances of the corresponding type.[5]

When a PDM system has three levels of entities as explained at the end of section 3.1, it is not obvious how the system should be implemented on a relational database with two levels.

As a concrete example, suppose a PDM system contains the object types 'drawing' and 'manual', drawings 'd1' and 'd2', and manual 'm1'. One way to represent this data in a relational database is to have one table for object types and another table for object instances. The latter table includes columns for object name and type. This alternative is illustrated in figure 11.

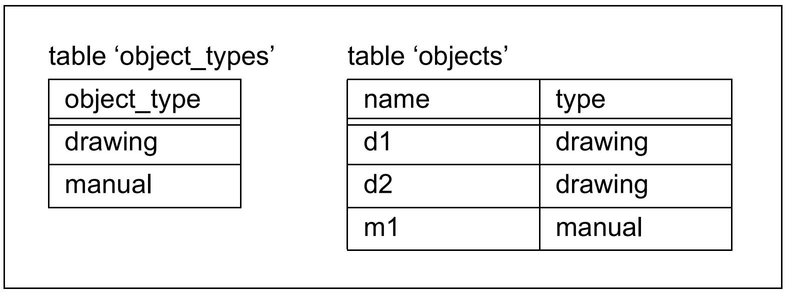


table 'object_types'

object_type
drawing
manual

table 'objects'

name	type
d1	drawing
d2	drawing
m1	manual

Figure 11. Two tables for types and instances

Next, one must consider that different object types have different attributes. For example, suppose that the object type 'drawing' has the attribute 'drawing_size', which stores a string (e.g., 'A3'), and the object type 'manual' has the attribute 'page_count', which stores an integer. One possibility is to store information about attributes in one table and the attribute values in another table. The attribute tables, which are used together with the tables of figure 11, are illustrated in figure 12. The

5. Although the relational model does not include the concept of an object, a row of a table can be interpreted as an object if the table has a column that stores unique object identifiers.

type of the column ‘attribute_value’ in the table ‘attribute_values’ must be ‘string’ so that the column can store any attribute value that can be represented as a string.

table ‘attributes’

object_type	attribute_name	attribute_type
drawing	drawing_size	string
manual	page_count	integer

table ‘attribute_values’

object_name	attribute_name	attribute_value
d1	drawing_size	A4
d2	drawing_size	A3
m1	page_count	26

Figure 12. Two tables for attributes and their values

In practice separate tables are needed for different attribute value types. Although numeric values can be stored as strings, strings are compared according to the alphabetical order, which gives the wrong result for numeric values.

This representation of objects and their attributes is called here the ‘fixed database schema’ approach because the database schema, i.e., the set of tables and their columns, does not depend on the object types and attributes in the company model.

This representation, however, is not the only possibility. The representation resulted from two assumptions: (1) the object types and their attributes must be represented dynamically as data, and (2) the relational database must have a fixed schema. If the first assumption is removed and one is simply asked to design a database that can store drawings and manuals with the given attributes, one probably creates separate tables for drawings and manuals as shown in figure 13.

table ‘drawings’

drawing_name	drawing_size
d1	A4
d2	A3

table ‘manuals’

manual_name	page_count
m1	26

Figure 13. Separate tables for different object types

Although figure 13 may be a natural representation for a fixed set of object types and attributes, a PDM system must have dynamic schema and provide operations for creating new object types and adding attributes to existing types. The tables ‘object_types’ and ‘attributes’ of figures 11 and 12 are thus needed. Nevertheless, a PDM system can still store objects and attributes in separate tables in the style of figure 13 because a PDM system is not limited to the data manipulation operations of a relational database (e.g., ‘insert a row into a table’). A PDM system can equally well execute data definition operations, such as ‘create a table’ or ‘add a column to a table’.

This approach, called here the ‘dynamic database schema’, is illustrated in figure 14. There are two kinds of tables in a particular database. The fixed metamodel is represented by the tables ‘object_types’, ‘attributes’ and ‘objects’, which exist in every database. The varying object types of a company model are represented by the rows of the fixed tables and by the tables ‘objects_XXX’. The instances of the object type ‘XXX’ are represented by the rows of the tables ‘objects_XXX’. The dual nature of a particular object type both as an instance with respect to the metamodel and as a type with respect to the company model is obvious when one considers the creation of a new document type. This operation inserts rows into tables ‘object_types’ and ‘attributes’, and creates a new table ‘objects_XXX’.

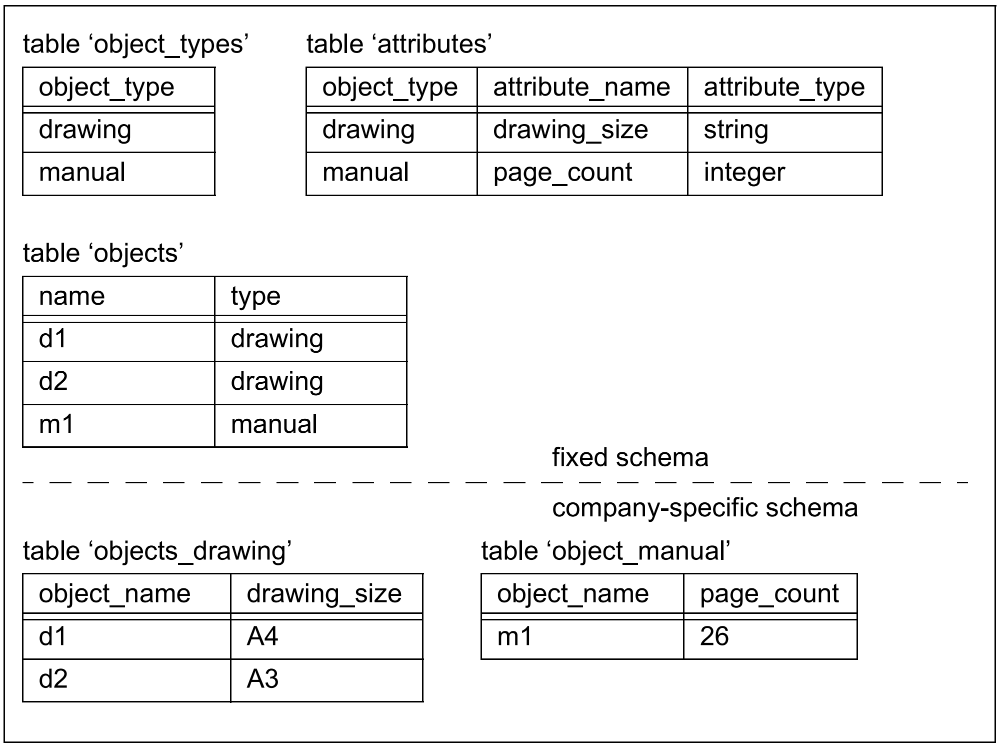


table ‘object_types’

object_type
drawing
manual

table ‘attributes’

object_type	attribute_name	attribute_type
drawing	drawing_size	string
manual	page_count	integer

table ‘objects’

name	type
d1	drawing
d2	drawing
m1	manual

fixed schema

company-specific schema

table ‘objects_drawing’

object_name	drawing_size
d1	A4
d2	A3

table ‘object_manual’

object_name	page_count
m1	26

Figure 14. Dynamic schema and type-specific tables

If objects are represented with a dynamic database schema, many of the SQL statements that manipulate the database must be generated at run-time. For example, consider a query to find objects of a particular type with a particular value for a particular attribute. The names of the table and the column cannot be written directly in program code. Instead, the table and column names must be formed at run-time from the names of the object type and attribute.

Note that the difference between a fixed and a dynamic database schema only deals with the representation of the company model in a relational database. Both approaches support dynamic company models, in which, for example, new object types and attributes can be added to an existing database.

The main advantage of the fixed database schema is that it scales well to an arbitrary large number of object types and attributes. When new object types and attributes are added to the company model, only new rows are added to the fixed tables. In a dynamic database schema, new tables and columns are added. This is not a problem when there are relatively few—a few dozen—object types. Nevertheless, there can be far more object types if, for example, different component types in a component class hierarchy (section 6.2) are represented as object types. In this case the large number of tables may become a problem.

In a dynamic database schema each attribute is stored in its own column. The properties of a particular column can thus be specified for the corresponding attribute. For example, each string attribute can have its own maximum length, and the corresponding column in a database table can have the same width. It is also possible to create indices for individual attributes.

Queries are simpler with a fixed database schema in the sense that the names of tables and columns do not have to be created dynamically. On the other hand, the queries are shorter with a dynamic database schema. For example, figure 15 shows a query that finds all objects of the type ‘manual’ with particular values for the attributes ‘page_count’ and ‘create_time’.

The difference in queries is probably not much of an issue when the queries are generated by the PDM system. When a system administrator has to execute ad-hoc queries, a dynamic database schema is probably more convenient.

With a dynamic database schema, a query over multiple object types is executed as separate queries to the tables that store objects of different types. Again, this solution works for a relatively small number of object types but is probably infeasible when the number of object types grows.

The system described in the second part of the thesis uses a dynamic database schema because the system is developed for a fairly small number of object types. The details are given in section 11.9. This approach works fine in the kind of environment to which the system was built (about ten object types). Nevertheless, as explained above, there may be problems with a larger number of object types.

Usually a database application has a fixed schema, which can, for example, be represented as a single UML class diagram. A PDM system is more complicated in this respect because two kinds of diagrams are needed. One diagram describes the meta-

Dynamic schema:

```
select object_name from objects_manual
where create_time > … and page_count < …
```

Static schema:

```
select name from objects obj where obj.type = "manual"
and
exists (select * from attribute_values_time attr
        where attr.object_name = obj.name and
        attr.attribute_name = "create_time" and
        attr.attribute_value > …)
and
exists (select * from attribute_values_integer attr
        where attr.object_name = obj.name and
        attr.attribute_name = "page_count" and
        attr.attribute_value < …)
```

Figure 15. A query with a dynamic schema and a static schema

model, which is mainly of interest to the developers of the system and to system administrators at companies that use the system. The users of the system in a particular company, however, are more interested in the company model, which includes the particular object types and attributes at this company. The company model can be described with another diagram, which is an instantiation, and not a specialisation or extension, of the metamodel diagram.

5.3 Schema Customisation

The object type hierarchy with attributes and relations, i.e., the "metadata" of a PDM database, is often called a database schema. Usually a PDM system has a "built-in" basic schema defined by the developer of the system. When the system is introduced in a particular organisation, the schema must be refined according to the needs of the organisation. For example, it is necessary to define new types for documents, products and other objects, the types must have proper attributes, and there must be proper relations between different types of objects.

Database schema is one aspect of customisation that is required by virtually any PDM system before the system can be used in a particular organisation. Other customisation areas include release procedures and authorisation.

There are three important questions to consider in connection with the customisation of a PDM system.

First, what things can be modified? Is it possible to define new object types? Can a new object type be defined as a subtype to an existing type? Is multiple inheritance possible? Is it possible to add new attributes to object types? What kinds of attribute value types are available? Is it possible to customise document release procedures? For example, if release procedures are based on state graphs, can completely new graphs be defined and can new states and state transitions be added to existing graphs?

Second, who can modify the system? Can the modifications mentioned above be made by the system administrator at a user organisation, or is it necessary to order the modifications from the system vendor? In the latter case the costs are often quite high.

Third, when can the system be modified? Must the object types and their attributes be fixed before the database is created? Is it possible, or easy, to add a new object type to an existing database or to add a new attribute to an existing object type?

The desired answers to the above questions are obvious. A PDM system should allow the system administrator to define object types and their attributes. It should also be possible to add attributes to an object type, remove attributes, and change attribute value types (e.g., to increase the maximum length of a character string attribute).

It is clear that the attributes cannot be changed lightly in a large database even when the operation is technically simple. If a new attribute is added to an object type, all existing objects have a null value for this attribute. The attributes needed for various objects in a PDM system must be considered carefully when a company plans the introduction of a PDM system. An attribute is useless unless the users are prepared to enter a value for the attribute when they create objects and maintain the value afterwards if necessary.

5.4 Access Control

A PDM system must have a mechanism for controlling who can read and modify data in the system. There are many more operations than simply 'read' and 'modify' that must be controlled. For example, it may be necessary to distinguish between reading the actual contents of a document and reading the attribute values of a document. Similarly, a document or other object can be modified in many ways: one can modify attribute values, modify document contents, create a new version, change the state of an object, etc. Attributes may be controlled in more detail so that particular users can read and modify particular attributes.

Usually access rights are not granted directly to individual users. Instead, the right to perform a particular operation is granted to a named user group, and each user can be a member of one or more user groups. The set of users who have rights to an object may depend on the properties of the object. For example, a document can have an attribute for the name of the department that the document belongs to, and each department can be associated with the names of users who can approve the documents of that department.

The operations that can be applied to an object can also depend on the properties of the object, such as its current state. For example, it is usually forbidden to modify an approved document.

Section 11.4 in the second part of the thesis contains one example of a powerful access control mechanism.

5.5 Integration between PDM and Other Systems

The usability of a PDM system greatly depends on how well the PDM system works together with other systems that must exchange data with it. This section briefly discusses the integration of PDM with document tools and ERP systems.

5.5.1 PDM and Document Tools

Usually the user of a PDM system does his or her "real work" with a document tool, which manipulates the document files associated with documents or document versions. It is convenient if at least the most common PDM operations, such as check-out and check-in, can be carried out directly within the document tool. This way the user does not have to switch between the document tool and the PDM system; in fact, some users may never use the PDM system as a separate tool.

What is needed is thus an interface between a document tool and the document management functions of a PDM system. One way to avoid developing this interface separately for all combinations of document tools and PDM systems is the Open Document Management API (ODMA) standard (AIIM 1997).

Basically ODMA defines an interface that allows the 'open' and 'save' operations of a document tool to retrieve a document file from a PDM system and store a modified document file back to the PDM system. When an "ODMA enabled" document tool executes an 'open' operation, the tool first checks if it has an ODMA connection to a PDM system. If a connection is present, the tool issues a 'select' command to the PDM system, which asks the user to select a document (or document version or something similar) from its database. Instead of selecting a document from the PDM system, the user can also cancel the whole operation or say that he or she wants to select a file using the regular file selection facilities of the document tool.

If, however, the user has selected a document from the PDM system, the 'select' operation returns a document identifier to the document tool, which issues an 'open' command with the document identifier as a parameter. In response to 'open', the PDM system executes check-out and copies the document file associated with the document to a temporary file that can be accessed by the document tool and returns the name of the file to the document tool. The tool then opens the temporary file in the normal way.

When document tool executes 'save' on a document retrieved from the PDM system, it writes the document to the temporary file and issues a 'save' command to the PDM system, which copies the contents of the temporary file to the PDM system.

After a ‘save’ operation the PDM system returns a new document identifier because the identifier may have changed, for example, because the PDM system has created a new document version.

In addition to ‘select’, ‘open’ and ‘save’, ODMA defines typical additional document management operations, such as ‘cancel check-out’, ‘create major version’, ‘create minor version’ and ‘show document history’. The PDM system does not have to include all additional functions because ODMA allows the document tool to check which operations are supported by the PDM system it is connected to.

ODMA also defines a number of document attributes, such as the name of the user who has checked out the document, the time of the check-out operation, the name of the latest version of the document, etc. A document tool can again check which attributes are supported by the PDM system and then read and write the available attributes of a document.

5.5.2 PDM and ERP Systems

If a company has both a PDM system and an ERP system, data must be shared between the two systems. For example, consider the parts list of a product. This data is needed in both systems, and possibly in further other systems, such as CAD tools. To keep the data consistent, it is necessary to define the system, or systems, that store the modifiable “master copy” of the data, and how the modified data is transferred to other systems that use the data. The integration between systems is often further complicated by the fact that product data is divided between the systems so that no single system stores all data needed by other systems. For example, a new product may first be created in a PDM system, which supports product development. Part of the product data is transferred from the PDM system to an ERP system, which adds its own data. As a result, data about a single product is stored in two systems, and some data must be maintained consistent between the systems. It may also be necessary to transfer some of the data managed by the ERP system back to the PDM system.

Data exchange and sharing between PDM and ERP becomes even more complex if a product has multiple product structures. In this case some structures, such as an ‘as-designed’ structure, may be manipulated in a PDM system while other structures, such as an ‘as-built’ structure, are manipulated in an ERP system (IPDMUG 1995).

A survey by Hameri and Nihtilä (1998) found that many companies were piloting integration between PDM systems and ERP systems. Although integration was in most cases technically feasible, there were often organisational problems relating to the question of whether the integration should be based on PDM or ERP.

6 PDM Standards

6.1 STEP Standard

As should become obvious from this thesis, PDM systems use a large number of concepts that are more or less related but for which there are no universally accepted standards. For example, practically all PDM systems have some notion of versions, but there is no agreement on the meaning of the terms ‘version’, ‘revision’, ‘variant’, etc.

One standardisation effort is the international standard for the Exchange of product Data, officially known as ISO 10303 and generally referred to as the STEP standard (Owen 1997). The scope of the standard is very large because the goal is to develop a standard for the representation of all data related to products.

The first parts of the standard were accepted in 1994, and new parts are continuously being developed and accepted as standards. In spite of the many years of hard work to develop STEP, the effect of STEP on the PDM field is still rather marginal. Time will tell whether STEP ever meets the high expectations in wider industrial use.

This section very briefly outlines the structure of the STEP standard and in particular the representation of product structures. STEP has a number of parts; in 1997 there were 14 approved parts and over 40 additional parts under development. The parts are divided into several classes, the most important of which are described here.

A very large portion of STEP deals with the representation of geometric data. At the moment this is probably the most successful part of STEP. The brief discussion in this thesis, however, mainly deals with the mechanisms that STEP provides for product structures. If STEP is to serve as a universal basis for product modelling tools of the future, it must clearly support generic product structures. Nevertheless, section 6.1.5 explains why it is presently difficult to incorporate generic product structures in the general STEP framework.

6.1.1 Express Language

STEP defines a number of data models for various aspects of product data. All data models are defined by means of a schema definition language called EXPRESS (ISO 1994a). EXPRESS can be regarded as a semantic database modelling language (Hull and King 1987). This means that EXPRESS can be used for defining a database schema that consists of object types, their attributes, relations between objects and validity constraints. These concepts will be discussed in slightly more detail shortly.

It is important to understand that EXPRESS only describes the structure of data, not any behaviour. Given a population of objects (i.e., a database instance) and an EXPRESS schema, one can say whether the object population is valid with respect to the schema. EXPRESS is not a programming language and does not include any mechanism for defining operations or methods for the objects described in the schema. A superficial glance at EXPRESS may be misleading in this respect because the language includes procedures and functions, which can contain familiar programming constructions, such as variables, conditional statements and loop statements. Nevertheless, these constructions can only be used in validity constraints and definitions of derived attributes. A validity constraint can thus be an arbitrarily complex algorithm written in a "programming language" but all the same the algorithm only defines a test for determining whether an object or a population of objects is valid.

6.1.1.1 Entities and Classification

An EXPRESS schema basically defines a number of object classes, called entities in EXPRESS. An entity declaration can specify attributes, uniqueness rules and domain rules (rules will be discussed later).

In section 3.2.1 the word 'entity' was suggested as a substitute for the word 'object'. In EXPRESS, however, the word 'entity' corresponds to an object type or an object class, and an individual object is an entity instance (i.e., an instance of an entity).

Compared to the classification mechanisms of section 3.2.1.2, EXPRESS has exceptionally powerful concepts for building class hierarchies. An entity declaration can specify one or more entities as the immediate supertypes of the new entity. EXPRESS thus allows multiple inheritance. What distinguishes EXPRESS from most object-oriented programming languages is the possibility to specify whether subtypes of an entity are mutually exclusive or mutually inclusive. Consider first mutually exclusive subtypes. Suppose that the entity 'computer' should be an abstract type with the subtypes 'portable computer' and 'desktop computer'. Each computer is thus either a laptop computer or a desktop computer. In EXPRESS this would be written as follows (reserved EXPRESS words are conventionally written in uppercase letters):

```
ENTITY computer
  ABSTRACT SUPERTYPE OF (ONEOF(portable_computer,
                               desktop_computer));
  …
END_ENTITY;

ENTITY portable_computer
  SUBTYPE OF (computer);
  …
END_ENTITY;

ENTITY desktop_computer
  SUBTYPE OF (computer);
  …
END_ENTITY;
```

The 'ONEOF(...)' subtype constraint thus specifies that a 'computer' entity is always exactly one of the listed entities. As 'computer' is abstract, no entity can be "just a computer".

Exclusive 'ONEOF' subtypes are the familiar case, which is usually the only alternative in object-oriented systems. EXPRESS, however, makes it possible to specify mutually inclusive subtypes. For example, suppose all computers are represented with the concrete entity type 'computer', and portable computers are a special case of computers represented with their own subtype. Moreover, a PC is another special case of a computer. Now, the two subtypes of computer are mutually inclusive because a computer can be a portable PC. These entities would be modelled as follows:

```
ENTITY computer
  SUPERTYPE OF (portable_computer ANDOR PC);
  …
END_ENTITY;

ENTITY portable_computer
  SUBTYPE OF (computer);
  …
END_ENTITY;

ENTITY PC
  SUBTYPE OF (computer);
  …
END_ENTITY;
```

As a third example, suppose a computer is either a portable computer or desktop computer, and at the same time either a home computer or a business computer. This classification according to two orthogonal dimensions would be represented as follows:

```
ENTITY computer
  SUPERTYPE OF (ONEOF(portable_computer, desktop_computer)
                  AND
                ONEOF(home_computer, business_computer));
  …
END_ENTITY;
```

6.1.1.2 Attributes

An attribute declaration within an entity declaration specifies the name and (value) type of the attribute. The possible attribute types include integer numbers, floating point numbers, strings, logical values (true, false and unknown) and references to entities. An attribute type can also be a list, set or bag (set with multiple identical values) of values. An attribute can be declared optional, which means that an instance of the entity does not have to have a value for the attribute.

The declaration of a derived attribute includes an expression that tells how the value of the attribute is computed from the values of other attributes.

An attribute can be declared to record a reference to an entity of a particular type. If an entity refers to another entity through an attribute, the second entity can declare an inverse attribute, which refers back to the first entity. In the following example the entity 'person' has the attribute 'hometown', which refers to an entity 'town'. The entity 'town' in turn declares an inverse attribute 'citizens', which records the people of the town.

```
ENTITY person;
  hometown : town;
  …
END_ENTITY;

ENTITY town;
  citizens : SET OF person FOR hometown;
  …
END_ENTITY;
```

The cardinality of a relation established with reference attributes is specified through the cardinalities of the attributes that create the relation. In the previous example, each person is related to exactly one town, and each town is related to any number of people. If, for example, each town must have at least one citizen, the corresponding attribute should be declared as follows:

```
INVERSE
  citizens : SET [1..?] OF person FOR hometown;
```

Entities inherit attributes in the usual way from their supertypes. An entity can also redeclare an inherited attribute. The new type of a redeclared attribute must be a specialisation (subtype) of the original attribute type. For example, if the entity 'customer' declares an attribute of the type 'computer', then a subtype of 'customer', such as the entity 'business customer', can redeclare the type of the attribute to be a subtype of 'computer', such as 'business computer'. Redeclaration of a reference attribute thus corresponds to the part refinement discussed in section 3.3.2.8.

6.1.1.3 Relations

As seen in the previous example, EXPRESS basically represents a relation between entities with reference attributes, optionally supplemented with inverse attributes to record the references "in the other direction". As discussed in section 3.2.3, the representation of relations as attributes means that relations are not "first-class citizens" and cannot, for example, have attributes. Therefore many parts of STEP represent relations by means of "relationship entities" that contain references to the actual entities that participate in a particular relation.

For example, consider the relation between people and towns in the previous example. The fact that a particular person lives in a particular town could also be represented with an entity 'residence' that has attributes referring to the related person and town. The 'residence' entity can now define additional attributes and it is possible to declare new entities as subtypes to this entity.

```
ENTITY residence;
  citizen : person;
  hometown : town;
  …
END_ENTITY;
```

6.1.1.4 Constraints

An entity can specify domain rules, which are conditions that must be satisfied by every individual instance of the entity. A domain rule is a logical expression, which can refer to the attributes of the entity and which always yields the value 'true' or 'unknown' in an instance of the entity. The value of the logical expression can be 'unknown' if the expression refers to an optional attribute that has no value in the instance.

Whereas a domain rule is a condition for individual instances of an entity, uniqueness constraints and global rules are conditions for an object population as a whole.

An entity declaration can include uniqueness constraints, which specify that all instances of the entity must have different values for a particular attribute or attribute combination (within a particular object population). For example, the entity 'component' with attribute 'id' could specify that all instances of the entity must have a different value for this attribute, and the entity 'component version' with attributes 'component id' and 'version id' could specify that the combination of the values of the two values must be unique in the instances of the entity in an object population.

Domain rules and uniqueness constraints declared in an entity are inherited by the subtypes of the entity. An instance of an entity thus also satisfies all domain rules and uniqueness constraints of its supertypes.

An EXPRESS schema can include global rules, which, unlike domain rules and uniqueness constraints, are not defined within a particular entity declaration. A global rule can make queries on the object population and, for example, say that there is at least one instance of a particular entity that satisfies a particular condition. A global rule can use all the "programming language" constructs of EXPRESS, and it is therefore possible to write any kind of algorithmic rule.

Consider the following EXPRESS entity, which defines an integer attribute and a domain rule that says that the value of the attribute is positive.

```
ENTITY E;
  i : INTEGER;
```

```
WHERE
  i > 0;
END_ENTITY;
```

It seems natural to imagine an object population that contains an instance of entity 'E' where the value of the attribute 'i' is negative and to say that this is an invalid instance of entity 'E'. Nevertheless, strictly speaking EXPRESS has no notion of an invalid instance of an entity. As EXPRESS is a data modelling language, a schema only describes what kind of objects can be found in an object population. In principle, it is as meaningless to talk about an instance of 'E' with a negative value of attribute 'i' as it is meaningless to talk about an instance of 'E' in which the value of 'i' is a string instead of an integer or which has value for some attribute 'x' instead of attribute 'i'.

The fact that EXPRESS does not recognise "different kinds of invalidity" is natural when one considers the original goal of EXPRESS and STEP in general. EXPRESS is a tool for describing product data that is exchanged between computer systems. It does not make sense to specify how a system should behave if it receives data that does not fully conform to the schema that it is supposed to conform to. Nevertheless, as will be seen later in this section, this property of EXPRESS causes problems if one tries to use EXPRESS outside its original domain of data exchange.

6.1.1.5 EXPRESS-G

EXPRESS-G is a graphical notation for schemas defined in EXPRESS. An EXPRESS-G diagram can only show entities and their attributes (including references to other entities) but not any rules. An EXPRESS-G diagram thus gives an incomplete but comprehensible overview of a schema, which must be described in detail with the textual EXPRESS language.

6.1.2 External Representation of EXPRESS Data

The original goal of STEP is to make it possible to exchange product data between organisations. STEP Part 21, called 'Clear text encoding of the exchange structure' therefore specifies how a set of instances of entities defined in an EXPRESS schema are represented as a textual physical file (ISO 1994c).

As a very simple example, consider the following schema:

```
SCHEMA residences;

ENTITY person;
  name : STRING;
  hometown : town;
END_ENTITY;

ENTITY town;
  name : STRING;
  country : STRING;
INVERSE
  citizens : SET OF person FOR hometown;
END_ENTITY;
```

A physical file with a couple instances of these entities could look as follows:

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(…);
FILE_NAME(…);
FILE_SCHEMA(('residences'));
ENDSEC;
DATA;
#1 = TOWN('Helsinki', 'Finland');
#2 = TOWN('Washington, D.C.', 'USA');
#3 = PERSON('Hannu', #1);
#4 = PERSON('Bill', #2);
ENDSEC;
END-ISO-10303-21;
```

Inverse (and derived) attributes do not appear in the physical file because their values are automatically determined from the values of the explicit attributes.

In addition to a text file, EXPRESS data can be stored in a repository, which can, for example, be implemented as a file or a database. The contents of a repository are accessed by means of operations defined as a Standard Data Access Interface (SDAI) in STEP Part 22. The SDAI is thus an Application Programmers' Interface (API) to an EXPRESS repository.

Part 22 is independent of any programming language. Further parts define language bindings, which tell how the operations of the SDAI are used from an application written in different programming languages such as C, C++ and Java.

6.1.3 Integrated Resources

The next subsection explains how the STEP standard ultimately defines a number of application protocols for exchanging product data between applications. Many application protocols must represent similar data. For example, almost all application protocols include some kind of geometric data.

The application protocols are built from integrated resources, which are divided into generic integrated resources and application integrated resources. As the names suggest, the former ones are intended for all kinds of applications while the latter have been developed for a range of similar applications.

The rest of this subsection briefly describes the generic integrated resources of Parts 41 and 44, which are the main resources for product structures.

6.1.3.1 STEP Part 41

STEP Part 41 is called 'fundamentals of product description and support' (ISO 1994d). Among other things, this part defines an application context in which product data can be defined. Each application context is associated with one or more application context elements, which can define the following aspects of the application context:

- Product context, which defines a discipline type, such as 'electrical' or 'mechanical'.
- Product definition context, which defines a life cycle stage, such as 'as designed' or 'as specified'.
- Product concept context, which defines a market segment type, such as 'luxury automobiles'.
- Library context, which defines a library reference, such as 'the products of company XYZ'.

STEP defines that "a product is the identification and description, in an application context, of a physically realisable object that is produced by a process" (ISO 1994d: 13). A product is associated with one or more product contexts within which the product is defined.

A product is described by means of product definitions, each of which is associated with a single product definition context (i.e., a life cycle stage). A product, however, is not directly related to product definitions. Instead, a product is associated with a set of product definition formations, which can for example represent different versions of the product, and each product definition formation is associated with a set of product definitions.

A product definition can be associated with properties, such as shape, which are further associated with property representations, such as a particular kind of geometric representation of a shape property. A product definition can also be associated with documents.

It is necessary to establish various relationships between product definitions, one obvious example being the 'has-part' relationship for a hierarchical product breakdown structure. Part 41 only defines a product definition relationship, which is an entity for representing any relationship between two product definitions. Since the relationship has no particular meaning at this level, the two product definitions are simply designated as 'relating product definition' and 'related product definition'. The next subsection shows an example of how other integrated resources and application protocols define subtypes of the relation entity for more specific relationships between product definitions.

6.1.3.2 STEP Part 44

STEP Part 44 is called 'product structure configuration' and defines a mechanism for the presentation of hierarchical product breakdown structures (ISO 1994e). Since this part is a generic integrated resource, the mechanism is used in all parts of STEP.

As mentioned earlier, Part 41 defines the entity 'product definition relationship' to represent a relationship between a 'relating' and a 'related' product definition. Part 44 defines the entity 'product definition usage' as a subtype of this entity. The entity 'product definition usage' has further two subtypes.

The entity 'make from usage option' is used for representing the fact that product P is made from product Q through machining or some other process. Product P is represented by the 'relating' product definition, and product Q is represented by the 'related' product definition.

The entity 'assembly component usage' is similar, and it represents the fact that product P has product Q as a part. Product P is again represented by the 'relating' product definition, and product Q is represented by the 'related' product definition.[6]

The entity 'assembly component usage' has further subtypes because Part 44 makes a distinction between the bill-of-material (BOM) structure of a product and parts list structure of a product. This is illustrated in figure 16 (which does not use the UML notation). Suppose a house has two floors, each floor has three rooms, and each room has four walls. The rectangles in the figure represent the corresponding product definition instances. The diamond shapes labelled with 'N' represent instances of the entity 'next assembly usage occurrence', which record the BOM structure of the product. As seen in the figure, there is only one instance of each product definition entity although the product contains multiple instances of the corresponding component. Nevertheless, there are multiple instances of 'next assembly usage occurrence' to record the fact that a floor, for example, has three rooms.

Sometimes it is necessary to refer to individual component instances. In STEP, the individual components are stored as a parts list structure, which is represented by means of the entity 'specified higher usage occurrence'. The entity has two attributes. The attribute 'upper usage' refers either to a 'next assembly usage occurrence' or to another 'specified higher usage occurrence', and the attribute 'next usage' refers to a 'next assembly usage occurrence'. In figure 16 the diamond shape 'S1' is a 'specified higher usage occurrence' that represents the third room of the second floor, and 'S2' represents the fourth wall of the third room of the second floor. The complete parts list structure requires altogether 2 × 3 × 4 = 24 similar 'specified higher usage occurrence' entity instances.

6. Here it might be convenient if EXPRESS would allow a subtype entity to rename inherited attributes. For example, it might be easier to read the descriptions of the use of the entity 'assembly component usage' if it could rename the inherited attribute 'relating product definition' as 'assembly product definition'. On the other hand, when examining the data at the level of a generic product definition relationship, it might be confusing if the same attribute could be referred to with different names in different subtypes.

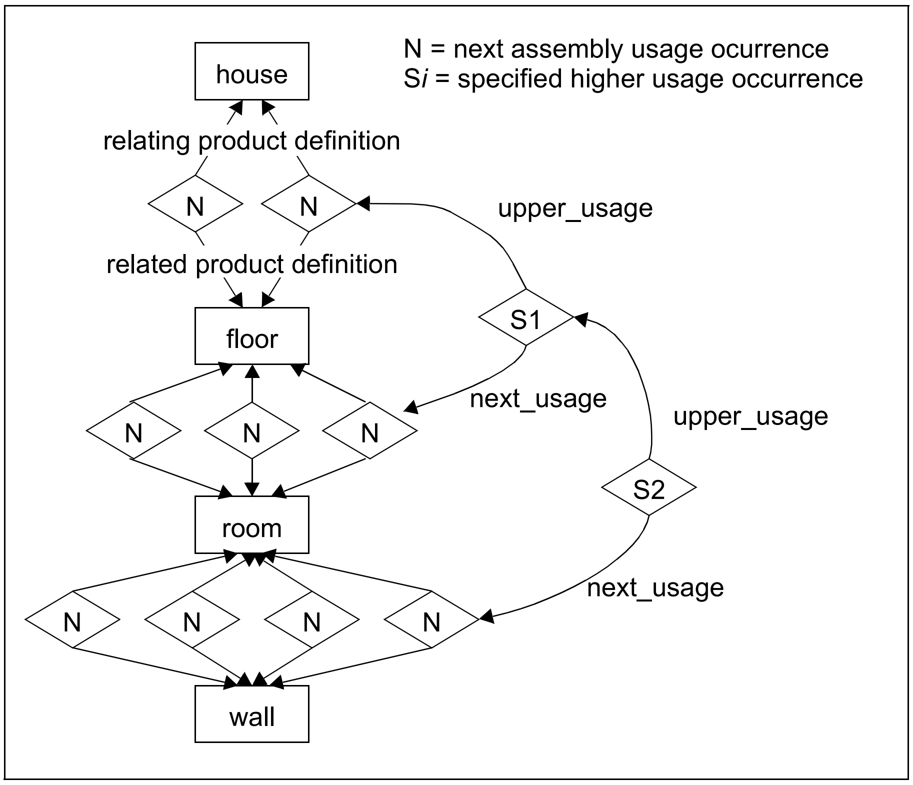

N = next assembly usage ocurrence
S*i* = specified higher usage occurrence
house
relating product definition
N
N
upper_usage
related product definition
floor
S1
next_usage
upper_usage
N
N
N
S2
room
next_usage
N
N
N
N
wall

Figure 16. Bill-of-Material and Parts lists in STEP Part 44.
The notation is explained in the text.

6.1.4 Application Protocols

The actual standardised product data models are defined as STEP application protocols (AP). Basically the definition of an application protocol consists of two parts. The first part is an application reference model (ARM), which defines the necessary concepts for the application domain to be covered by the application protocol. The application reference model is in principle written regarding its eventual implementation. The second part of an application protocol is an application interpreted model (AIM), which shows how the application reference model is implemented with the integrated resources.

An application interpreted model gives an interpretation to entities defined in the integrated resources. An application interpreted model can also define entities as subtypes of entities in the integrated resources.

What STEP basically standardises are the application protocols. In order for two applications to exchange STEP product data, the data must be exchanged with some application protocol “understood” by both applications. Sometimes a software tool, such as a PDM system, is advertised as “STEP compliant”, “STEP compatible” or something similar. These statements do not make much sense unless one specifies that the tool can manipulate data according to a particular application protocol. In extreme cases, the fact that the data model of a system has been described in EXPRESS may be used as a justification for touting the system as "STEP based".

There are problems with application protocols. The most immediate observation that can be made from an application protocol standard, such as AP203 for configuration controlled design (ISO 1994b), is the almost incomprehensible format of the standard. For example, the bulk of AP203 consists of the specification of the application interpreted model in the form of over 200 pages of mapping tables and rules. Most concepts are presented in alphabetical order, which makes it almost impossible to form an overall picture of the standard.

Application protocols are independent of each other. All application protocols are based on the same integrated resources but the application level concepts that are built on top of the integrated resources can be quite different in different application protocols. This causes problems if different application protocols should be used together (Teeuw et al. 1996).

STEP was originally designed for data exchange. The problems with integrating different application protocols become especially pressing when STEP is used as a basis for sharing and archiving product data within an organisation (Owen 1997: 133).

6.1.5 STEP and Generic Product Structures

The present subsection examines the possibilities of STEP in the description of generic product structures (Männistö et al. 1998).

The EXPRESS language as such seems suitable for describing generic product structures. As seen earlier, the language provides many useful constructs for this purpose, such as a powerful subtyping mechanism, reference attributes with redeclaration in subtypes, and rules. Given a configurable product, in many cases it is probably fairly convenient to model the product as an EXPRESS schema with entities and reference attributes representing components and parts, respectively.

Nevertheless, EXPRESS cannot be used in this way within the general STEP framework. Applications exchange data that conforms to a particular schema defined in a STEP standard. In other words, applications read and write instances of predefined entities using, for example, the external data representation methods mentioned in section 6.1.2.

Suppose a company describes its configurable products directly in EXPRESS. Whenever the company creates a new configurable product or modifies an existing product, the company creates new entities and modifies existing entities in its own company-specific schema. In order to access a configurable product, an application must thus also access the declaration of appropriate entities instead of accessing only instances of some fixed entities. This whole notion of representing information about individual products as part of a schema is completely against the very basic principles of STEP, which does not say anything about the possibility of applications exchanging entity declarations and other schema data.

Some application protocols, such as AP214 for the automotive industry and AP221 for the process industry, include a product classification mechanism. Conceptually the application protocols deal with product classes and instances of the classes. As all data in STEP must be represented as instances of standardised entities, the application protocols define entities both for the product classes and for their instances. Basically, the entity for a product class has attributes to record the classification relationships between classes, and the entity for product instances has an attribute to record the product class that the product instance is an instance of. Ignoring all details, the entities look roughly as follows:

```
ENTITY product_class;
  superclass: OPTIONAL product_class;
INVERSE
  subclasses: SET OF product_class FOR superclass;
END_ENTITY;

ENTITY product_instance;
  class: product_class;
END_ENTITY;
```

To represent generic product structures, the product classes must include attributes and constraints. The entity 'product_class' must be extended with EXPRESS attributes so that an instance of 'product_class' stores information about the attributes and constraints of the product class represented by the instance of 'product_class'. If the attributes and constraints of product classes are similar to the attributes and rules in EXPRESS, in the end this approach must represent a considerable subset of EXPRESS as EXPRESS data.

As an alternative to implementing "EXPRESS in EXPRESS", it might be possible to extend STEP so that configurable products could be described directly in EXPRESS. Roughly speaking, a STEP standard would define an entity for a generic product structure, and individual organisations would describe their products by defining new entities as subtypes to the standard entity.

This approach to generic product structures would require fundamental changes in the STEP framework. Above all, if would be necessary to define a mechanism for exchanging EXPRESS entities in addition to instances. Another problem is the notion of validity discussed at the end of section 6.1.1.4. If a particular generic product structure is represented with its own EXPRESS entity, and the configuration constraints are represented as EXPRESS rules in the entities, a configuration is an instance of such an entity. During a configuration process it is necessary to represent incomplete and invalid configurations, and accordingly it is necessary to have invalid instances of an entity that represents a generic product structure.

There are many other difficult questions with the approach outlined above. For example, there should probably be some restrictions on the entity declarations created to represent individual generic product structures. These restrictions should be defined in the standard entity. This seems to imply a need for a mechanism for writing "EXPRESS metarules", which specify validity conditions for entity declarations that are subtypes of a given entity.

6.2 Component and Supplier Management

One field within PDM to have recently gained an increasing amount of attention is component and supplier management (CSM). This functionality can be implemented as part of a PDM system or it can be provided by a separate system, which must be able to communicate with a PDM system.

Component supplier management within a company deals with the standard components bought by the company from outside suppliers. For example, in electronics it is typical that a particular component, such as a particular kind of transistor, is available from many manufacturers. Although the components from different manufactures can have the same specifications, often the company does not want to use a particular component from a particular manufacturer until the company has tested the component for quality and other suitability in its products.

One important issue with standard components is their identification. Although different manufacturers of the "same" component identify their components with their own codes, the company that uses the components must be able to refer to the components with a single code as long as the components from different manufacturers are interchangeable from the company's point of view. Different codes for the "same" component can also be found within different departments of a single company. Unless a company identifies the "same" components from different manufacturers with the same codes, it is very difficult to answer important questions on the components, such as "how much of component X do we buy?" or "how much of component X do we have in stock?".

CSM systems make it possible to search a company's own catalogues and from catalogues provided by the component manufacturers. The search capabilities are based on component class hierarchies and attributes. These concepts are in principle the same as the ones already discussed in section 3.2. Nevertheless, then it was more or less tacitly assumed that different object types represent different kinds of objects in regard to the processes that manipulate the objects. Therefore one could perhaps expect to have at most dozens of types. A component database, however, can have hundreds of types because classification is the primary way to search for components in a component database. For example, the IEC 61360 standard for electric components defines a component class hierarchy with almost 200 component types (IEC 1997). One can perhaps also say that there is more variation among different types of components than among different kinds of documents when one considers what kind of information can be represented as attributes.

There are various standardisation efforts for component management. The IEC 61360 standard, which was already mentioned, is closely related to the ISO 13584 Parts Library standard. Whereas IEC 61360 defines a class hierarchy for electric components, ISO 13584 defines a general mechanism for the representation and exchange of part library data. According to the standard, components from different suppliers are described in supplier libraries. A company that wants to access the component data creates a user library by integrating, and possibly adapting, one or more supplier libraries. Library end users, such as product designers, access the user library by means of a library management system (ISO 1997).

A part library is organised in a familiar class hierarchy. Each component types (called a part family in the standard) can define attributes (called properties). Nevertheless, there is an interesting addition to the normal inheritance of attributes in a class hierarchy. If an object type defines an attribute, all instances of the type and of its subtypes usually have the attribute. In the parts library, attributes are "defined" in two steps. A component type first specifies a number of visible attributes. These attributes are visible in this component type and in its subtypes. The fact that an attribute is visible in a particular component types does not yet mean that instances of the component type could have a value for the attribute. If an attribute is visible in a component type, the component type can specify the attribute as applicable, and only then can instances of this component type and of its subtypes have a value for the attribute (ISO 1996).

ISO 13589 deals extensively with components and suppliers. Nevertheless, the standard fails to distinguish between component manufacturers and component suppliers. The distinction is important because a particular component made by a particular manufacturer can often be bought from many different suppliers, and often for different prices.

The relations between components, manufacturers and suppliers, and the most important attributes and of the entities and the relations are illustrated in figure 17. The figure is based on a similar figure by Asko Martio and Tomi Männistö at the Product Data Management Group. The figure shows the data from the point of view of a particular company that buys the components and uses them in its products. The "owner" of the database is here referred to simply as 'the company'.

In the figure, 'generic component' represents the notion of an "abstract" component with a particular specification. The attributes of a generic component include a code used by the company to identify the component, and a specification, which may be based on a classification standard such as the IEC 61360 standard for electric components.

Each generic component is related to one or more manufacturer's components, each of which represents a "concrete" component made by a particular manufacturer. The attributes include the code that the manufacturer uses for the component, and testing status, which tells whether the company has tested the manufacturer's component and found it suitable to be used by the company. There can also be an attribute that records statistical quality about the manufacturer's component.

A manufacturer's component represents a particular component made by a particular manufacturer. Usually a manufacturer's component is related to exactly one generic component, for which the manufacturer's component is one of the available

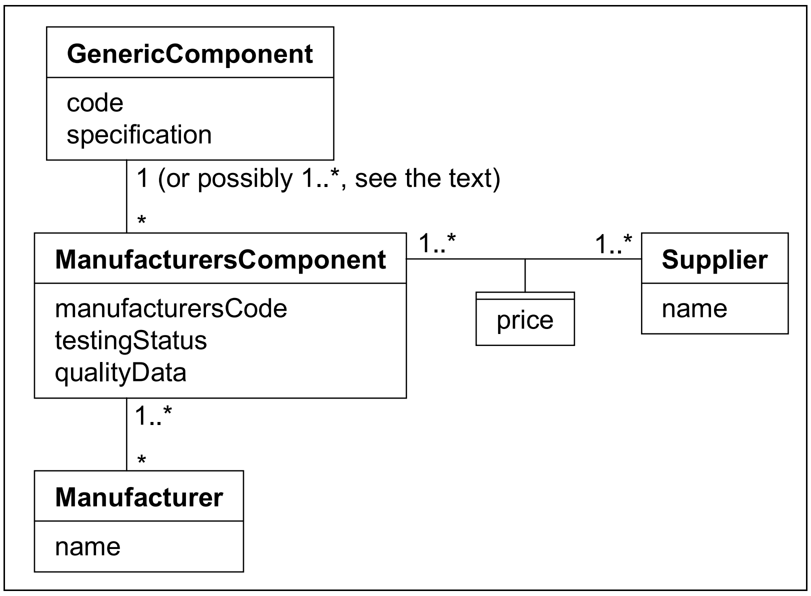


Figure 17. Components, manufacturers and suppliers

alternative “realisations” that fulfil the specification of the generic component. In a way the manufacturer’s components related to a generic component can be seen as variants of the generic component.

It is possible to imagine situations in which a single manufacturer’s component should be related to more than one generic component because the manufacturer’s component fulfils multiple specifications. As an imaginary example, suppose that there are three generic components that only differ in the allowed operating temperature. One component is specified to operate in normal temperature only, while the second and third component also operate in low and high temperatures, respectively. If a manufacturer has a component that operates in all temperatures within the three specifications, the single manufacturer’s component should be related to all three generic components.

Each manufacturer’s component is related to exactly one manufacturer, and to the multiple suppliers that sell the manufacturer’s component. Each supplier is also related to multiple manufacturer’s components. The price of a component is an attribute of the relation between a manufacturer’s component and a supplier because different suppliers can have a different price for the same component.

The above discussion and most CSM systems deal with atomic components, which are not considered to be composed of subcomponents. Nevertheless, sometimes this is too restrictive an assumption. For example, consider two generic components ‘basic A’ and ‘A with B’.[7] At one manufacturer, X, the generic components correspond to two distinct manufacturer’s components. Another manufacturer, Y, however, has manufacturer’s components A' and B'. The generic component ‘basic

A' corresponds to manufacturer Y's component A', and the generic component 'A with B' corresponds to a combination of manufacturer Y's components A' and B'.

Assembled components complicate component management considerably. For example, if a company has a certain number of manufacturer's components A' and B', it is impossible to say that the inventory contains a certain number of generic components 'basic A' and 'A with B'.

The ISO 13584 Part Library standard addresses the issue of assembled components by distinguishing between level 1 and level 2 libraries. A level 1 library can only contain atomic components, whereas a level 2 library can also contain assembled components (ISO 1995: sec. 4.3.12). Note that the terminology in the standard differs from the one in this thesis. The terms 'component' and 'atomic component' in this thesis correspond to the terms 'part' and 'component' in the standard.

In addition to the lack of assembled components, the model discussed so far suffers from another simplification. The testing status of a manufacturer's component now records whether the company has approved the use of the component. Sometimes, however, it is necessary for a company to test whether a particular manufacturer's component can be used in a particular product. The data model becomes quite complicated because a product uses a number of generic components, each generic component is related to a number of manufacturer's components, and the testing status is associated with the combination of a particular product and a particular manufacturer's component, which is related to a generic component used in the product.

7. This is a real example kindly provided by Asko Martio. The components A and B are actually some electrical contactors. As the author of the thesis is unfamiliar with the technical details of these components, it seems best to refer to abstract components A and B.

Part II: EDMS Document Management System

This second part of the thesis describes a document data management system, known as EDMS, that was built by the Product Data Management Group at Helsinki University of Technology in a joint project with KONE Elevators, which is a large Finnish lift manufacturer.

In its present form the system is more a document management system than a complete PDM system. Above all, the implemented system does not support product structures. However, chapter 9 describes product structures, which will be added to the system.

This part first describes the concepts of the system. The system is built around a versatile document data model with document versions, subdocuments and multiple representations of document files. The concepts are followed by a description of the system architecture and the implementation. The core of the system is a server program built on top of a commercial relational database system. The server communicates with client programs using a protocol that refers to the concepts of the data model. The most important clients are a graphical user interface program, an Application Programming Interface that is used for the integration between EDMS and a CAD system, and a Web server.

Chapter 14 contains a summary of the strengths and weaknesses of the system. On the whole the system has been a success at KONE. Although part of the success can certainly be attributed to the properties of the system, one must remember that the overall success of a PDM project—like any information system project—also depends on many organisational issues, such as the commitment of company management and training for the users.

7 Background on the EDMS Project

7.1 KONE Elevators

KONE Elevators is the fourth largest lift manufacturing company in the world with an annual revenue of over 2 billion USD. KONE sells lifts, escalators and related services world-wide, and has mainly grown by acquisitions as most nationally operated lift companies have merged into global corporations.[8]

KONE offers a comprehensive product range from simple two stop hydraulic lifts to sophisticated fast lift groups for high rise buildings. As KONE manufactures its products on a make-to-order basis, information processes related to products and deliveries are fundamentally important. The production of high-quantity lift components (doors, gears, etc.) is centralised in component factories, whereas lift deliveries to installation sites start from delivery centres, which are distributed closer to customers. The delivery centres are also responsible for engineering the products to customer specifications.

The last step in the delivery chain is installation, which accounts for about a third of total lift costs. This phase demands accurate product information because the environment is managed by the constructor.

More than half of the revenue comes from the maintenance of lifts and escalators made by KONE and other manufacturers.

7.2 Project Starting Point and Goals

At the beginning of the 1990s, KONE was global but operated locally with very few common processes. Consequently, the product range was very wide and difficult to manage due to local variations.

Although the importance of technical information was acknowledged, there was no common document management system. Drawings were archived on microfilms, and there was no centralised file backup system. Since 1982, the factory in Hyvinkää in Finland had used a custom-built mainframe-based drawing information system (DIS), which managed drawing numbers and about 80 characters of attribute data for each drawing. Other KONE sites had no comparable systems.

In the late 1980s KONE decided to get a new document management system, which was to provide much more functionality than DIS and to serve as a basis for the overall improvement of product data management.

The main function of the new system was to provide a document vault, i.e., a database for both the attributes and the actual contents of all types of documents. Users had to be able to view the documents in the database without the original document creation tool. The database was also to replace microfilming with a safe document backup archiving system.

8. Asko Martio has provided most of the material in this chapter.

Change management is essential for technical documents. Whereas the old document system only stored information about the latest approved version of a document, the new system had to store the complete version history of a document and track its release status to support product development processes.

Most of the documents in the system are associated with products. Although the project started with document management, the long-term goal was a system for both products and related documents. In particular, the system was required to maintain hierarchical product structures with product versions and variants. A prototype of this functionality was built in EDMS and demonstrated. Although this work was discontinued when KONE decided to buy a new ERP (Enterprise Resource Planning) system, product structures are now being added to the system in a more advanced form.

Finally, to support KONE globally, the system had to be scalable and use client-server technology. Licence fees were expected to be less than 50 % of medium priced CAD package fees.

Because several companies had contacted KONE and offered commercial document management products, KONE thought it would be easy to find a system meeting its goals.

7.3 Motivation for an In-house System

Introduction to Product Data Management was easy with the PDM Buyer's Guide (Miller, MacKrell and Mendel 1997). However, the early discussions with vendors in 1991 showed that there were no turn-key PDM or document management systems. A lot of specification work was needed before system implementation.

The system suppliers were found to sell concepts instead of solutions. It was impossible to get clear answers even to the most basic questions such as 'If I have a Finnish document variant, how can I find the corresponding English variant?' or 'We have about 100 000 bilingual documents. How could we manage those with your system?'.

The prices were also far too high unless KONE had ordered a large number of licences (minimum 1000). For a distributed company this kind of commitment was impossible. Even to learn about the functionality of the systems, KONE was asked to buy consultant services.

Finally KONE broke up the negotiations to get away from fruitless discussions like 'Can your system do this? It might be possible but …'. KONE felt that product data management products were not yet mature for manufacturing companies operating in a competitive market-place. KONE wanted to give vendors time to improve their products and lower their prices, clarify its own requirements and raise the awareness of document management within the company, which was still at a very low level in the early 1990s. In spite of several internal seminars, lectures and demos the interest and feedback from potential users were very modest.

KONE started a research project with the Product Data Management Group at Helsinki University of Technology to learn more about product data management. The project, which was originally only aimed at a prototype system but eventually resulted in the EDMS system described here, was under the responsibility of the Engineering Systems Department, a corporate function at KONE. As a research project its structure was loose and communication with other departments informal. This method was chosen because both qualitative and quantitative results were uncertain in the beginning.

The project gave the research group a valuable opportunity to study PDM in real life. Often the concrete requirements of KONE resulted in more general concepts, which were eventually implemented in the system.

At the moment the system is maintained and developed further by the research group. The group is starting a new project, which will above all extend the system with products structures discussed in chapter 9. The new project is planned to have two or three new industrial partners in addition to KONE. The result of the new project should be a system that can be used as a basis for commercial operations outside the university (e.g., a new company).

8 EDMS Data Model

This chapter describes the data model of EDMS. The data model is the core of the system because it determines the data that can be stored in the system and the operations for manipulating the data.

The model is in some respects very fixed. The basic object types, called object kinds in EDMS, and the related operations are fixed. On the other hand, within each object kind the model is flexible because the administrator can define new object types, which can have many different kinds of attributes.

Although the present system lacks product structures, plans for them have been made. Logically product structures should be described in this chapter together with the rest of the data model. Nevertheless, as product structures have not yet even been properly specified, the present state of product structures is discussed separately in chapter 9.

EDMS defines five object kinds related to documents. They are described in more detail in sections 8.3 to 8.6. Section 8.8 contains a UML diagram of the document model.

In addition to documents, an EDMS database also stores information about projects and users of the system. This information is described in sections 8.9 and 8.10.

The administrator must define different object types for each object kind. For example, the administrator defines a number of document types. Object types are discussed in section 8.11. The main purpose of an object type is to define attributes, which are discussed in section 8.12.

The life cycles of documents and other objects are modelled by means of state graphs, which are described in section 8.13.

This chapter describes the current EDMS data model. Shortcomings and possible extensions of the model are discussed in chapter 14.

8.1 EDMS Administrators

EDMS makes a clear distinction between properties that are programmed in the system and properties that can be modified by a system administrator.

Object kinds are examples of programmed properties. If a new object kind were to be added to the system, the developers of the system would have to do a considerable amount of programming. Object types, on the other hand, are defined by a system administrator without any programming.

In principle, EDMS does not distinguish between administrators and other users of the system. In practice, only a single user (or a small group of users) is supposed to carry out "administrative" operations, such as to create a new object type or to add a new attribute to an object type. When this thesis says that the administrator can perform an operation, it means that the operation can be performed by an EDMS user and typically the operation is performed by the administrator instead of an "ordinary" user. The authorisation mechanism in EDMS makes it possible to specify that only particular users can perform the "administrative" operations.

8.2 Object Kinds

Each object belongs to one of the following *object kinds*:

- document
- document version
- subdocument
- subdocument version
- representation
- user
- project

There is also an object kind 'product'. Nevertheless, this object kind has only been used for a simple material register. As the current 'product' objects have not been used for product structures, they are not discussed here. However, chapter 9 describes the future product structures.

8.3 Documents and Files

In EDMS, the term 'document' refers to a structure of document versions, subdocuments and other elements described shortly. The "concrete document" corresponds to a single document file, which can for example contain a drawing or a 3D geometric model created with a CAD tool. Document files are stored within representations (section 8.6) and are accessed through check-out and check-in operations, which copy document files out from the database for modification and return the modified files back to the database.

From the system's point of view, a document file is simply a sequence of bytes. The basic system does not "understand" anything about the contents of a document file. However, the attributes of a document file can specify an application that should be started to open the document file. There are also additional tools, such as the indexing tool described in section 13.1, for processing particular kinds of document files in the system.

8.4 Document Versions

Here it is important to distinguish between the general version model of EDMS and the way the model is used at KONE. For example, EDMS as such has no concept of a language variant for documents. Nevertheless, the versions are arranged and named at KONE in a particular way to represent language variants.

8.4.1 General Document Version Model

A document has a number of *versions*. There are three ways to create a new version of a document:

(1) The new version can be created as a *child* to an existing version, called the *parent version*, of the same document. Initially the new version has the same contents as the parent version. The document files associated with the parent version cannot be modified after the child version has been created. (See section 14.1.1.4)

As will be seen later, no data is copied when the child version is created. Instead, the new version is marked to share its contents with the parent version.

(2) The new version can be created without a parent version. There are two further alternatives for the initial contents of the new version:

(2.1) The new version is initially empty.

(2.2) The new version can be created without a parent so that the initial contents of the new version are copied from an existing version, called the *source version*, of the same or another document. The name of the source version is stored in the attributes of the new version, but there is no other connection remains between the new version and its source version. For example, the source version can be freely modified or deleted.

The source version must be of the same type as the new version so that they have the same attributes that can be copied from the source version to the new version.

As illustrated in figure 18, the versions of a single document thus form a number of trees so that each version without a parent is the root of a tree, and other versions have exactly one parent. In this structure it is irrelevant whether a version without a parent was initially empty or whether its initial contents were copied from a source version. The system does not support version merging.

In general, EDMS allows document versions to have arbitrary names as long as all versions of a single document have different names. The parent-child relation between versions is not recorded in version names. The version naming convention at KONE will be described shortly.

8.4.2 Document Versions at KONE

One of the requirements of EDMS was to support documents that are available in different languages. In general, the versions of a document in EDMS form a number of trees. At KONE, each language variant of a document is stored as a separate version tree. As there is no branching within the trees at KONE, each tree is actually a

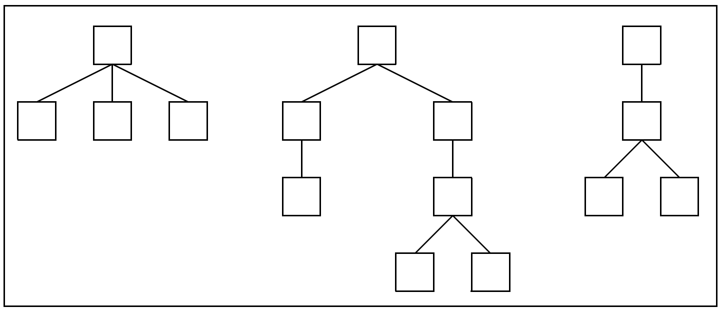


Figure 18. EDMS document versions in general

sequence of versions in the same language. The resulting structure is illustrated in figure 19.

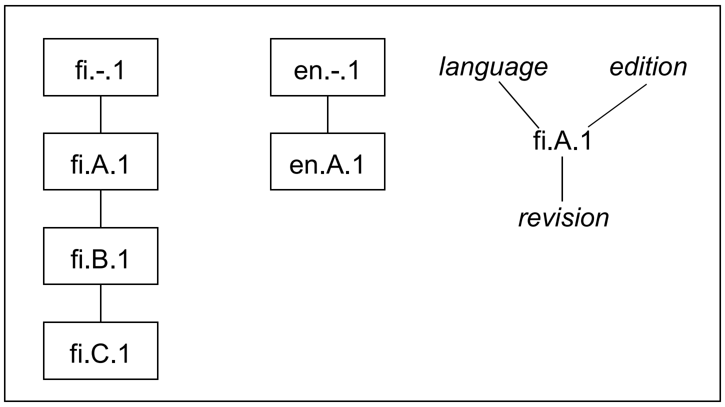


Figure 19. EDMS document versions at KONE

At KONE, the name of a document version is composed of a code that tells the language in which the version is written, a revision letter and an edition number. Section 3.5.1.3 introduced the distinction between the major and minor revisions. At KONE, the major and minor revision are specified by the revision letter and edition, respectively.

Edition numbers and language variants are not supported directly by EDMS. Versions are simply arranged and named in a particular way at KONE. The system does not "know" that versions 'fi.C.1' and 'en.C.1' contain in some sense the same data or that the difference between versions 'fi.A.1' and 'fi.A.2' is "smaller" than between versions 'fi.A.2' and 'fi.B.1'. However, the authorisation mechanism (section 11.4) can be programmed to check that versions are named correctly.

8.5 Subdocuments and Subdocument Versions

In addition to having multiple versions, each document is composed of one or more *subdocuments*. Each subdocument has in turn a number of *subdocument versions*.

The document structure always has a fixed number of levels; a subdocument cannot be composed of further subdocuments. This means, for example, that subdocuments cannot be used for representing a hierarchical document in which a document consists of chapters, which consist of sections, which consist of paragraphs, etc. Other limitations of the current subdocument model are discussed in section 14.1.1.3.

The behaviour of document versions, subdocuments, and subdocument versions is the most complex part of the data model. The following example illustrates the evolution of a single document. To simplify the presentation, versions are named with single letters. The notation 'd/X' means 'document version X' and 's*i*/X' means 'version X of subdocument s*i*'.

The description refers to the modification of a subdocument in a document version. As will be explained in the next subsection, each subdocument version has a number of representations. The modification of a subdocument means that the user modifies the contents of a representation of the subdocument version associated with the particular document version and subdocument.

The sample document consists of two subdocuments 's1' and 's2'. Each subdocument is versioned separately so that a document version can contain a particular version of each subdocument of the document. At first the document has a single version A, which is composed of version A of both subdocuments:

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A

The user then creates document version B, which originally consists of the same subdocument versions as the parent version:

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	**s1/A**	**s2/A**

When the user modifies subdocument 's2' in document version B, the system creates a new subdocument version B of subdocument 's2' with the modified data and includes it in the document version B:

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	s1/A	**s2/B**

If subdocument 's2' is subsequently modified in document version B, no new subdocument version is created because the document version already has its "own" version of the subdocument.

Document version A cannot be modified after version B has been created as its child. Typically the modification of a document version is further restricted with state graphs and the authorisation mechanism to be described later.

The user then creates document version C:

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	s1/A	s2/B
d/C	**s1/A**	**s2/B**

When the user modifies subdocument 's1' in document version C, a new subdocument version is again created:

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	s1/A	s2/B
d/C	**s1/C**	s2/B

In summary, a user creates a new document version explicitly when the work on the new version begins, not when the version is ready. Information about whether the version is ready or not is recorded by means of state graphs discussed in section 8.13.

Subdocument versions, on the other hand, are created automatically by the system when users modify subdocuments. A new subdocument version always gets its name from the document version in which the subdocument version is created. This means that the composition of a document version directly shows which subdocuments have been modified in the document version. This also means that the subdocument versions are not necessarily named with consecutive letters. For example, subdocument 's1' of the previous example has versions A and C, but no version B. KONE has found this naming practice convenient.

8.5.1 Dropped Subdocument Versions

A document version does not have to contain a version of each subdocument of the document. When a new subdocument is added to a document, no version of the document contains any version of the subdocument. A document version without children can then be modified with an operation that adds an empty version of the new subdocument to the document version. Similarly, a subdocument can be *dropped* from a document version that does not have children.

Suppose a document has subdocuments 's1' and 's2'. Document version A contains version A of both subdocuments.

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A

Document version B is created and should only contain subdocument 's1'. One possibility would be to simply say that document version B does not contain any version of subdocument 's2'. (Subdocument 's1' has also been modified in the new document version):

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	s1/B	

No concept of a dropped subdocument would be needed. In the present model, however, subdocument 's2' is marked as dropped in document version B. The document thus looks as follows (subdocument version name in parentheses indicates here a dropped subdocument):

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	s1/B	(s2/A)

The "composition row" for document version B thus reveals that this document version does not contain any version of subdocument 's2', and the last time an ancestor of this document contained a version of 's2', it contained version 's2/A'.

Next, the user creates document version C:

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	s1/B	(s2/A)
d/C	s1/B	(s2/A)

The user decides that the document should after all contain subdocument 's2', too. Accordingly, the user adds subdocument 's2' back to document version C:

document version	subdocument 's1'	subdocument 's2'
d/A	s1/A	s2/A
d/B	s1/B	(s2/A)

document version	subdocument ‘s1’	subdocument ‘s2’
d/C	s1/B	s2/A

Subdocument ‘s2’ can now be modified in document version C:

document version	subdocument ‘s1’	subdocument ‘s2’
d/A	s1/A	s2/A
d/B	s1/B	(s2/A)
d/C	s1/B	s2/C

When a subdocument is removed from a document version, the “current” subdocument version is thus “saved” and only marked as dropped so that the “last valid” subdocument version is available as a basis for further editing if the dropped subdocument is later added back to a document version.

8.5.2 Subdocuments at KONE

This behaviour of subdocuments is modelled after the procedures at KONE. The concept of a subdocument was originally added to EDMS because some electrical drawings at KONE consist of multiple sheets, which are stored by the drawing tool in separate files and which are represented as subdocuments in EDMS.

Another application for subdocuments at KONE is a document that consists of a “master file” with text and a number of graphics files that are linked to the master file. However, to avoid a very large number of subdocuments, the master file and all graphics files are not represented as separate subdocuments. Instead, the master file is one subdocument, and all auxiliary files are combined into a single file, which is stored as another subdocument. As explained in section 12.2.4, the EDMS user interface can be tailored with scripts that are executed in connection with certain operations. The administrator at KONE has written scripts that automatically create the single graphics subdocument from the separate files and vice versa.

8.6 Representations

Each subdocument version has a single *primary representation* and optionally a number of *secondary representations*. Each representation has contents, which correspond to a single document file. The contents of a primary representation corresponds to the file that can be edited with a document tool (e.g., a CAD tool) and the secondary representations store the primary representation in tool-independent formats for viewing and printing (e.g., PDF or PostScript). Only the contents of the primary representation are edited directly; the contents of the secondary representation are generated from the primary representation.

The document file associated with a primary representation is updated with a conventional check-out / check-in mechanism. The user must first *lock* a document version. He or she can then *check out* a primary representation of a subdocument in the locked document version. This operation copies the contents of the representation from the database to a document file, which is an ordinary file typically located in the user's own workstation. The user then manipulates the file with appropriate tools, such as a CAD application in the case of a drawing. When the file is ready, the user *checks in* the representation, causing the system to copy the document file to the database as the new contents of the primary representation. As explained earlier, at this stage the system may create a new subdocument version. Finally, the user *unlocks* the document version.

A representation can be in three different states with respect to the check-out operation. The contents of a primary representation can be empty (no document file has been stored in the database), checked out (the document file is being edited by a user) or checked in (the document is not being edited). If a document has multiple subdocuments, the primary representations of multiple subdocuments can be in the 'checked out' state at the same time. In this case the document version cannot be unlocked until all representations have been checked in.

The 'lock' and 'unlock' operations are not necessary for the consistency of the database. Without locking, the 'check-out' and 'check-in' operations would still prevent two users from modifying the contents of the same subdocument of the same document version at the same time. Nevertheless, the subdocuments are usually so closely related that it seems better that the whole document version must be locked for a particular user before he or she can modify the contents of any subdocument within document version.

In the original user interface the user must explicitly lock and unlock document versions as explained above. The new user interface is easier to use because it automatically locks the document version before a check-out operation and tries to unlock the version after a check-in operation (the unlock operation fails if the primary representation of another subdocument of the same document version is still checked out).

A primary representation in the 'checked out' state can also be *updated* and *discarded*. Like check-in, the 'update' operation copies a document file to the database. Nevertheless, the representation remains in the 'checked out' state for further modifications. The 'discard' operation changes the representation back to the 'checked in' state without updating its contents in the database.

A secondary representation is updated with a *replace* operation, which is similar to the 'check-in' operation of primary representations and copies a document file to the database as the new contents of the secondary representation. There is no corresponding 'check-out' operation for secondary representations because their contents are not edited directly.

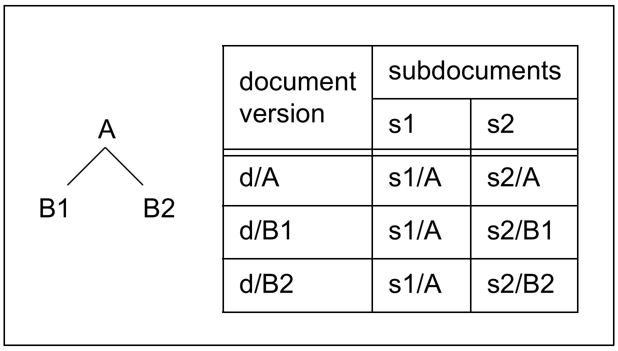
A secondary representation records whether its contents are *valid* with respect to the primary representation. When the primary representation of a subdocument version is checked in, all secondary representations of the subdocument version are marked as invalid. When the contents of a secondary representation are replaced, the representation is marked as valid.

Both primary and secondary representations have the operation 'check out read-only'. This operation simply copies the current contents of the representation from the database to a file. This operation leaves no record in the database, and the operation can also be done for a primary representation in the 'checked out' state.

At KONE some documents have a PDF file as a secondary representation. A document tool that does not create a PDF file may create a PostScript file instead. A regularly executed batch program examines all latest document versions in the database and replaces PostScript representations with PDF representations.

8.7 Document Components

The target of a 'check-out' or a 'check-in' operation is not only a particular representation, which belongs to a particular subdocument version. For example, consider figure 20, which shows the versions of a document and their composition. Document version A has child versions B1 and B2. The document has subdocuments 's1' and 's2'. The second subdocument has been modified in document versions B1 and B2. For example, document version B1 contains subdocument version B1 of subdocument 's2'. The first subdocument has not been modified in B1 or B2. All document versions therefore still contain version A of subdocument 's1'.



document version	subdocuments	
	s1	s2
d/A	s1/A	s2/A
d/B1	s1/A	s2/B1
d/B2	s1/A	s2/B2

Figure 20. Document versions with shared subdocument versions

Suppose a user wants to modify the first subdocument in document version B1. The user locks the document version and checks out the primary representation of subdocument 's1' in document version B1. If the 'check-out' operation only specified the representation to be checked out, it would be impossible to know which document version should be modified because all document versions contain the same subdocument version (i.e., version A of subdocument 's1') with the specified representation.

The document model may be easier to understand if one regards each combination of a document version and a subdocument as a "virtual object" called *document component*. A document component is either associated with a single subdocument version (which is always a version of the subdocument associated with the document component) or not associated with any subdocument version. In other words, a document component represents a cell in the "document composition table", and each cell is either empty or occupied with a subdocument version. If a subdocument has been dropped from a document version, the cell is occupied with a subdocument version but the cell has been marked as dropped.

The document component is a "virtual object" because such objects do not exist in the EDMS database. Document components do not have attributes and one cannot make queries on them. Nevertheless, the implementation of the graphical user interface of the system is based on an object manager (section 12.2.1), which represents document components as a class in the same way as it represents documents, subdocuments and other "real" objects.

8.8 UML Diagram for Documents

Figures 21 and 22 show a UML class diagram and the corresponding constraints for the document model. The diagram only shows the objects in the database; the "virtual" document component objects, which were discussed in the previous section, are not shown.

Constraint 1 says that all documents have different names. Constraints 2 and 3 say that all versions of a document have different names and all subdocuments of a document have different names.

As will be explained in section 8.11, each document is of a particular document type with a particular name. Constraint 4 says that each version of a document is of a document version type with the same name as the type of the document. For example, if a document is of the document type 'drawing', all its versions are of the document version type 'drawing'.

Constraint 5 says that a document version cannot be its own ancestor. In other words, the parent-child relation between document versions must not contain cycles. This constraint uses a non-standard extension to the Object Constraint Language, which is described in appendix A.

Each document version is associated with the subdocument versions that the document version is composed of. Constraint 6 says that a version of a document can only be associated with a version of a subdocument of the same document. Constraint 7 says that a document version cannot be associated with two different versions of the same subdocument. Note that a version of a document does not have to be associated with a version of every subdocument of the document. Constraint 8 says that a subdocument version associated with a particular document version has the same name as the document version or the same name as some ancestor of the document version. This constraint also uses the non-standard extension.

Constraint 9 is similar to constraint 4 and says, for example, that if a document is of a particular document type, all its subdocuments are of a subdocument type with the same name. Constraint 10 says that all subdocuments of a document have different names.

Constraint 11 is again similar to constraint 4 and says that all subdocument versions within a document are of the same subdocument version type, which has the same name as the type of the document. Constraint 12 says that all representations of a subdocument version have different names. Constraint 13 says that a subdocument version can have secondary representations only if it has a primary representation. Constraint 14 says that a secondary representation is valid if and only if it has been modified (i.e., been given new contents with a 'replace' operation) after the corresponding primary representation has been modified (i.e., has been given new contents with a 'check-in' operation).

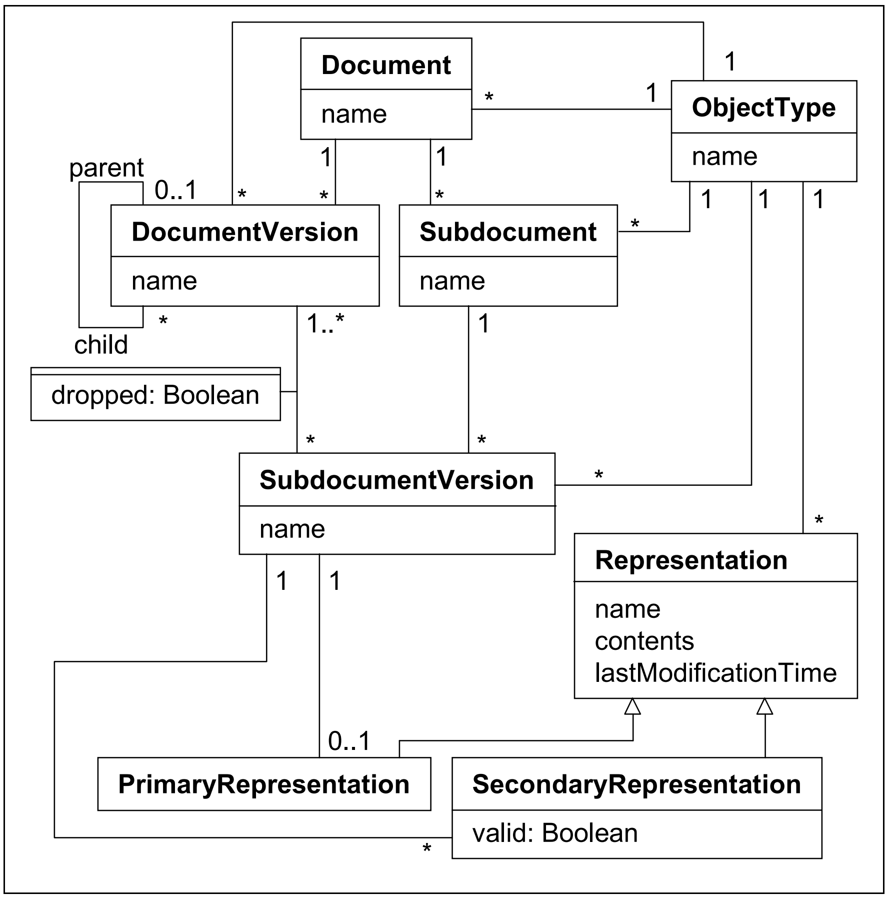


Figure 21. UML class diagram of the EDMS document model. Constraints are shown in figure 22.

```
Document
(1) Document.allInstances->forAll(d1, d2 | d1 <> d2 implies d1.name <> d2.name)
(2) self.documentVersion->forAll(dv1, dv2 |
      dv1 <> dv2 implies dv1.name <> dv2.name)
(3) self.subdocument->forAll(sd1, sd2 |
      sd1 <> sd2 implies sd1.name <> sd2.name)

DocumentVersion
(4) self.objectType.name = self.document.objectType.name
(5) not self.(parent+)->includes(self)
(6) self.subdocumentVersion->forAll(sdv |
      sdv.subdocument.document = self.document)
(7) self.subdocumentVersion->forAll(sdv1, sdv2 |
      sdv1 <> sdv2 implies sdv1.subdocument <> sdv2. subdocument)
(8) self.subdocumentVersion->forAll(sdv |
     sdv.name = self.name or self.(parent+)->exists(dv | sdv.name = dv.name))

Subdocument
(9) self.objectType.name = self.document.objectType.name
(10) self.subdocumentVersion->forAll(sdv1, sdv2 |
         sdv1 <> sdv2 implies sdv1.name <> sdv2.name)

SubdocumentVersion
(11) self.objectType.name = self.subdocument.document.objectType.name
(12) (self.primaryRepresentation->union(self.secondaryRepresentation))
          ->forAll(r1, r2 | r1 <> r2 implies r1.name <> r2.name)
(13) self.primaryRepresentation->isEmpty implies
       self.secondaryRepresentation->isEmpty
(14) self.secondaryRepresentation->forAll(sr |
         sr.valid = (sr.lastModificationTime >
                   self.primaryRepresentation.lastModificationTime))
```

Figure 22. Constraints for document UML diagram.
Constraints 5 and 8 use a non-standard notation described in appendix A.

8.9 Projects

EDMS provides very primitive support for projects. A system administrator can define project types, and attributes (sections 8.11 and 8.12) for each project type. Users can then create projects in the database, store attribute data on the projects and search for projects according to the attributes. Nevertheless, the system does not provide any special project management operations. The system should probably not be extended in this direction even in the future.

Database objects can contain attributes that always have the name of a project as their value. A document, for example, can include an attribute that stores the name of the project to which the document is connected. One can then make a database query that finds all documents with a particular project name for this attribute.

8.10 Users

The database also stores data about users. The data for a user includes a Unix login name, which can be empty. If the login name in the database is not empty, a user with this login name can access the system. A user with an empty login name in the database cannot access the system, but the database can contain references to the user.

User names can be used as attribute values in the same way as project names. For example, a document can have an attribute that stores a list of users to whom new versions of the document should be delivered. This list can only contain names of users who are found in the database.

8.11 Object Types

The administrator must define object types for each object kind. For example, the object kind 'document' could have the object types 'drawing' and 'manual'.

Each object in an EDMS database is of a particular object kind and type. For example, each document is of some document type defined by the administrator.

Object types cannot be organised in a class hierarchy. The possibilities to extend the system in this direction are discussed in section 14.1.5.

The object kinds 'document', 'subdocument', 'document version' and 'subdocument version' are related so that when the administrator creates or removes a document type, the system automatically creates or removes a subdocument type, a document version type and subdocument version type with the same name.

Related objects always have related types. For example, suppose there is a document type 'drawing' and consider a document of this document type. All subdocuments of the document are of the subdocument type 'drawing', all versions of the document are of the document version type 'drawing', and all versions of the subdocuments are of the subdocument version type 'drawing'. When a new document is created, one must specify its type. The type of a subdocument, document version or subdocument version, however, is never specified by a user because the type is determined by the type of the "containing" document.

Representation types, however, are created and removed independently of document types. When a new representation is created, its type must be specified because it does not depend on the type of the document it is part of.

Object kinds, object types and their relations are illustrated in figure 23. The upper part of the figure shows the UML classes for object kinds and types. The association between object kinds represents the fact that an object kind (e.g., 'document') can serve as a "master kind" to a number of "dependent kinds". Each object kind is associated with a number of object types. Constraint 1 says that the object types associated with a single object kind must have different names. Constraint 2 says that an object kind cannot be both a "master kind" and a "dependent kind". Constraint 3 says for each object type of a "master kind", each "dependent kind" must have an object type with the same name, and the “dependent kind” cannot have other object types. The lower part of the figure shows the available object kinds and their relations.

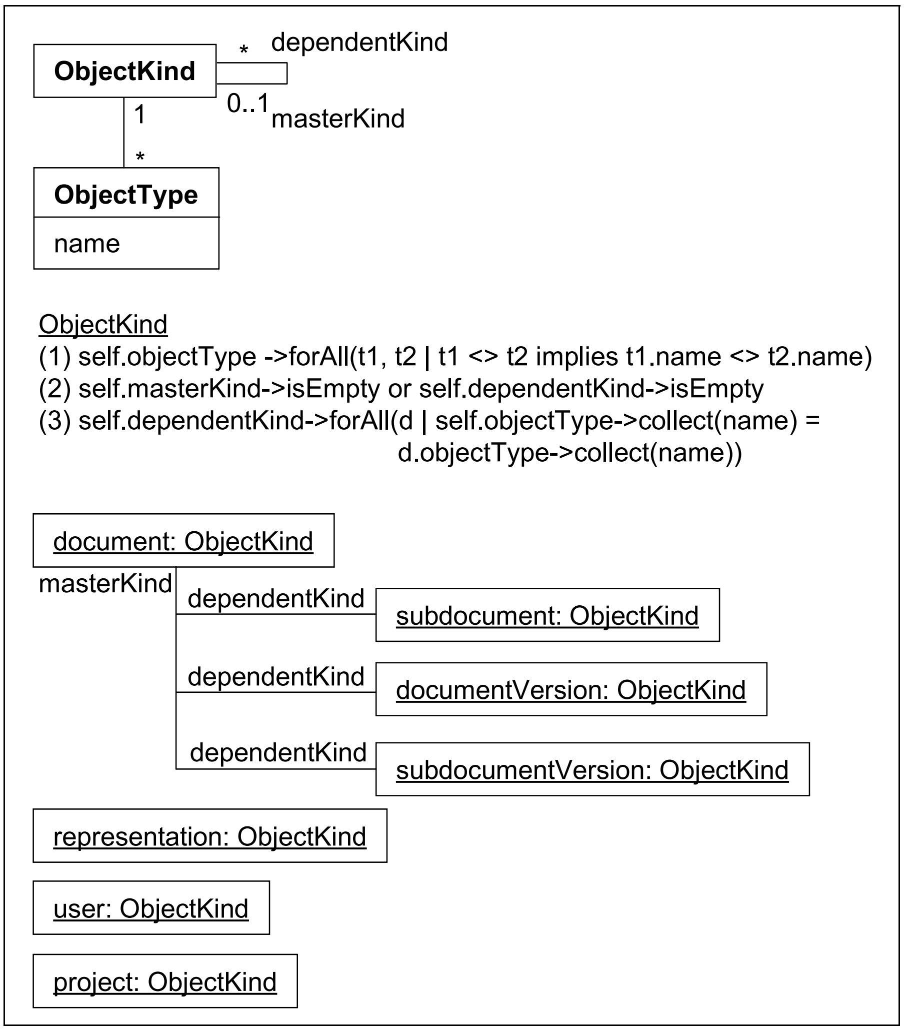

ObjectKind
*
dependentKind
0..1
masterKind
1
*
ObjectType
name
ObjectKind
(1) self.objectType ->forAll(t1, t2 | t1 <> t2 implies t1.name <> t2.name)
(2) self.masterKind->isEmpty or self.dependentKind->isEmpty
(3) self.dependentKind->forAll(d | self.objectType->collect(name) = d.objectType->collect(name))
document: ObjectKind
masterKind
dependentKind
subdocument: ObjectKind
dependentKind
documentVersion: ObjectKind
dependentKind
subdocumentVersion: ObjectKind
representation: ObjectKind
user: ObjectKind
project: ObjectKind

Figure 23. EDMS object kinds and types

8.12 Attributes

Each object in the database, such as a document version or a user, has a number of attributes, which store various information on the object. Users can set and retrieve attribute values for individual objects and make database queries on the basis of the attributes (e.g., ‘find all document versions that have been approved by user X’).

Each attribute has the following properties:

- *Name*. The name of an attribute is used for referring to the attribute within the system. The name is similar to an identifier in programming languages and can only contain letters, digits and underline characters.
- *Title*. The graphical user interface of the system displays the titles of the attributes instead of their names. The attribute title can contain any characters (including spaces) and be given in different languages.
- *Description*. The description of an attribute is a longer piece of arbitrary text, which is displayed by the user interface when a user wants to have more information on the attribute. The description can be given in different languages in the same way as the title.
- *Value type*. The value type of an attribute specifies the allowed values of the attribute. Value types are discussed in section 8.12.5.
- *Default value* and *copy action indicator*. Default values are discussed in section 8.12.8.

8.12.1 System Attributes

One of the main goals in the design of EDMS is a flexible database schema definition mechanism. The system itself only defines a minimal set of system attributes for the various object kinds (documents, document versions, etc.). For example, the system attributes of a document include document name, creation time, and the name of the user who has created the document.

8.12.2 Type-specific Attributes

As explained in the previous subsection, the EDMS administrator can define a number of object types. The main purpose of an object type is to define type-specific attributes for objects of that type. An object type definition therefore contains a list of attribute definitions. The previous subsection also explained that certain object kinds are related. For example, when creating the document type 'drawing', the administrator also creates subdocument type, a document version type and a sub-document version type with the same name. During the creation of a document type the administrator must therefore supply four attribute lists to specify the attributes of the document type, the attributes of the subdocument type, etc.

8.12.3 Common Attributes

In addition to the type-specific attributes, the administrator can define common attributes for each object kind. All objects of a particular object kind have the same common attributes regardless of the object type.

The system attributes and common attributes of an object kind are collectively called the *base attributes* of the object kind.

8.12.4 Object Types and Attributes Seen as a Hierarchy

The system and common document attributes and the different document types with their type-specific attributes can be regarded as a two-level type hierarchy with inheritance. The system and common attributes are attributes of the type 'document'. The different document types defined by the administrator can be seen as subtypes of the supertype 'document' and they can define their own attributes in addition to the "inherited" system and common attributes. Moreover, the supertype 'document' is an abstract supertype because no document object is directly an instance of this type. Instead, every document in the database must be of a particular document type.

An object thus has a set of base attributes determined by the object kind (e.g., 'document'), and a set of type-specific attributes determined by the object type (e.g., the document type 'drawing').

This view on document types and attributes immediately raises the question of a more generalised type mechanism with an arbitrary number of levels. As already mentioned, the issue will be discussed in section 14.1.5.

8.12.5 Attribute Value Types

The values that can be given to an attribute are determined by the value type of the attribute. The available value types include the types supported directly by SQL (integers, strings, dates, etc.) and some additional types.

Section 3.2.2.1 mentioned the idea of an 'attribute type', which would specify what information is needed in the definition of an attribute of a particular attribute type. EDMS does not have multiple attribute types in this sense because all attribute definitions specify the same information: attribute name, value type, default value, etc.

8.12.5.1 Numeric Value Types

Numeric value types include 32 bit integers and 64 bit floating point numbers. A numeric value type can optionally specify a minimum and maximum value for the attribute.

8.12.5.2 String Value Type

A character string value type must specify the maximum length of the attribute value.

8.12.5.3 Date and Time Value Type

The value of an attribute with the value type 'date' consists of year, month and day. The value of an attribute with the value type 'time' consists of year, month, day, hours, minutes and seconds.

8.12.5.4 Value Lists and List Item Value Types

If the value type of an attribute is 'list item', the value of the attribute is selected from a named *value list* created by the administrator. For example, the administrator can first define the value list 'languages' that contains the names of the available languages. A document type can then be defined to include an attribute with the value type 'list-item languages', which stores any available language name.

Each item in a value list consists of a string that is the actual attribute value, a string that describes the value, and an indicator that tells if the item has been deactivated. Consider an attribute with value type 'list-item L', and suppose an item with value 'X' in the value list 'L' has been deactivated. The database can now contain objects in which the value of the attribute is 'X' while it is impossible to give 'X' as a new value to the attribute.

8.12.5.5 User and Project Names

The value type 'user name' is similar to 'list item'. The value of an attribute of this type is the name of some user in the database. If the value type specifies an optional user type, the value of an attribute of this type is the name of a user of the specified user type in the database. If the value type does not specify a user type, the name of any user can be used as a value for the attribute.

Users can be deactivated in the same way as items in a value list. If a user has been deactivated, the name of the user can remain the value of an attribute but the name cannot be assigned as a new value to an attribute. A user cannot be deleted if the name of the user is used as the value of any attribute with the value type 'user name'.

Value type 'project name' is analogous to the value type 'user name'.

8.12.5.6 Long Text

A string attribute has a specific maximum length (e.g., 20 characters). An attribute of the value type 'text' can store a string of arbitrary length. The contents of a text attribute, however, cannot be tested in database queries because the underlying database system does not support this operation.

8.12.5.7 Collections

The value types discussed so far have been scalar types, which means that an attribute in a particular object stores a single value, such as a single integer or a single string. One of the most important advantages of EDMS over many other similar systems is the possibility to define the value type of an attribute to be a collection. This means that the value of an attribute can consist of multiple elements, and the type of the elements is one of the basic types described above. A single attribute can, for example, store multiple user names instead of a single name.

There are two kinds of collection attributes: sets and sequences. A set does not record the order of the elements, nor can it contain duplicates. A sequence is similar to a set except that the order of the elements in a sequence is maintained and duplicates are allowed.

8.12.5.8 Multilingual Strings

In a multilingual environment one also needs attributes that store text in multiple languages. For example, the title of a document may be given in Finnish and English. The system therefore has a special value type 'multilingual string'. The value of an attribute of this type is a set of strings, and each string in the set is of the form 'language:text' where language is an item from the value list 'languages'. For example, suppose that the title of a document must be stored in different languages. The corresponding attribute could be a multilingual string and the value of this attribute could be a set with strings "en:Lift cabin" and "fi:Hissin kori".

8.12.6 Case-Insensitive Search

An attribute stores a string value if its value type is 'string', 'list item', 'user name' or 'project name'. The definition of such an attribute can specify that the attribute allows a case-insensitive search. For example, if an attribute allows a case-insensitive search, for the string 'AB' it finds the values 'ab', 'aB', 'Ab' and 'AB' while an ordinary case-sensitive search only finds 'AB'.

8.12.7 Attribute Indexing

To make object queries faster, the administrator can create indexes on attributes. Indexes are created automatically on attributes that identify the objects. For example, document versions always have indexes on the document name and the version name.

8.12.8 Default Values

The administrator can specify default values for common and type-specific attributes. In fact, each common and type-specific attribute always has a default value, but the default value is a null value if the administrator has not specified any other default value.

When a user creates a new object and does not supply a value for an attribute, the attribute will usually have the default value. Nevertheless, sometimes a new object is partly created as a copy of an existing object. For example, suppose that a document version has an attribute for the language in which the version is written and another attribute for the name of the user who has approved the version. When a new document version is created as a child to an existing parent version, the value of the 'language' attribute should be copied from the parent version to the new version because the attribute probably has the same value in the new version as in the parent version. On the other hand, the value of the 'approved by' attribute should obviously not be copied. Instead, the attribute should have the default value (in this case null) in the new version.

This difference in the behaviour of attributes is specified in an attribute definition with a 'copy action' setting, which can be either 'default' (use the default value) or 'copy' (copy the attribute value if the new object is created as a partial copy of an existing object).

8.12.9 Attribute Management

The administrator can add new common and type-specific attributes to an existing database and its object types. Attributes can also be deleted.

The value type of an existing attribute can be changed if the new type is "compatible" with the old one. For example, the value type of an attribute can be changed from 'integer' to 'floating point number'. Moreover, the value type cannot be changed if the attribute value in any object is invalid for the new value type. For example, the maximum length of a string attribute can always be increased, but the maximum length can be decreased only if the current value of the attribute does not exceed the new maximum length in any object (that has the attribute).

8.12.10 Class Diagram for Attributes

A UML diagram and constraints for attributes are shown in figures 24 and 25. Note that an attribute can be associated with multiple default values because a common attribute, which is associated with an object kind, has a separate default for each object type of the object kind.

Constraint 1 says that an attribute is either a system attribute, a common attribute or a type-specific attribute. Constraint 2 says that all system and common attributes of an object kind must have different names. Constraint 3 says that all type-specific attributes of a particular object type must have different names. Constraint 4 says that a system attribute or a common attribute of an object kind must not have the same name as a type-specific attribute of any object type of the object kind. Constraint 5 says that a multilingual string attribute or a text attribute must always be a scalar attribute (i.e., cannot be a set or sequence). Constraint 6 says that an attribute default value is associated with a type-specific attribute or a common attribute. Constraint 7 says that if a default value is associated with a type-specific attribute, then the default value must be associated with the same object type as the attribute. Similarly, constraint 8 says that if a default value is associated with a common attribute, then the default value must be associated with an object type that is associated with the same object kind as the attribute. Finally, constraint 9 says that there cannot be multiple default values for the same object type and attribute.

[This page is left empty to place the following two figures on facing pages.]

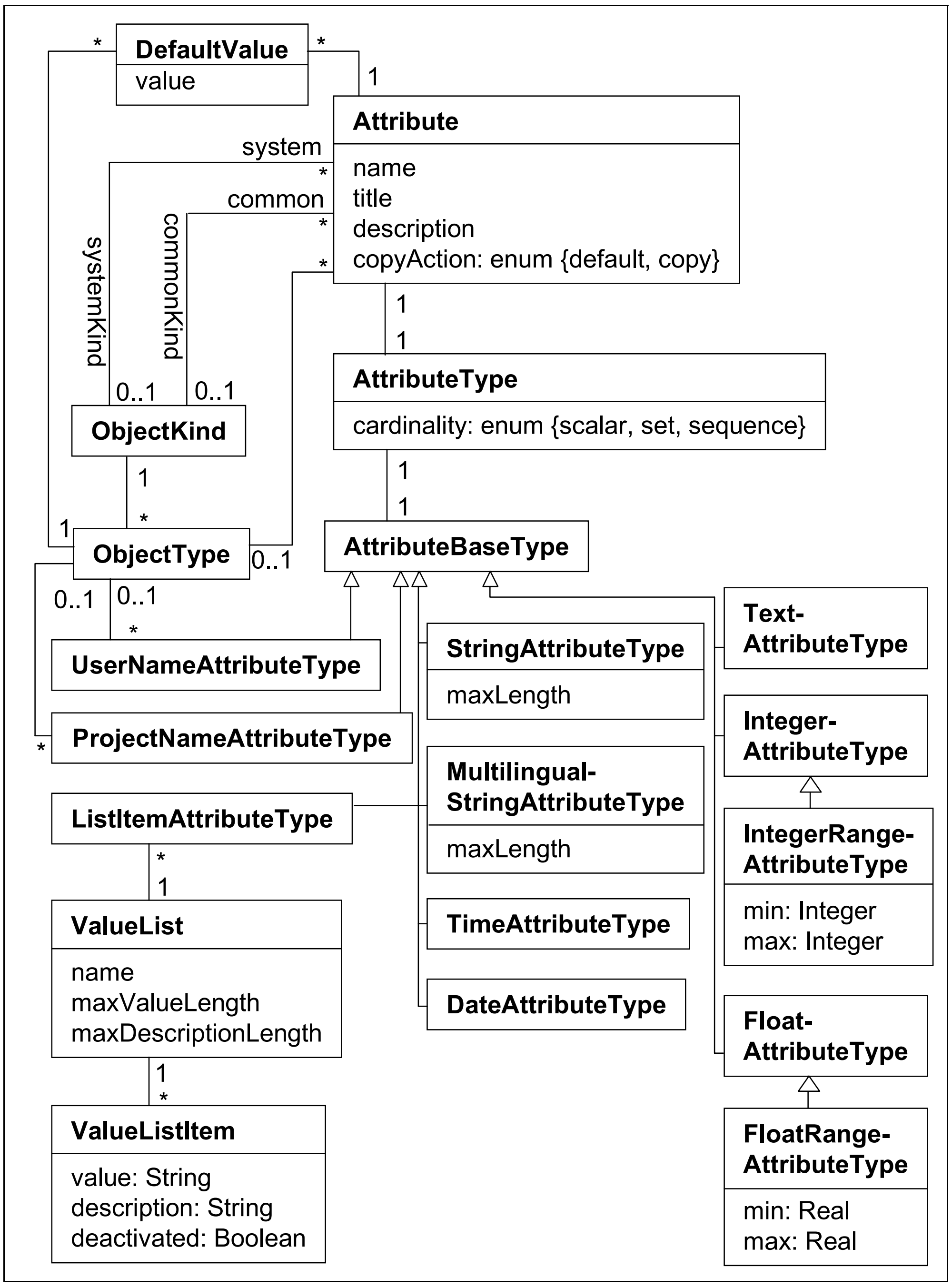


Figure 24. Class diagram for EDMS attributes.
Constraints are shown in figure 25.

```
Attribute
(1) self.systemKind->size + self.commonKind->size +
      self.objectType->size = 1

ObjectKind
(2) (self.system->union(self.common))->
        forAll(a1, a2 | a1 <> a2 implies a1.name <> a2.name)

ObjectType
(3) self.attribute->forAll (a1, a2 | a1 <> a2 implies a1.name <> a2.name)
(4) self.attribute->forAll (a |
        self.objectKind.system->forAll(s | a.name <> s.name) and
        self.objectKind.common->forAll(c | a.name <> c.name))

AttributeType
(5) (self.attributeBaseType->oclIsKindOf(MultilingualStringAttributeType) or
      self.attributeBaseType->oclIsKindOf(TextAttributeType)) implies
     self.cardinality = #scalar

DefaultValue
(6) self.attribute.objectType->notEmpty or self.attribute.commonKind->notEmpty
(7) self.attribute.objectType->notEmpty implies
        self.objectType = self.attribute.objectType
(8) self.attribute.commonKind ->notEmpty implies
        self.objectType.objectKind = self.attribute.commonKind
(9) DefaultValue.allInstances->forAll(d1, d2 |
        d1 <> d2 implies (d1.objectType <> d2.objectType or
                          d1.attribute <> d2.attribute)
```

Figure 25. Constraints for the attribute UML diagram

8.13 State Graphs

One of the main functions of EDMS is to support document life cycle processes, which typically involve formal approval and release procedures. In many companies these well-established procedures have been neglected after the introduction of CAD and other computerised document tools.

To model document life cycles, the administrator can define state graphs. Figure 26 shows the state graph for document versions at KONE.

In this particular graph the document version is initially in the state 'draft'. When the version is ready for checking, it is moved to the state 'ready'. If the version passes the check, it is moved to the state 'checked'; otherwise it is returned to the state 'draft' for corrections. Finally a checked document version must be approved before it is released for general use.

The definition of a state graph consists of a set of states, an initial state (which is one of the states in the set), and a set of pairs ⟨old, new⟩ where old and new are two

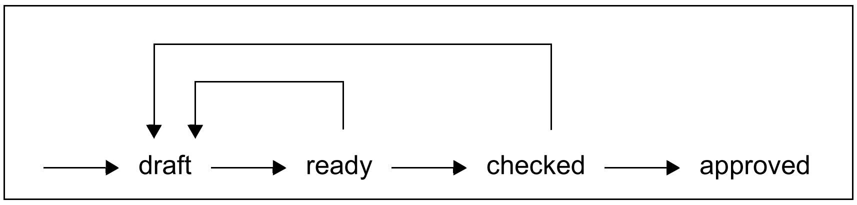


Figure 26. Sample EDMS state graph

states and which means that it possible to move from the state old to the state new. All states must be reachable from the initial state.

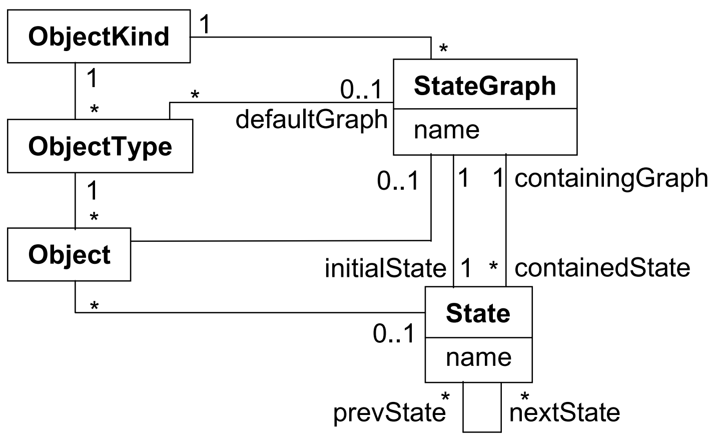
The state of a document version is important for determining which operations can be applied to it. For example, only a draft document version can be modified, and only an approved document version can be used as a parent for a new version. These rules are specified with an authorisation mechanism. The state graphs can thus be regarded as a simple workflow mechanism.

The previous state graph is defined for document versions. There can also be a separate state graph for documents as a whole. Furthermore, different state graphs can be defined for different document types. Actually, the state graph defined for a document type is only a default graph because it is possible to assign a particular graph to an individual document or document version regardless of its type. Nevertheless, this possibility has not been used at KONE.

Object kinds that support states have system attributes for the name of the state graph assigned to the object, the name of the current state, the time the object was moved to its current state and the name of the user who moved the object to its current state. At the moment states can be used with documents and document versions. It is easy to add states to other object kinds.

The system attributes only record the current state of an object. There is no built-in mechanism for recording a log of state transitions. A commit procedure (section 11.5), however, can be programmed to write an entry to a file or to the database when the state of an object is changed.

Figure 27 shows a UML diagram for state graphs. The numbers in parentheses in front of the constraints are not part of the actual constraints; the numbers are only for referring to the constraints in the following description. Constraint 1 says that if an object type has a default graph, the graph must be associated with the same object kind as the object type. Constraint 2 says that all state graphs must have different names. Constraint 3 says that all states in a particular graph must have different names. Constraint 4 says that the initial state of a graph must be one of the states of the graph. Constraint 5 says that all states of a graph must be reachable from the initial state. This constraint uses the non-standard extension of the constraint language described in appendix A. Constraint 6 says that the states that can be reached from a state in a particular graph must belong to the same graph. Constraint 7 says that an object is associated with a state graph if and only the object is also associated with a state. Constraint 8 says that if an object is associated with a state graph, the graph must be associated with the same object kind as the object. Constraint 9 says that if an object is associated with a state, the state must belong to the graph that is associated with the object. (Constraint 7 guarantees that the object is also associated with a state graph.)



```
ObjectType
(1) self.defaultGraph->notEmpty implies
      (self.objectKind = self.defaultGraph.objectKind)

StateGraph
(2) StateGraph.allInstances->forAll(g1, g2 |
        g1 <> g2 implies g1.name <> g2.name)
(3) self.containedState->forAll(s1, s2 |
        s1 <> s2 implies s1.name <> s2.name)
(4) self.initialState.containingGraph = self
(5) self.containedState->forAll(s |
        s = self.initialState or self.initialState.(nextState+)->includes(self)

State
(6) self.nextState->forAll(next | next.containingGraph) = self.containingGraph

Object
(7) self.stateGraph->notEmpty = self.State->notEmpty
(8) self.stateGraph->notEmpty implies
        (self.stateGraph.objectKind = self.objectType.objectKind)
(9) self.state->notEmpty implies
        (self.state.containingGraph = self.stateGraph)
```

Figure 27. Class diagram for EDMS state graphs.
Constraint 5 uses a non-standard extension described in appendix A.

9 Product Structures in EDMS

The original goal of the project was to develop a system for managing products and related documents. The project started with document management because of the more pressing needs and more easily definable requirements in this area. A model for products and product structures was developed only much later in the project.

Actually, two different models for product structures have been considered during the history of EDMS. Section 9.1 describes the first model, which is based on product revisions and variants. This model was developed according to the requirements of KONE and a preliminary implementation was included in the system. Nevertheless, these product structures were never used at KONE because the company bought the SAP R/3 ERP system, which will eventually store the product structures. However, as mentioned in section 5.5.2, the fact that a company uses an ERP system that stores product structures does not necessarily mean that a separate PDM should not deal with product structures. What is needed is a mechanism for sharing product structures between the two systems.

The model of section 9.1 contains no concept of configurable products or components with parameters. It is therefore of little interest for the further development of EDMS and is described here mainly as historical background to the more advanced model.

Section 9.2 outlines the second, more recent, model, which supports configurable products and is very similar to Generic Product Structures described by Erens (1996: sec. 4.3). Although the model has not yet been implemented, it has been developed in close co-operation with Rocla Oyj, a Finnish company that manufactures configurable battery-operated fork-lifts, and some real products of the company have been successfully described with the model. The currently specified product structures are mainly intended to represent the manufacturing structure of a product.

At the moment it seems that the implementation of product structures in EDMS will be based on the second model with the addition of many details and new concepts for managing product evolution. Preliminary ideas on this are given in section 9.2.9.

The configuration concepts in this chapter are simpler than those discussed in section 3.3.2. The more elaborate concepts are also being implemented by the Product Data Management Group. At least initially, however, this implementation will be independent of EDMS and will mainly serve as a research tool for investigating and demonstrating the concepts.

9.1 Product Revisions and Variants

The concepts of successive and alternative versions can also be applied to products and components. The product data model described here, however, is somewhat different from the document model. Whereas document versions in EDMS represent both the evolution and different variants of a document, components have separate object kinds for these two purposes. The evolution is represented with component revisions, and alternatives with component variants.

Typically the variants of a single component differ only in small details. If one considers a drawing or other description of the component, most of the description is common to all variants. Revisioning therefore treats all variants of the component as a single unit. When creating a new revision of a component, one actually creates new revisions of all variants of the component. A component thus has a number of revisions, and each revision has a number of variants, as illustrated in figure 22.

9.1.1 Parts

A fundamental property of components is that a component can have other components as parts, which can again have their own parts, etc. A component that has parts is called an assembly. The terms 'part' and 'assembly' are relative to the component being considered; a component can be a part in an assembly and at the same time be an assembly of lower level parts.

Different revisions and variants of a component can have different parts. Parts are therefore connected to component variants, which can contain a number of part references. Each reference specifies

- the part component (i.e., the component that is used as a part in the assembly component that contains the part reference),
- optionally the variant of the part component,
- the number of part instances, and
- an indicator that tells whether the part is compulsory or optional.

Roughly speaking, the variant of the part component must be specified if the part component has more than one variant.

The number of part instances is a positive integer and tells how many identical instances of the part component are included in the assembly.

A compulsory part is always included in the assembly (more precisely, in each instance of the assembly in a manufactured product), while an optional part can, but need not, be included in the assembly.

Figure 28 shows component 12345 with revisions A and B. Variant V3 of revision B has a single instance of component 45678 and two instances of component 7777 as parts. The first part reference further specifies variant V2 of the component; the second reference does not specify a variant because the revisions of component 7777 have only one variant.

9.1.2 Revision Resolution and Effectivity

A part reference does not specify the revision of the part component. When a product instance is manufactured, the part reference must be resolved, i.e., the system

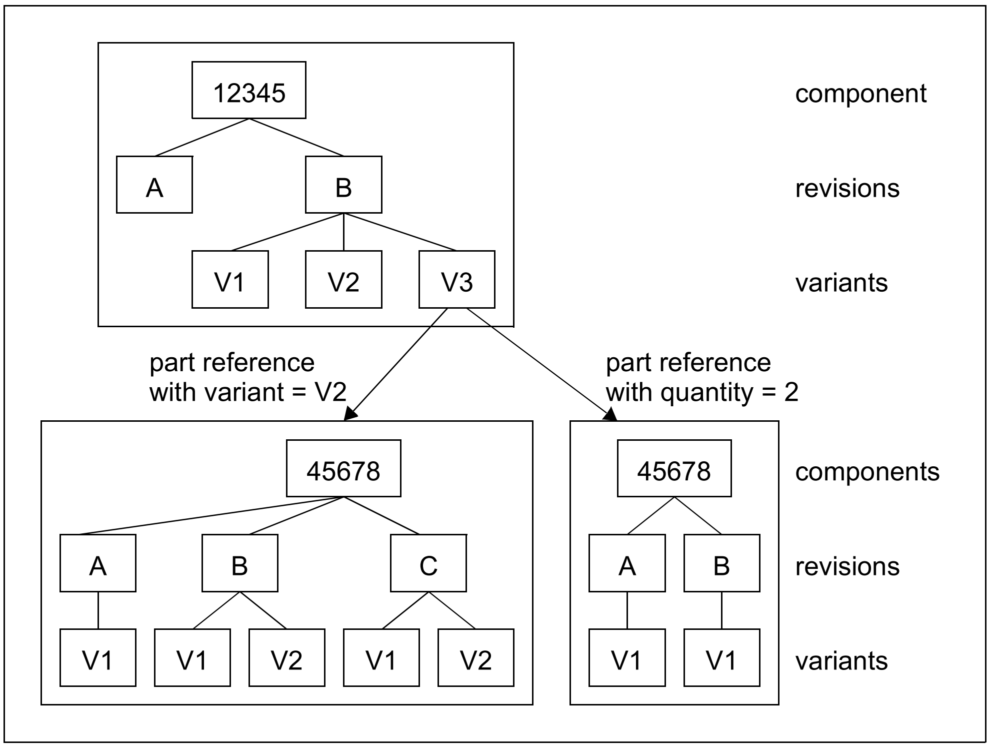


Figure 28. Component relationships in EDMS

must select proper component revision for the part components. The reference is resolved each time a product instance is manufactured, and the result depends on the available revisions at that time.

A simple (and probably simplistic) method for reference resolution is to use product revision effectivity. Consider a single component with revisions. In a simple model only one of the revisions is effective at any time. The effective revisions can, for example, be found using effectivity dates, i.e., each revision has an effectivity start date, and possibly also an end date.

Consider again figure 28 and suppose that the revision with the last letter in alphabetical order is always the effective revision of a component. The system can now be asked to generate the structure of variant V3 of component 12345. The effective revision of component 12345 is B. Variant V3 is thus selected from this revision. This variant has altogether three instances of two kinds of parts. The effective revisions of both part components are selected, yielding 45678/C and 7777/B. The first part reference also specifies variant V2. Variant V2 of revision 45678/C is thus selected.

Suppose that a new revision, D, of the component 45678 is created, and this revision no longer has variant V2. An attempt to resolve the part reference to component 45678 and variant V2 fails when the new revision becomes effective. Similarly, suppose a new revision of component 7777 has more than one variant. The part reference to product 7777 can no longer be resolved because it does not specify the variant to be selected from the effective revision.

9.2 Product Families

The simple model of the previous subsection will probably not be used as such in EDMS. Instead, product structures will be added according to the ideas presented in this subsection. The central concept is a product family, which is composed of generic items. A generic item is similar to a configurable product, and a particular variant of a generic item is generated by means of parameters, which are used for selecting correct parts from a conditional parts list.

The basic concepts of this model are by no means new (van Veen 1991; Schönsleben and Oldenkott 1992; Erens 1996). Nevertheless, even today few PDM systems seem to support configurable products properly.

Sections 9.2.1 to 9.2.5 describe a simple model in which parameters are associated with a product family as a whole. This model, however, is probably too simple. Sections 9.2.6 to 9.2.9 therefore outline a more realistic model in which parameters are associated with individual items. Section 9.2.10 contains a UML diagram of the model. Finally, section 9.2.11 discusses the limitations of the model.

9.2.1 Product Families and Product Variants

The product range of a company can be grouped into product families. A product family consists of product variants, which are in general similar to each other but at the same time differ from each other with respect to properties that can be specified by customers when they make orders.

Note that the term 'variant' is used here in the same sense as in section 3.3.2 in connection with configurable products. A product family can thus have thousands or even millions of variants, of which typically only a small percentage is ever manufactured. This use of the term 'variant' differs from sections 3.5.3 and 9.1 in which all variants of a product or other object are identified and stored explicitly.

Each product variant has its own variant structure, which consists of items arranged in the normal fashion into a hierarchical breakdown structure. Each item represents a physical component of the product variant, or work to be done to manufacture the product variant, or a document connected to the product variant.

When ordering a product from a product family, the customer must specify the desired properties of the product. A product family specifies both the input data needed for the generation of a variant structure and the rules for generating the variant structure from this data.

9.2.2 Sales Catalogues, Sales Items and Parameters

A product is ordered by means of a sales catalogue. A sales catalogue presents a number of alternatives and options to a customer, and the choices made by the customer guide the generation of a proper variant structure.

Ideally the choices available for customers would correspond directly to the physical components to be included in a product variant. Nevertheless, in practice the relation between the choices made by a customer and the components of a product are more complex. The generation of a variant structure is therefore based on parameters. A product family has a number of parameters, which must be given values before a variant structure can be generated. Parameters are discussed in more detail in the next subsection.

Moreover, the sales catalogue does not present parameters to a customer. Instead, the customer selects sales items from the sales catalogue. Each sales item specifies a value for one or more parameters. The rules that describe the generation of a variant structure refer to the parameters, not to the sales items.

One benefit of using sales items instead of parameters in a sales catalogue is that the sales catalogue can contain predefined "option packages", which specify values for multiple parameters in the same way as a set of separate sales items. As the variant structure is generated according to parameter values, it does not matter during the generation how the parameter values have been specified. Nevertheless, as prices are connected to sales items, the price of an "option package" can differ from the total price of corresponding separate sales items.

9.2.3 Parameter Lists

Usually a company has many product families with different parameters. Some parameters are specific to a single product family but some parameters are used in more than one family. To ensure consistent usage of parameters across product families within a company, a company has a global parameter list. The definition of a parameter is similar to an attribute definition (section 3.2.2.1) and specifies at least the name and value type of the parameter.

As all product families do not have the same parameters, each product has its own family-specific parameter list, which selects parameters from the global parameter list. When a product family selects a parameter for its parameter list, the product family can optionally restrict the value type so that the set of allowed values of the parameter within the product family is a subset of the allowed values in the original parameter definition in the global list. A product family can also specify a fixed value for a parameter, which means that the parameter always has this value within the product family and the value cannot be specified in a custom order.

9.2.4 Sales Catalogues

A product family is associated with one or more sales catalogues. As mentioned earlier, a sales catalogue consists of sales items, and each sales item specifies a value for one or more parameters. A sales item can give a value to a parameter only if the parameter is included in the parameter list of the product family and the family-specific parameter list does not specify a fixed value for the parameter. A sales catalogue can also specify default values for parameters that do not have a fixed value.

A sales catalogue can contain optional and alternative items. It is also useful if a sales catalogue can include additional validity constraints, such as 'optional item C can be selected only if optional items A and B are selected'.

All valid combinations of sales items selected from a sales catalogue must specify a unique value for every parameter of the product family that does not have a fixed or default value.

9.2.5 Parts Lists

When all parameters of a product family have values, it is possible to generate a variant structure. As already mentioned, a variant structure is a hierarchically arranged collection of items, which represent physical components, work and documents. A product family is associated with a particular item, called the root item of the product family, which represents the product as a whole.

Each item can have a parts list, which is basically very much like an ordinary parts list. Each row of a parts list thus contains a position code (e.g., a position number), the code of an item to be included as a part, and a quantity. However, an item and its parts list are generic in the sense that the variant parts list of an item depends on parameter values, which select a subset of all rows in the generic parts list of the item. To generate a variant structure, one creates a new empty structure, adds the root item and the items on its variant parts list to the structure, and then recursively processes the variant parts lists of the new items that were added to the structure.

A parts list of a generic item contains a number of positions, which are identified with the position codes on the rows of the parts list. A variant parts list, which describes a particular variant of the generic item, associates each position with exactly one item or no item at all.

One simple way to define a generic parts list is to include a selection condition on each row of the parts list. A selection condition is a logical expression that can refer to parameters and use comparison operators ('=', '<', etc.) and logical operators ('and', 'or', etc.). The meaning of a selection condition on a parts list row is that the row is included in the variant parts list only if the present parameter values satisfy the condition. The condition can also be missing, which means that the row is always included regardless of parameter values.

A selection condition on a row makes it easy to represent an optional component, which is either taken to a variant structure or left out depending on parameter values. To represent alternative components, the rows of a parts list are divided into groups, each of which is called a 'generic part'. All rows that constitute a single generic part have the same position code, and different generic parts must have different position codes. In other words, a generic part as a whole is associated with a single position code.

If a generic part contains a single row, this row can contain a selection condition if the part is optional and should only be selected with particular parameter values. If a generic part contains more than one row, each row must have a selection condition. As not more than one item can be associated with a position in a variant parts list, at most one selection condition within a generic part can be satisfied with any parameter value combination.

It must be possible to specify that with some parameter values no item is selected for the position associated with a generic part. There are at least two ways to do this. One possibility is to write the selection conditions within a generic part so that any parameter condition satisfies exactly one condition or no condition at all. In the latter case, no item is selected for the position.

This rule for selection conditions, however, has the drawback that a generic part does not explicitly specify whether the selection conditions are supposed to select exactly one item or whether the position can also be left empty. In other words, if particular values of the parameters do not satisfy any selection condition, it is impossible to know whether this is a mistake in the conditions or whether the position is left empty on purpose.

It therefore seems better to say that the parameter values must always satisfy exactly one selection condition within a generic part (unless the generic part contains a single row, which case is discussed shortly). To represent the case in which a position is to be left empty, a row in a generic part with multiple rows does not have to specify an item. If this kind of row is selected, the corresponding position in the variant parts list is left empty.

If a generic part contains a single row, and this row has a selection condition, it is not true that exactly one condition of a group is always satisfied. Nevertheless, the purpose of the rule "exactly one satisfied condition" is to distinguish between the cases "one of N alternatives" and "one or none of N alternatives", and this distinction is meaningful only if $N > 1$.

Given a combination of parameter values, it is easy to check that exactly one of the conditions within a group is satisfied. Nevertheless, in general it is impossible to check if all parameter value combinations satisfy exactly one condition. In other words, this kind of error in the parts list is not detected until a variant structure with particular parameter values is being generated.

In the approach described above, the selection of parts does not depend on the order of the rows. Sometimes the conditions would be simpler if the rows in a generic part were processed in the order in which they are specified in the parts list, and the row with the first satisfied condition was selected to the variant structure. Moreover, the last row could have the code 'otherwise' as its condition, meaning that this row is selected if the condition is not satisfied on an earlier row. In other words, the selection of a part would be similar to the ‘if-elseif-else’ construction found in many programming languages. Although this construction simplifies the selection conditions, it does not record explicitly the condition for selecting a particular part. Therefore, at least until practical experience is available, it seems better to have unordered rows and require that exactly one condition is satisfied.

In addition to an item code and an optional selection condition, a row in a parts list specifies the quantity of the selected item (e.g., ‘1 piece’ or ‘2 m’). The row can also specify a role for the selected part. For example, the role of a document can be ‘installation drawing’, ‘operating instructions’, ‘maintenance manual’, etc.

9.2.6 Item Parameters

The model outlined in the previous section associates all parameters with product families instead of individual items. An item is said to be used by a product family if the item is the root item of the family or the item is mentioned in the parts list of an item used by the family. In other words, a product family uses an item if the item can be reached from the root item by following the references on the parts lists.

Suppose a product family uses an item, and the parts list of the item has a selection condition that refers to a particular parameter. The parameter must then be among the parameters of the product family and it must be given a value when a product is ordered (unless the product family specifies a fixed value for the parameter).

This simple model assumes that all parameters correspond to properties that are specified in a customer order. Nevertheless, sometimes an item has a parameter, which is “internal” to the product so that it is unnatural to specify its value directly in a customer order. Instead, the value of the parameter depends on the values of other parameters.

It is thus better to associate parameters with individual items. Basically, an item can define a number of parameters. When a reference to an item B appears on the parts list of item A, the reference must assign values to the parameters of item B. The assigned parameter value can be specified as a constant or it can be computed from the values of the parameters of item A. Parameters that must be given a value when ordering a product from a product family can be represented as parameters of the root item of the product family. Parameter assignments correspond to conversion functions described by Erens (1996: sec. 4.3.9).

For example, item 111 in figure 29 defines parameters A and B. The parts list of item 111 contains two rows. The first row selects item 222 if parameter B of item 111 equals ‘X’. The second row unconditionally selects item 333 so that the value of parameter C of item 333 is always 1, and the value of parameter D of item 333 is computed from the value of parameter A of item 111.

Many details of this model are still open. For example, it may be convenient if the selection conditions on the parts list of an item can also directly refer to the parameters of “higher level” items that have this item as a part. This mechanism avoids the need to write parameter assignments that only copy parameter values from one level of product structure to lower levels. On the other hand, if the selection conditions in

item 111
parameters: A:int, B:choice{X, Y}
parts list

position	item	parameter assignments	selection condition
1	222		B = 'X'
2	333	C = 1, D = A + 2	

item 222
parameters: -

item 333
parameters: C:int, D:int

Figure 29. Example of a parts list with parameters

an item refer to the parameters of other items, the first item makes assumptions about the context in which it is used. This notion of items having access to a parameter defined by higher-level items in a product structure is called an external parameter by Erens (1996: 72, 138).

If an item has a (non-empty) parts list, the parameters of the item are used in selection conditions to select rows from the parts list. Parameters can also be used in parameter assignments to specify values for the parameters of the selected items. If, however, an item is primitive in the sense that is does not have a parts list, the item can still have parameters. In this case the parameters together with their values are included in the variant structure, which is used as a basis for manufacturing the product variant. For example, a product can contain a steel rod, which can be manufactured to an arbitrary length within certain limits and with certain precision (e.g., 100–200 cm in steps of 1 cm). The steel rod can be represented as an item that has a parameter for the length. The parameter is not used for selecting an appropriate rod from a predefined set of rods with different lengths. Instead, the value is included as such in the variant structure.

If items have parameters, one must also decide whether the items still select their parameters from a global parameter list. If not, two items can probably define parameters with the same name. If the selection conditions on a parts list can refer to the parameters of other items, as suggested in the previous paragraph, and two items can have parameters with the same name, a reference to a parameter must specify the item in which the parameter is defined in addition to the name of the parameter.

9.2.7 Parameters and Attributes

If items define parameters as described above, what is the relation between attributes defined by object types and parameters defined by items? One possibility would be to represent each item as an object type, which could then define the parameters of the item as attributes. In principle this could be an elegant solution because parameters could then be manipulated with the existing attribute mechanism. Nevertheless, a database would then contain thousands of object types, and as was discussed in section 5.2, the present implementation of object types and attributes is designed for a much smaller number of object types.

It thus seems that there must be a relatively small number of item types. Each item is an instance of some item type and has values for the attributes defined by the item type. Each item can then define parameters.

If a variant structure contains items that have parameters, the structure must actually contain an item instance, which has values for all parameters of the item. If an item does not have parameters, there is no difference between the item and its instances.

9.2.8 Global Parameter Assignments

The idea that parameters are associated with items instead of product families was motivated by the fact that it should be possible to determine the values of "derived" parameters on the basis of "primary" parameters, which are given values in a customer order.

There are other ways to compute parameter values from other parameters. Suppose that parameters are associated with product families as in the first model. Parts lists could be extended so that in addition to selecting items as parts, a row in a parts list could give a value to a parameter of the product family This kind of row would have the same kind of selection condition as rows that select items.

Now all parameters of the product do not have to be given values before the product variant is generated because additional values are determined while the parts lists are examined.

Although this model may seem a simple extension to the original model, it has problems. One problem is to ensure that all parameters that need a value have an unambiguous value. If a selection condition refers to a parameter, this parameter must have been given a value before the condition is tested. If a parameter has been given a value, either in the customer order or through a value assignment in a parts list, no parts list must try to give another value to the parameter. The "global value assignments" also make it impossible to have two instances of the same item with different parameter values in a single product variant.

9.2.9 Versioning within Product Families

The product family model outlined in this section must be extended by some mechanism to deal with the evolution of product families and the items they are composed of. No definite solution is proposed here, as even the details of the basic model without versioning are still open.

Before the versioning of items can be discussed, one must know what information is associated with an item and which part of this information, if any in addition to the item code, is common to all versions of an item and what information can differ between versions. If an item is associated with a set of parameters and a parts list, at least the parts list, and probably also the parameters, can be different in different versions of the item.

The two basic versioning concepts are revisions and variants, which are treated separately in the following discussion.

As a result of the parameters, an item has a number of "implicit" variants, which are generated with different combinations of the possible parameter values. In theory, this parameter-based variation could be combined with the "explicit" variants of section 9.1. Each variant of an item would have its own parts list, and a reference to an item in a parts list would specify both an item and its variant. In practice, however, this kind of model is only confusing because the same effect can be achieved with parameters. After all, the code for identifying different explicit variants is simply a parameter, which can be used in the parts list in the same way as other parameters.

As parameters take care of variants, the versioning of items is reduced to the question of dealing with revisions, which represent the evolution of items. Basically, the issues are very similar to those already discussed in section 9.1. An item consists of a sequence of revisions. Each revision has its own set of parameters and parts list. If a reference to an item on a parts list does not specify a revision, the reference is generic and must be resolved when the reference is encountered during the generation of a variant structure. The resolution can, for example, be based on revision effectivity.

A reference to an item on a parts list does not have to specify a revision. As different revisions of an item can have different parameters, it is possible that a reference that specifies a value to a particular parameter becomes invalid because the reference is resolved to a new item revision that does not have the parameter. Similarly, the new revision may have a new parameter, which is not given a value in the reference.

9.2.10 Initial Data Model for Product Structures

This section contains a data model for product structures in which parameters are associated with individual items. The model must be regarded as an initial version because it has not yet been implemented. The model does not support the idea that a selection condition could refer to parameters defined by items higher in the product structure. The model includes constraints for checking whether a reference to a particular item can be bound to a particular revision of the item as far as parameter assignments are concerned. Nevertheless, the model does not say anything about how the revision is actually selected.

Figures 30 and 31 show the initial UML class diagram for product family structures. Each item has a number of revisions. Each item revision can define parameters. A parameter definition associated with an item revision specifies a parameter and optionally a default value for the parameter.

An item revision is associated with a sales catalogue if the item represents a product that can be sold to customers. A sales catalogue contains sales item groups, which in turn consist of sales items. A sales item group specifies the minimum and maximum number of items that can be selected from the items in the group. For example, if the minimum number is 0 and the maximum number is 1, the group selects a set of alternative sales items from which a user can optionally select at most one item. Each sales item specifies a code and a price and assigns values to one or more parameters defined by the item revision. A sales catalogue can include constraints that further restrict the selection of sales items. The detailed format of the constraints is still unspecified.

Constraint 1 specifies the allowed range for the minimum and maximum number of choices in a sales item group. Constraint 2 says that a sales item cannot assign two values to a single parameter, and constraint 3 says that a sales item can only assign values to parameters that are defined by the item revision associated with the sales catalogue.

An item revision can also be associated with parameter constraints. Each parameter constraint is a logical expression (i.e., an expression that evaluates to true or false), which must be satisfied by the parameter values when the item revision is used in a variant structure. Each parameter constraint is associated with the parameters that the expression refers to. UML constraint 4 of figure 25 says that a parameter constraint can only refer to parameters defined by the item revision that the constraint is associated with.

An item revision is associated with zero or more generic parts, which together constitute the parts list of the item revision. Each generic part has a position code, and the generic parts in a single parts list must have different position codes (constraint 5). A generic part contains one or more parts, which correspond to the rows of a parts list. A part has a role as an attribute. Unless a part specifies that the corresponding position in the parts list should be left empty, a part is associated with an item reference. At least one part in a generic part must refer to an item (constraint 6), and if a generic part contains more than one part, all parts in the group must have a selection condition (constraint 7). A part specifies a quantity if and only if it also specifies an item (constraint 8).

An item reference specifies an item and assigns values to the parameters of the specified item. A parameter assignment in an item reference specifies a single parameter to which a value is assigned. The assigned value is specified by means of an expression that can refer to other parameters.

When a variant structure is created, an item reference is bound to some revision of the item specified in the reference. As different revisions of an item can define different parameters, the parameter assignments in an item reference are not necessarily valid for all revisions of the item specified by the reference (the validity rules are given shortly). The dashed line represents the association between an item reference and the item revisions that the reference can be bound to. This association is marked with a dashed line because an item reference does not directly specify the possible item revisions, and the association is not stored explicitly in the system. Instead, the validity of parameter assignments is probably only checked after an item revision has been selected as a “candidate” for the target of an item reference.

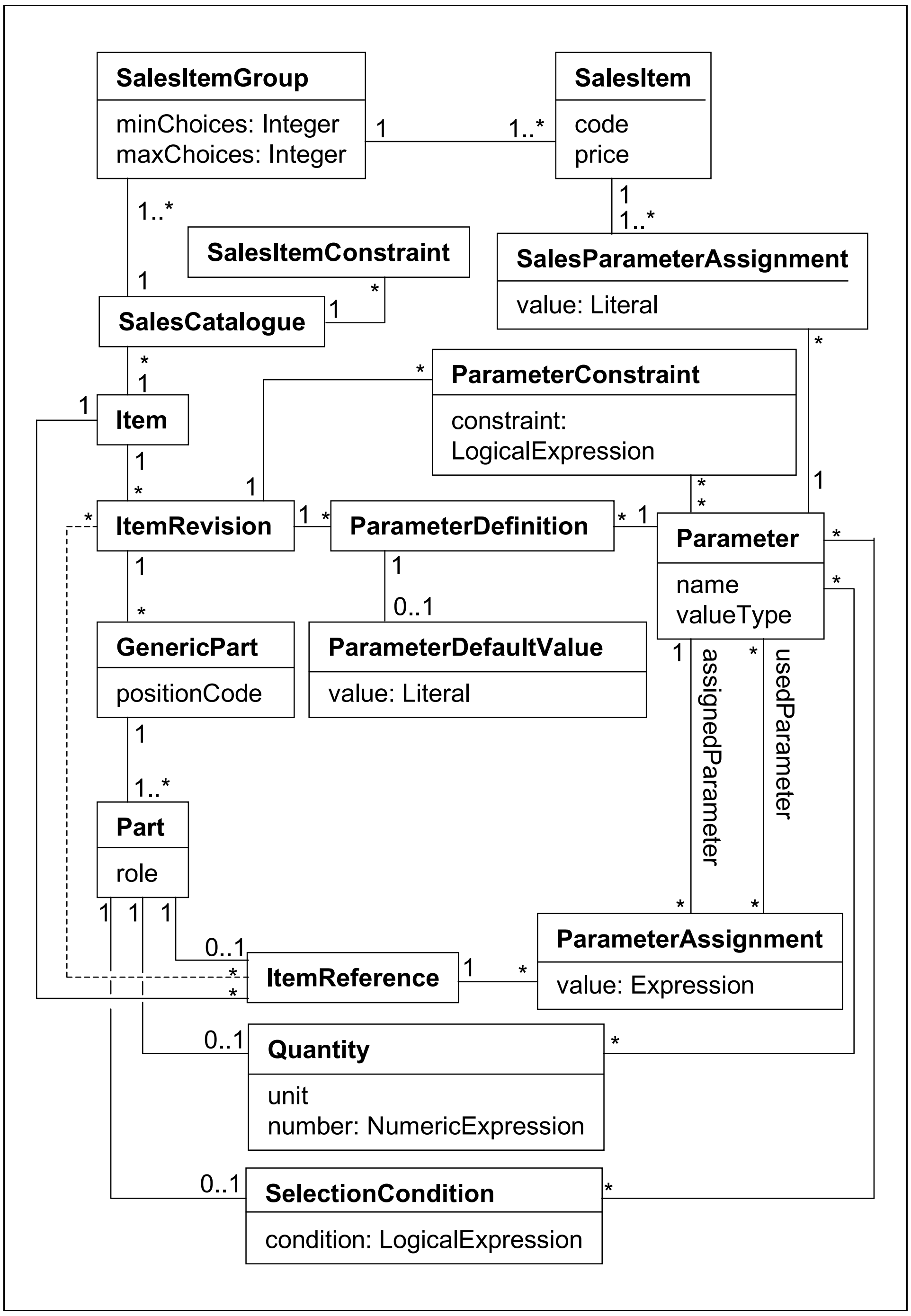


Figure 30. Initial data model for product structures in EDMS. The dashed line, which is not part of the standard UML notation, is explained in the text. Constraints for the diagram are shown in figure 31.

```
SalesItemGroup
(1) self.minChoices >= 0 and
    self.maxChoices >= self.minChoices and
    self.maxChoices <= self.salesItem->size

SalesItem
(2) self.salesParameterAssignment->forAll(a1, a2 |
       a1 <> a2 implies a1.parameter <> a2.parameter)

SalesParameterAssignment
(3) self.salesItem.salesItemGroup.salesCatalogue.itemRevision
      .parameterDefinition.parameter->includes(self.parameter)

ParameterConstraint
(4) self.ItemRevision.parameterDefinition.parameter
      ->includesAll(self.parameter)

ItemRevision
(5) self.GenericPart->forAll(g1, g2 | g1 <> g2 implies
                              g1.positionCode <> g2.positionCode)

GenericPart
(6) self.part->exists(p | p.itemReference->notEmpty)
(7) self.part->size > 1 implies
     self.part->forAll(p | p.selectionCondition->notEmpty)

Part
(8) self.itemReference->notEmpty = self.quantity->notEmpty

ItemReference
(9) self.itemRevision->forAll(r | r.item = self.item)
(10) self.parameterAssignment->forAll(a1, a2 |
       a1 <> a2 implies a1.assignedParameter <> a2.assignedParameter)
(11) self.itemRevision.parameterDefinition.parameter
       ->includesAll(self.parameterAssignment.assignedParameter)
(12) self.itemRevision->forAll(r |
       r.parameterDefinition->forAll(d |
         d.parameterDefaultValue->notEmpty or
         self.parameterAssignment.assignedParameter->includes(d.parameter)))

ParameterAssignment
(13) self.itemReference.part.GenericPart.itemRevision.
      parameterDefinition.parameter->includesAll(self.usedParameter)

Quantity
(14) self.part.GenericPart.itemRevision
      .parameterDefinition.parameter->includesAll(self.parameter)

SelectionCondition
(15) self.part.GenericPart.itemRevision
      .parameterDefinition.parameter->includesAll(self.parameter)
```

Figure 31. Constraints for the product structure UML diagram

Constraint 9 says that an item reference can be bound to a revision of the item specified in the reference. Constraint 10 says that an item reference cannot assign multiple values to a parameter. Constraint 11 says that an item reference can only assign values to parameters that are defined by the item revision that the reference is bound to. Finally, constraint 12 says that when an item reference is bound to an item revision, the item reference must assign a value to all those parameters defined by the item revision that do not have a default value.

The parameter value in a parameter assignment is specified with an expression that can refer to the parameters defined by the item revision that contains the part with the assignment (constraint 13). Similarly, the quantity and selection condition of a part can refer to the parameters of the item revision that contains the part (constraints 14 and 15).

In section 3.3.2, a configuration model was said to consist of an explicit structure, constraints and generation procedures. Constraints were further divided into specification constraints, implementation constraints and structural constraints. The EDMS product model represents the explicit structure as parts lists, generic parts and parts. Specification constraints are represented as parameter constraints. The EDMS model does not contain implementation constraints because the selection conditions should rather be interpreted as simple generation procedures. The model presented so far does not contain structural constraints either, but their possible addition to the model will be discussed shortly.

9.2.11 Limitations of the Parameter-Based Approach

The parameter-based method described in this section is straightforward and it should be suitable for the description of many configurable products. Nevertheless, the method has its limitations.

Section 3.3.2 on configurable products introduced (1) an explicit structure, which describes the unrestricted set of potential configurations, (2) constraints, which define the valid configurations within the set defined by the explicit structure, and (3) procedures, which help a user to create valid configurations.

The parameter-based approach to product families deals mainly with issues 1 and 3 above. The explicit structure is defined by the generic parts and the parts. The selection conditions define a simple mapping from parameter values, which represent the desired properties of a product variant, to a variant structure, which describes the components of a product variant.

Nevertheless, the parameter method provides no way to define explicit constraints for the variant structure. For example, it is impossible to specify that a single variant structure cannot contain both item A and item B, or that if a variant structure contains item C, it must also contain item D. It remains the responsibility of the author of the selection conditions to make sure that, for example, no combination of parameter values satisfies the selection conditions of the two incompatible items A and B.

It may be useful to add "structural" constraints, such as 'items A and B are incompatible' or 'item C requires item D', to the present model. These constraints make it possible to define additional validity checks for a variant structure, which is generated with the selection conditions. If the system notices that a variant structure violates a structural constraint, the system cannot do more than inform the user on the problem, which indicates an error in the selection conditions.

Obviously it would be better if the system could directly check the selection conditions, instead of individual generated variant structures, against the structural constraints. However, this task is difficult in the same way as the task of checking that every parameter value combination satisfies exactly one selection condition in each generic part.

The selection conditions are a straightforward way to define configuration procedures. If the product is simple enough, as many products are, this mechanism is probably quite good because of its simplicity. Nevertheless, there are configuration problems that cannot be solved with such means.

The parameter approach assumes that for any customer specification, represented with parameters, there is exactly one variant structure. However, there are products in which a specification can be fulfilled with a number of alternative product structures, and the final choice between the alternatives is made with some additional criterion, such as cost or delivery time, which may depend on the inventories and delivery times of different components.

In this case it is often impossible to write a "deterministic" procedure that generates the "best" configuration. Instead, the configuration must be searched for with "trial and error" methods, such as backtracking, investigated in artificial intelligence and logic programming.

10 EDMS Architecture Overview

The main components of the system are shown in figure 32. All data, including the representation contents, are stored in a commercial relational database. The database is accessed through the EDMS server program, which accepts service requests from client programs. The clients communicate with the server using a protocol developed for this purpose. The server is discussed in more detail in chapter 11. The most important clients include the 'access' program (section 12.1), graphical user interfaces (sections 12.2), an Application Programming Interface to integrate EDMS with document tools (section 12.3) and a Web server (section 12.4).

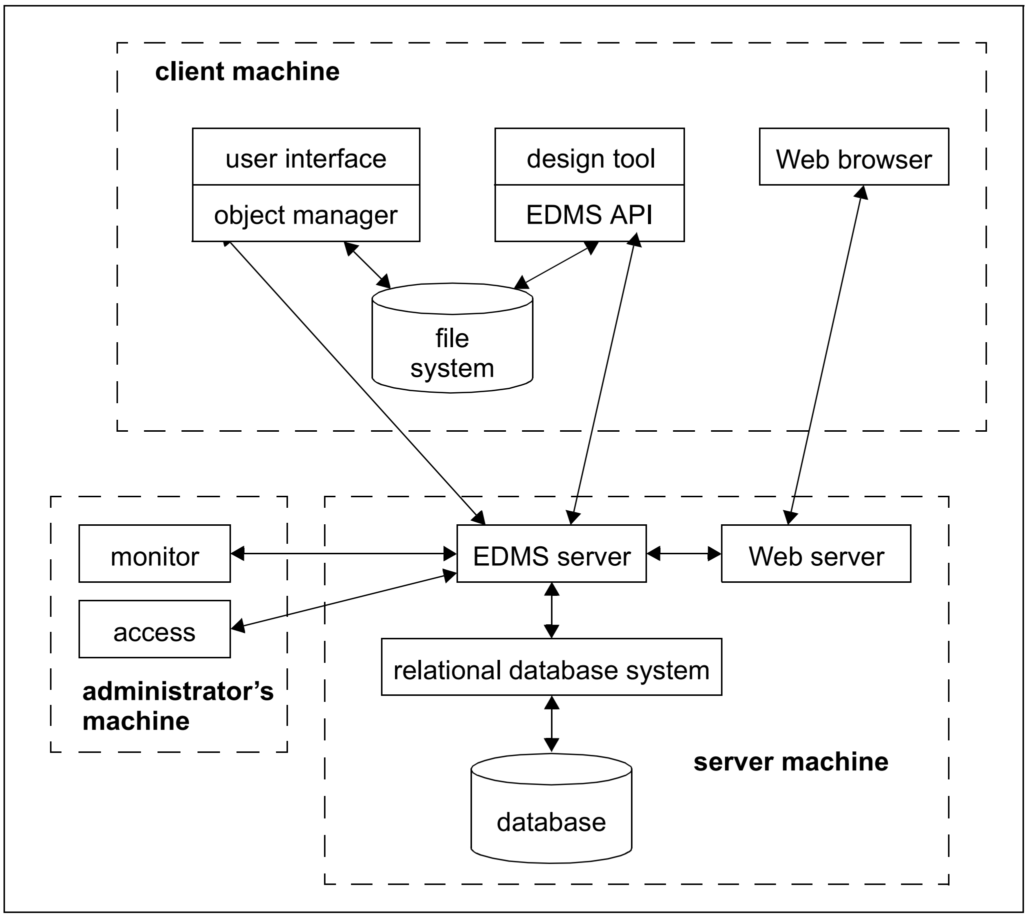


Figure 32. EDMS system architecture

In addition to clients, the server can also be contacted by 'monitor' programs, which send simple commands to the server. The monitor commands include commands for printing information about the clients that are currently connected to the server, and debug commands for setting the server in a mode in which it prints all service requests received by all clients or a selected client.

The client programs and monitor programs communicate with the server over TCP/IP socket connections. An encryption facility, such as SSL (Secure Socket Layer), will probably be added later.

11 EDMS Server

The server program implements the EDMS data model on a relational database. EDMS clients access the server by sending service requests defined in the server protocol.

11.1 Server Protocol

The server protocol defines about 120 requests and corresponding replies (Peltonen 1993). The communication between the clients and the server is synchronous. The server basically executes a loop in which it reads a request from a client, carries out the operation specified by the request, sends a reply to the client, and is ready to read the next request from the same or another client.

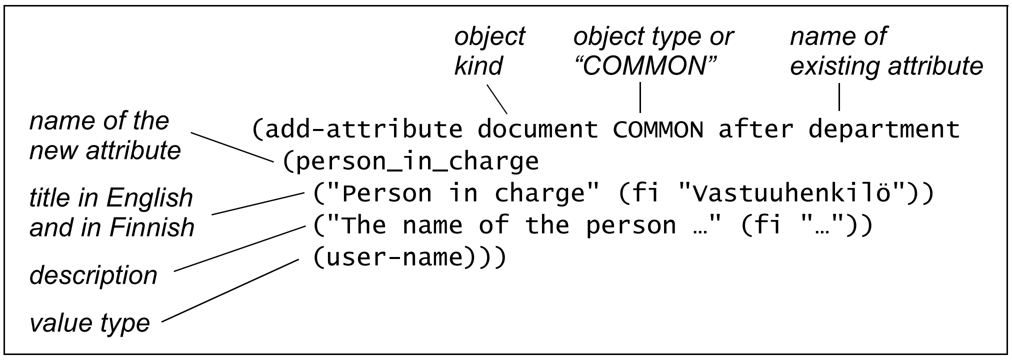
The protocol defines a new abstraction level on top of a relational database. All requests refer to the concepts of the EDMS data model, such as documents and document versions. The implementation of these concepts in a relational database is hidden within the server. If the present database is replaced with another database, the server has to be modified, but no changes are needed in the protocol. Since the user interface and other clients access the database through the protocol, the clients need not be modified either.

Set-valued attributes are a good example of the higher abstraction level of the protocol. The complexity of implementing sets in a relational database does not show up in the server protocol, which handles set-valued attributes in much the same way as simple attributes. The server protocol has proved very useful as an abstraction mechanism for concepts that are not found directly in relational databases but can be conveniently implemented in the server.

The requests and replies consist of plain text with a syntax similar to the Lisp language. Each request and reply is a parenthesised list that contains strings, numbers and parenthesised sublists.

11.1.1 Schema and Data Manipulation Requests

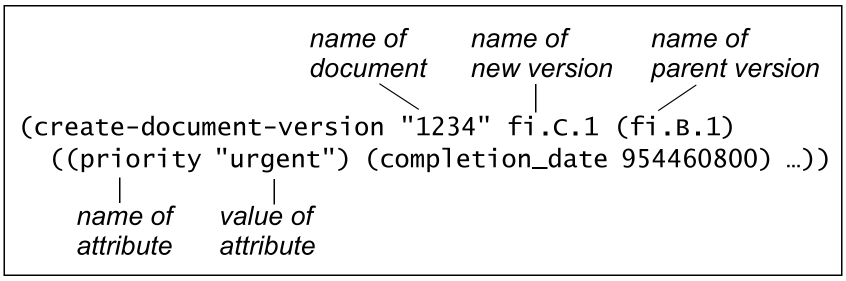
The protocol contains requests that modify and query the database schema, such as object types and their attributes, and requests that modify and query the actual data, such as documents and their versions. Figure 33 shows an example of a schema modification request, which adds a common attribute to documents. A type-specific attribute would be added by replacing the word ‘COMMON’ with the name of a document type. The attributes have a specific order, and the new attribute is added after an attribute with name ‘department’. The name of the attribute is ‘person_in_charge’, its title is ‘Person in charge’ in English and ‘Vastuuhenkilö’ in Finnish. The description of the attribute is also given in English and Finnish. The value type of the attribute is ‘user name’.


object kind
object type or "COMMON"
name of existing attribute
name of the new attribute
title in English and in Finnish
description
value type

```
(add-attribute document COMMON after department
 (person_in_charge
  ("Person in charge" (fi "Vastuuhenkilö"))
  ("The name of the person …" (fi "…"))
  (user-name)))
```

Figure 33. Sample schema manipulation request

Figure 34 shows an example of a data manipulation request, which creates a new document version. The version is created in document '1234'. The name of the new version is 'fi.C.1' and is created as a child to version 'fi.B.1'. The attribute 'priority' of the new version is given the value 'urgent'. The value type of this kind of attribute would typically be 'list item'. The attribute 'completion_date' of the value type 'date' is given the value '31 March 2000'. As can be seen from the request, date and time values are represented in the protocol in Unix format (seconds after 1 January 1970).



```
(create-document-version "1234" fi.C.1 (fi.B.1)
  ((priority "urgent") (completion_date 954460800) …))
```

Figure 34. Sample data manipulation request

11.1.2 Compound Requests

A single server request may involve several updates in the database. The server processes each request as a single database transaction. The database is thus never left in an inconsistent state after any failure during the processing of a request. Nevertheless, sometimes a single logical operation consists of several separate requests. For instance, the user interface provides an operation that creates a new document together with a subdocument and the first document version. This operation takes several requests: 'create document', 'create subdocument', etc.

It would be convenient for the server protocol to include a mechanism for executing an arbitrary sequence of requests as a single transaction. The protocol would include two new requests for starting and committing a transaction, and requests between these two requests would constitute a single transaction.

Unfortunately, it is impossible to implement this kind of mechanism with a normal database system. If the clients could start and commit transactions with separate requests, there could be several active transactions at the same time. However, the server is a single database application and the database systems usually allow each application to execute only a single transaction at a time.

Although separate requests for starting and committing transactions are infeasible, a simpler mechanism is included in the server. A request sent by a client to the server can be a *compound request*, which consists of a number separate requests that are executed as a single transaction. Figure 35 shows a compound request that corresponds to the operation ‘create document with structure’ in the user interface.

```
((create-document "1234" drawing (…))
 (create-subdocument "1234" main (…))
 (create-document-version "1234" fi.-.1 () (…))
 (create-subdocument-version "1234" fi.-.1 main (…))
 (lock-document-version "1234" fi.-.1)
 (create-representation "1234" fi.-.1 main CAD
                        primary CAD_rep (…))
 (unlock-document-version "1234" fi.-.1))
```

‘1234’ = document name	‘fi.-.1’ = document version name
‘drawing’ = document type	‘CAD’ = representation name
‘…’ = attribute names and values	‘primary’ = create primary rep
‘main’ = subdocument name	‘CAD_rep’ = representation type

Figure 35. Compound request

If a compound request fails, all its effects in the server and in the database must be rolled back. Database updates are easy to cancel because this operation is directly available as the database roll-back operation. It is, however, more difficult to roll back the modifications made in the internal data structures of the server application.

A compound request can therefore only contain requests that only update the database but do not modify any server data structures. In practice this means that compound requests can contain data manipulation operations (e.g., ‘create a new document’) but cannot contain schema manipulation operations (e.g., ‘create a new document type’).

11.2 Subservers

Most requests are executed “quickly”; more precisely, if access to a relational database through an indexed column is considered to take a constant time, most server requests are executed in roughly constant time. Some requests, however, can take a much longer time. The protocol includes a request for an arbitrary query. If the query contains a condition for an attribute that has not been indexed, the query has to make a sequential scan over the whole database. The check-out and check-in operations, which transfer representation contents between clients and the server, may also take a long time depending on the representation size and the data transfer rate between the client and the server. It would be unacceptable if the server did not accept any requests from other clients during these long operations.

This problem has been solved with subservers. Queries and copy operations are not executed directly by the server. Instead, the server launches a separate subserver process, which executes the time-consuming operations. Each client has its own subserver process. The process is started when the client sends the first request that requires the subserver and terminated when the client connection is closed. When the main server is started, one can specify the maximum number of concurrent subservers. If the server has to start a new subserver for a client and the maximum number of subservers has been reached, the server first terminates the subserver that has been idle for the longest time.

After the main server has forwarded a request to a subserver, the main server can process requests from other clients. To avoid conflicting access, the main server maintains a data structure that tells which representations are currently being copied by subservers.

The contents of an EDMS representation are copied from the database to a user's file with a check-out operation, and from a file to the database with a check-in operation. The copying can take a long time depending on the amount of data to be copied and the speed of the network between the server and the client. Representations are therefore copied by the subserver over a direct socket connection between the client and the subserver.

To reduce the amount of data to be transferred, the contents of representations are compressed with the publicly available 'gzip' program before they are transferred from the server to a client or vice versa. The contents are also stored in the database in the compressed format.

11.3 Server Notifications

In the basic client-server model the server sends replies to requests from the clients but never sends anything to the clients on its own initiative. The EDMS server, however, sends server notifications to the clients. A client can register an object, e.g. a document or a document version. When the server modifies the object, e.g., a document by creating a new version of it or a document version by locking it, the server sends a notification message to all clients that have registered the affected object. Server notifications are sent over a separate socket connection between a client and a server.

Server notifications are not sent for any schema modifications, such as the creation of a document type or modification of an attribute type.

Although this notification mechanism is elegant, its implementation is somewhat unreliable. It also seems difficult to make the new Java user interface client read the asynchronous notification messages over a separate socket connection. The present notification mechanism will probably be replaced with a simpler mechanism in which the clients receive the notifications as part of ordinary server replies. This means that a client does not become aware of the relevant modifications until the next time it sends a request to the server.

11.4 Authorisation Procedures

An engineering management system must include a flexible authorisation mechanism for specifying which users are allowed to perform various operations under various circumstances.

In the Unix operating system, each file is assigned to an owner, i.e., a user, and a user group. The owner of the file can specify read and write privileges separately for the owner, for the group and all other users. A much more flexible mechanism was needed for EDMS.

For example, whether a document version can be changed, depends not only on the user and the identity of the document, but also on the current status of the document version. As another example, suppose each document is assigned to a department and each department has a manager. One could then have a rule that a document version can only be approved by the manager of the department to which the document whose version is being approved has been assigned.

EDMS handles authorisation by means of an authorisation program. The program can contain an authorisation procedure for each server request that modifies the database. The procedures, which are written in a special language designed for this purpose, can read attribute values and make database queries (Peltonen et al. 1994a). In addition to modification requests, an authorisation procedure is executed when a user wants to have a read-only copy of the contents of a representation (i.e., a copy of a document file). Although the present authorisation mechanism cannot control users' rights to read individual attribute values, it is possible to define filter conditions, which completely hide particular documents and projects from particular users.

When the server is started, it reads the authorisation program from a file specified as command line argument. Whenever the server receives a request from a client, the server first executes the corresponding authorisation procedure, which must eventually execute either an 'accept' or a 'reject' statement. If the procedure executes a 'reject' statement, the server does not perform the operation requested by the client and sends an error reply, which includes an error message specified in the 'reject' statement.

As an example of authorisation procedures used at KONE, suppose document versions are associated with the state graph that was shown in figure 26 on page 120. The authorisation program should enforce the rule that a document version can normally be locked only when it is in the state 'draft'. As an exception, the user 'edms_admin' can lock a document version regardless of its current state. The rule would be described with the authorisation procedure in figure 36.

```
event lockDocVersion (user, version)
  if user = "edms_admin" then
    accept;
  end;
  if version.current_state = "draft"
then
    accept;
  else
    reject "must be in state 'draft'";
  end;
end;
```

Figure 36. Sample authorisation procedure

As a more complex example from KONE, consider the creation of a new document version in the versioning scheme that was illustrated in figure 19 on page 99. The authorisation procedure for document version creation does the following checks:

- If the new version with the name 'xx.Y.n' is created as a child to an existing parent version, the name of the parent version must begin with the same language code 'xx'.
- If the new version is created without a parent (i.e., as the first version of a new language), no existing version of the document is allowed to have a name that begins with the same language code as the new version.

The authorisation procedures are executed by the server when it receives a request from a client. For instance, suppose a user is creating a new document and enters attribute values in the 'create document' dialogue of the user interface. When the user has filled the dialogue, the user interface client sends a single 'create document' request with the attribute values to the server. The server then executes an authorisation procedure, which can check the attribute values and reject the request if necessary.

In addition to constructs for accessing the attributes of documents and other EDMS objects, authorisation procedures can query the database by means of arbitrary SQL 'select' statements. This mechanism allows the administrator to create additional tables with data that can be read by the authorisation procedures. The queries can also read the tables that contain the EDMS objects. Nevertheless, to read these tables, the administrator must know how the EDMS objects and attributes are represented as tables and columns in the relational database. It would of course be more convenient if the queries could be formulated in some "extended SQL" that would correspond more directly to the concepts of the EDMS data model (Keim, Kriegel and Miethsam 1993).

The authorisation procedures thus have the disadvantage that they cannot check anything immediately after the user has entered a value in the user interface. On the other hand, now that the authorisation procedures are implemented in the server, the procedures are always applied to all requests from all clients.

There are separate authorisation procedures for the data manipulation requests 'create document', 'create document version', 'change attribute values', etc. All schema manipulations, such as 'create document type', call a single authorisation procedure 'modifySchema', which has no other arguments than the name of the user that issued the request. Typically only the system administrator is allowed to modify the schema, and it is not necessary to distinguish between different kinds of schema modifications within the authorisation procedure.

Typically a graphical user interface allows a user to select an object and then displays the available operations as (activated) push buttons and menu items. Even when the user interface determines that a particular operation can be executed according to the general rules of EDMS, the operation may still be rejected by an authorisation procedure. A client can determine if an operation is available to the user by means of a request called 'check-request' that has another request as a parameter. When the server receives a 'check-request' request, it checks if the request given as a parameter could be executed. If not, 'check-request' returns the same error reply that would be returned by the parameter request; otherwise, the server returns 'ok' without actually executing the parameter request.

11.5 Commit Procedures

Commit procedures are similar to authorisation procedures. Whereas an authorisation procedure checks whether an operation is allowed, a commit procedure can modify attribute values. The name comes from the fact that the server executes these procedures immediately before committing a transaction, i.e., before storing the modified data permanently in the database.

At KONE, document versions have been defined to contain the attributes 'checked_by' and 'approved_by' that disclose the names of the users who have checked and approved the version. When a document version is moved to a new state, the commit procedure in figure 37 automatically updates the attributes as necessary.

Appendix B contains a more complex example of a real commit procedure used at KONE.

```
event changeState (user, obj, newState)
  if kind(obj) = "doc-version" then
    test newState
    when "draft":
      update obj.checked_by := NULL;
      update obj.approved_by := NULL;
    when "checked":
      update obj.checked_by := user;
    when "approved":
      update obj.approved_by := user;
    end;
  end;
end;
```

Figure 37. Sample commit procedure

Commit procedures, as well as authorisation procedures, can also send e-mail, write messages to a log file and insert log records into the database. This mechanism can, for example, be used for creating an audit trail of database updates.

11.6 User Authentication

While the purpose of an authorisation mechanism is to determine whether user 'xyz' is allowed to carry out a particular operation, the purpose of an authentication mechanism is to determine reliably that the person who logs into the system as user 'xyz' really is that person.

User authentication in EDMS is based on passwords. When a client program connects to the server, the client must first send a 'set-user' request, which specifies a user name and a password. The server then compares the password in the request with the password stored in the database.

When the server is started, one can optionally specify the address of a Windows NT authentication server and a domain name. In this case, the server first checks the password in the 'set-user' with the NT server. A user who has already been registered in the NT server thus does not need a separate password for EDMS.

11.7 Object Filters

Authorisation procedures only control operations that modify the database as well as the operation that copies the contents of a representation to a client for read-only use. However, a company may also want to restrict users' rights to see attribute values in the database.

In principle, an authorisation procedure could be called before the server sends an attribute value to a client. Nevertheless, if would be far too inefficient to call an authorisation procedure for every attribute of every object returned by a database query.

Although access to individual attributes cannot currently be controlled, the administrator can define *object filters*, which hide selected documents, users and projects from selected users. To define a filter, an authorisation procedure can call the built-in procedure ‘set_filter_condition’ with arguments that specify an object kind, optionally an object type, and a condition on the attributes of the specified object kind and type. (If object type is not specified, the filter applies to all objects of the specified kind.) As a result of the call, a filter condition is added to all queries on the specified objects in the client session in which the filter was defined. If the attribute values of an object do not satisfy the filter condition, the server behaves from the client’s point of view as if the object did not exist. An object that does not satisfy the filter condition is thus “hidden” from the client (with some exceptions discussed shortly). The procedure ‘set_filter_condition’ is usually called in the event procedure ‘userLogin’, which is always called at the beginning of a client session.

The filter condition is an SQL condition. The notation ‘$X’ within the condition refers to the attribute with the name ‘X’. If the attribute is a scalar attribute, ‘$X’ is replaced with a reference to the column that stores the value of the attribute. If the attribute is a collection attribute, ‘$X’ is replaced with a subquery that retrieves all elements in the value of the attribute.

As an example, suppose that documents have the attribute ‘classification’. If the value of this attribute in a document is ‘secret’, the document is hidden from a user unless the attribute ‘sec_clear’ (for “security clearance”) of the user has value ‘trusted’. Figure 38 shows the event procedure ‘userLogin’ that defines a document filter if necessary. The first argument of the event procedure is the name of a user, which is given as an argument to the function ‘user’, which returns the corresponding user object. The filter condition tests separately for a null value because in SQL a comparison yields ‘false’ for a null value.

```
event userLogin (userName, …)
  if user(userName).sec_clear != "trusted" then
    set_filter_condition("document", "",
                         "$classification is null or " +
                         "$classification != \"secret\"");
  end;
  accept;
end;
```

Figure 38. Sample object filter

If a document is hidden from a client, almost all requests behave as if the document did not exist. For example, a query on document versions does not find versions of a hidden document. Nevertheless, the existence of a hidden document is revealed to a client in the following cases:

- If a client tries to create a new object and a hidden object with the same name already exists, the server returns an error reply for duplicate name.
- Even if a user or project is hidden from a client, the client is able to assign the name of the user or project as a value to an attribute of value type 'user name' or 'project name'.

If a client tries to create a new object that would be hidden from the client, no object is created and the server sends an error reply.

11.8 Schema Maintenance

The administrator must perform various schema maintenance tasks, such as create new object types, add attributes, and add values to value lists. The administrator uses the 'access' program (section 12.1) and the server protocol as a simple "command language". For example, to add a new common attribute to documents, the administrator sends the 'add-attribute' request from figure 33 on page 141 to the server.

The system has no separate administrator's tool apart from the simple 'access' program by which one can send protocol requests to the server. A prototype of a graphical administrator's tool has been built as a student project, but the tool has not actually been used. The tool provided a graphical interface for the basic administration tasks, such as 'create a new attribute' or 'add a value to a value list'. Nevertheless, there has been no pressing need for this kind of tool because the server protocol directly serves as a simple "command language" interface.

There is thus no separate file that would describe the database schema (document types, attributes, value lists, etc.) as a whole. Instead, the schema is built incrementally from an empty database with the server requests 'create-document-type', 'add-attribute', etc. Nevertheless, if the requests are stored in a single file, the file is in effect a "schema definition file".

There is also a utility program that examines a database and prints the requests that would create a new database with the same schema. The same program can also print the schema in a more human-readable format.

The administrators at KONE have been technically competent and have not minded using the protocol directly with the 'access' program. In the future a proper graphical administrator's tool is probably necessary. The question also depends on whether these kinds of administration tasks will be carried out by the personnel of the end-user organisation or-possibly in the future-by a company that sells the system and configures it according to the requirements of the end-user organisation.

11.9 EDMS Objects in Relational Database

This section describes how the server represents the object types, attributes and other concepts in the EDMS data model in a relational database.

Section 5.2 described ‘fixed database schema’ and ‘dynamic database schema’ as two alternative ways to store object types and instances in a relational database. EDMS uses the latter approach. Basically each object type is represented as a table, and the attributes of the object type are represented as columns of the table. The tables are complicated by the “class hierarchy” with common and type-specific attributes and by the set and sequence valued attributes.

11.9.1 Object Types

As explained in section 8.12, all objects of the same object kind (e.g., ‘document’) have the same base attributes, which consist of the “built-in” system attributes and the common attributes defined by the administrator. Each object is of a particular object type (e.g., document type ‘drawing’) and has additional type-specific attributes also defined by the administrator.

EDMS stores each attribute in its own column. After this decision is made, there are three alternative ways to store objects in a relational database. In the first alternative, all objects of the same kind are stored in a single table, which has an additional column for the type of the object.[9] In the second alternative the base attributes and the system-specific attributes of an object are stored in separate tables. In the third alternative, actually used in EDMS, all objects of the same kind and type are stored in a single table with all attributes. All alternatives have their advantages and disadvantages.

As an example, consider a database with the document types ‘drawing’ and ‘manual’. Suppose that the only common document attribute is ‘department’; drawings have the type-specific attribute ‘paper_size’, and manuals have the attribute ‘no_of_pages’. For simplicity’s sake, consider only the system attributes ‘name’ and ‘create_user’ (the name of the user who has created the document). As all attributes have a scalar value type (i.e., not a set or sequence), they can be represented simply as table columns in the database.

In the first alternative, all documents with all attributes are stored in a single table. As illustrated at the top of figure 39, the table has columns for the base attributes and for the type-specific attributes of all document types. An additional column stores the type of the document. A document of a particular type is stored as a single row with the document type and the base attributes and the type-specific attributes in the appropriate columns. The columns for the type-specific attributes of other document

9. The author realised the existence of this alternative only from the slides of Michael Carey presented at a seminar on Post-Modern Database Systems at Berkeley on 27 January 1999 (‘http://db.cs.berkeley.edu/postmodern/stonelecture’, accessed on 3 September 1999).

types remain empty. Queries and other operations are straightforward in this alternative but storage space is wasted because of the many empty columns.

Alternative 1: All objects in a single table.
table 'documents'

name	type	create_user	department	paper_size	no_of_pages
1	drawing	John	manufacturing	A4	
2	drawing	Mary	maintenance	A3	
3	manual	Mary	sales		137

Alternative 2: Base attributes and type-specific attributes in separate tables.
table 'documents'

name	type	create_user	department
1	drawing	John	manufacturing
2	drawing	Mary	maintenance
3	manual	Mary	sales

table 'd_drawing'

name	paper_size
1	A4
2	A3

table 'd_manual'

name	no_of_pages
3	137

Alternative 3: All attributes of objects of the same type in a single table.
table 'documents'

name	type
1	drawing
2	drawing
3	manual

d_drawing

name	create_user	department	paper_size
1	John	manufacturing	A4
2	Mary	maintenance	A3

d_manual

name	create_user	department	paper_size
3	Mary	sales	137

Figure 39. Three alternative ways to store objects on tables

In the second alternative the documents are stored in three tables. The table 'documents' has a column for each base attribute and an additional column for document type. Each document corresponds to one row of this table. For each document type T there is table 'd_T' with columns for document name and type-specific attributes. For example, the middle of figure 39 shows how two drawings and one manual could be stored in the three tables.

In this alternative the attributes of a particular document are read with two queries. First the document type and the base attributes are read from the table 'documents'. The type-specific attributes are then read from the appropriate table.

A query over all objects of a particular kind is simple because the query can only refer to base attributes, which are stored in a single table. For example, to find all documents with particular values for the attributes 'create_user' and 'department', only the table 'documents' needs to be examined. On the other hand, to find all drawings with particular values for 'department' and 'page_size', it is necessary to make a more complicated query that joins the tables 'documents' and 'd_drawing'.

The bottom of figure 39 illustrates the third alternative, which is actually used in EDMS. This time only document names and types are stored in the "master" table. In the same as in the first alternative, there is a separate table for each document type. This time, however, a type-specific table, called an object table, stores all attributes. Each object table thus has the same columns for the base attributes and different columns for the type-specific attributes.

If only the name of a document is known, the type of the document is first retrieved from the 'documents' table, and all attributes of the document can then be retrieved from the appropriate object table. If the type of the document is known, all attributes can be retrieved directly from an object table.

Queries that were easy in the second alternative are now difficult and vice versa. To find all documents with particular values for some base attributes, it is necessary to make the same query separately in each object table. On the other hand, all documents of a single type together with all attributes are found in a single query, and the query can refer to both base attributes and type-specific attributes.

In the first and second alternative each attribute is represented with a single column. If an attribute is added or removed, or the type of an existing attribute is changed, it is only necessary to add, remove or modify a single column in a single table. In the third alternative the columns for the base attributes are repeated in all object tables for the object kind. If a common attribute is added, removed or changed, the corresponding column must be added, removed or modified in each object table.

11.9.2 Set and Sequence Attributes

Whereas scalar attributes can be represented directly as columns of the object tables, sets and sequences must be stored in separate tables.

The first column of each object table actually contains an integer called the object number. All rows in a table have a different value in this column.

Collection attributes (sets and sequences) are stored in separate tables. Each attribute has a unique attribute number. The values of a type-specific set-valued attribute are stored in the table 'set_999', where 999 is the attribute number. One column of the table stores the object number, while the other column stores one element of the attribute value.

Similarly, the elements of a type-specific sequence-valued attribute are stored in the table 'seq_999', where 999 is the attribute number. The table is similar to 'set_999' except for an extra column which records the order of the elements in a single attribute value.

The values of a common or system set-valued attribute are stored in separate tables for each object type. Values for a single type are stored in the table 'set_111_222' where 111 is the attribute number and '222' is the type number (each object type has its own internal number). Common and system sequence-valued attributes are stored in the table 'seq_111_222'.

11.9.3 Case-insensitive Search

If a string attribute is specified to allow case-insensitive search, an object table or table 'set_999' or 'seq_999' contains two columns for the attribute. The first column contains the attribute value as such, while the second column contains the attribute value in upper case letters. Whenever the attribute value is updated, the server updates the values in both columns. If a query condition for the attribute specifies case-insensitive search, the server changes the letters in the condition into upper case letters and then examines the column with the upper case values.

11.9.4 Representation Contents

The contents of a representation correspond to a document file which can be copied between the server and a client. To store the contents, an object table for representations has a column of the type 'Binary Large Object' (BLOB), which means that the column can store an arbitrary sequence of bytes.[10] Section 14.2.2 explains why this was not a good choice.

10. Within the server the contents of a representation are represented as a special system attribute, which is hidden from the client programs.

12 EDMS Clients

12.1 Access Program

The simplest client program is the ‘access’ program. The program simply reads protocol requests from standard input (i.e., keyboard) or from a file, sends the requests to the server, and prints the replies returned by the server. An example of the use of the program is shown in figure 40.

In addition to being an essential tool during the development of the system, the ‘access’ program also serves as a simple administrator’s tool (section 11.8).

```
% edms_access

request?
(create-value-list countries 2 40)
(
  "ok"
  ""
)

request?
(add-to-value-list countries "fi" "Finland")
(
  "ok"
  ""
)

request?
(add-to-value-list "se" "Sweden")
(
  "*ERROR*"
  "invalid-parameters"
)

request?
(add-to-value-list countries "se" "Sweden")
(
  "ok"
  ""
)

request?
*
%
```

Figure 40. Sample ‘access’ program session

12.2 User Interface

This project has again proved that the success of a program depends not only on the operations provided by the program but to a large extent also on the way these operations are made available through the user interface. A feature is worthless if the users do not know how to use it.

Users who enter new data and modify existing data in the database access the system through a graphical user interface client. Users who only read data from the database use the Web interface described in section 12.4. The user interface client allows a user to make more complex queries than the Web interface.

During its history, EDMS has had three user interface clients. The first graphical user interface was written in C++ for the X/Motif environment on Unix. The program communicated directly with the server. For example, whenever the user interface wanted to display the versions of a document, it sent a 'get-document-versions' request to the server.

The largest rewrite effort during the development of EDMS was made for the second user interface client. The client was divided into the object manager (the next subsection) and the actual graphical user interface. The second user interface was also written in C++ for X/Motif.

The biggest problem with the Motif user interface was that it only ran in Unix although people at KONE, like in many other companies, were increasingly moving to the MS Windows environment (Windows 95, 98 and NT). Some users also found the Motif user interface too complex. The current user interface is written in Java and can thus be used on a large range of platforms.

All EDMS user interfaces read the database schema from the server. No information on object types or their attributes (except system attributes) is present in the program code of the user interfaces. When the administrator adds a new document type or a new attribute to the database, the type or attribute automatically appears on the user interface the next time the user interface is started.

12.2.1 Object Manager

Both the second X/Motif user interface and the current Java user interface are based on an object manager, which communicates with the server using the server protocol and provides a higher level interface to the actual graphical user interface (figure 41).

The object manager of the X/motif client was a set of C++ classes. The object manager was rewritten in Java for the current client, but its structure has largely remained the same.

The object manager contains classes that represent the basic concepts of the data model, such as documents and subdocuments. The document class, for example, includes a method that returns a reference to the first subdocument within the document (represented by an instance of the subdocument class) and a method in the

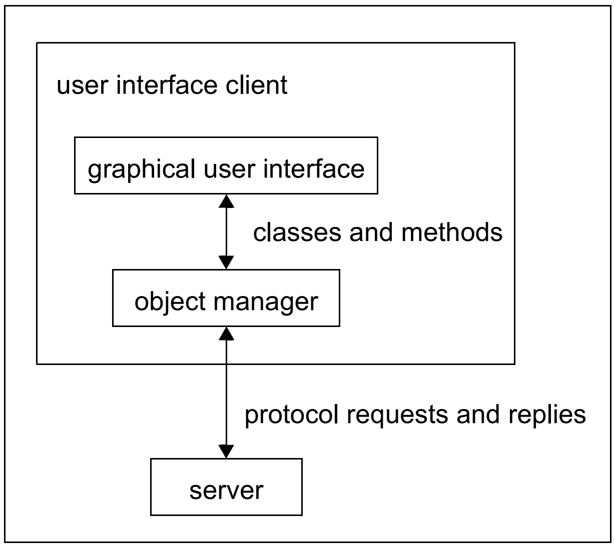


Figure 41. User interface client

subdocument class returns a reference to the next subdocument of the same document.

The introduction of a separate object manager has brought two important advantages: firstly, it is much more convenient for the actual user interface to access the document database using the classes than by sending the server requests directly. The user interface knows nothing about the server protocol and operates on a higher and more natural abstraction level.

Secondly, the object manager increases performance significantly by means of a cache mechanism. As an example, consider the retrieval of subdocuments. The document class has a variable that tells whether the names of the subdocuments of the document have already been retrieved from the server, and another variable that points to the first subdocument. When a new instance of the document class is created, the subdocuments are marked as unknown. The function that returns the pointer to the first subdocument checks if the subdocuments are known, and sends a request to the server only if the subdocuments are still unknown.

The obvious problem with this scheme is the maintenance of cache consistency. What happens when a client adds a new subdocument to a document whose subdocuments have already been retrieved in the cache of another client? The problem was solved in the X/Motif object manager with the server notification mechanism described in section 11.3. When an object manager inserted a document to its cache, it also registered the document with the server. When the server added a new subdocument to a document, it sent a server notification message to all clients that had registered the document. When an object manager received the notification, it marked the subdocuments of the affected document as unknown in the cache. The new subdocuments were thus not retrieved from the server until this information was needed.

As was already mentioned, server notifications are not used in the Java client. At the moment the object manager of the Java client provides an explicit ‘refresh’ operation on documents. The operation makes the object manager read the current data of the document from the server and is initiated manually from the graphical user interface. In the future there must be a more automatic mechanism, such as the “notifications in replies” mechanism that was outlined at the end of section 11.3.

Although the object manager was written for the user interface client, it can be used with any client that wants a Java class interface for the server. Alternatively, a client can use the much more primitive Application Programming Interface described in section 12.3.

12.2.2 X / Motif User Interface

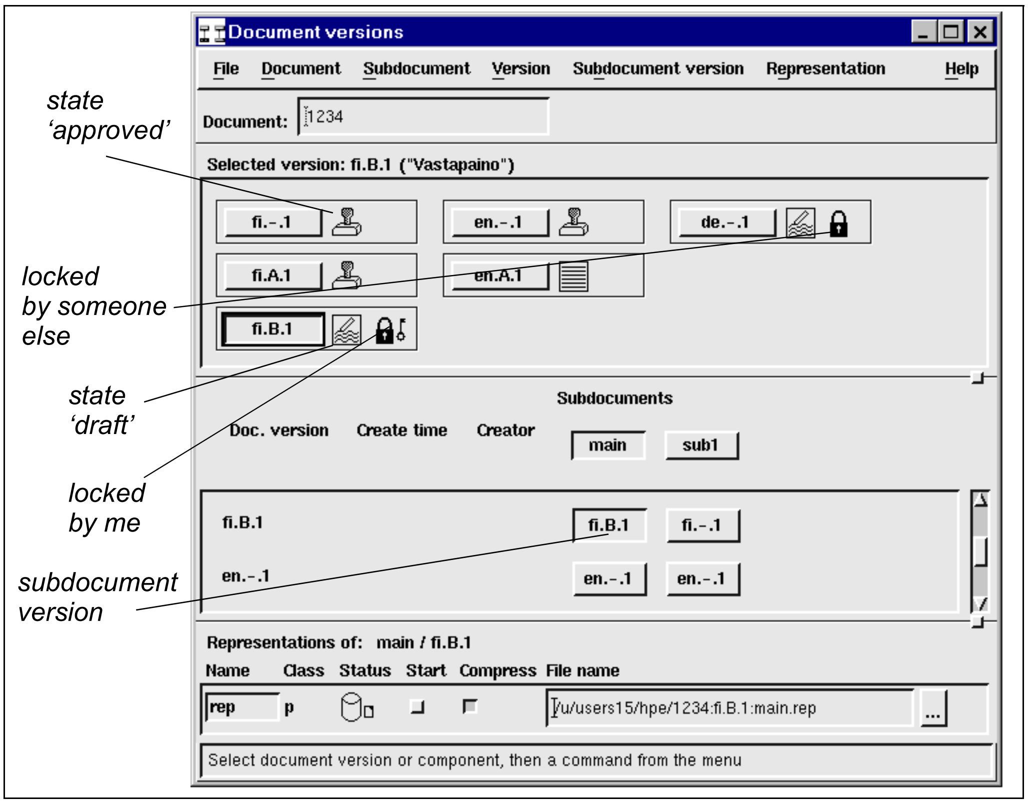
Figure 42 shows the most important window of the old X / Motif user interface. In this sample, the window shows document ‘1234’ with its six versions in three languages. The top pane corresponds to figure 19 on page 99 and shows the versions and their parent–child relationships. The icon next to the document version name indicates the state of the version. The lock icon next to version ‘fi.B.1’ indicates that the version is locked by the user running the system; a lock without a key next to version ‘de.-.1’ indicates that the version has been locked by someone else (the name of this user is available in one of the system attributes of the version). Incidentally, other people have come up with the same idea of representing version locking status with a picture of a lock with or without a key (Reichenberger 1995: fig. 3.6-1).

The middle pane shows the subdocuments and the composition of the document version. For example, document version ‘fi.B.1’ contains versions ‘fi.B.1’ and ‘fi.-.1’ of subdocuments ‘main’ and ‘sub1’, respectively.

The bottom pane shows the representations of the selected subdocument version. The icon under the heading ‘status’ indicates that the contents of the representation are currently checked out.

Figure 43 shows the attribute window that the user interface generates automatically from the attributes that are defined in the database. For each object type, a user can select a subset of the attributes of the object type. When the attributes of an object of a particular type are displayed, the user can choose whether the user interface displays all attributes of the type or only the selected ones.

The attribute list always displays the system attributes, the common attributes and the type-specific attributes in this order. Within each group the attributes are displayed in the order specified in the database. The administrator can change the position of a common or type-specific attribute in the database with a server request. A user, however, cannot have the attributes displayed in his or her personal order.



Document: 1234

Selected version: fi.B.1 ("Vastapaino")

Doc. version | Create time | Creator

fi.B.1

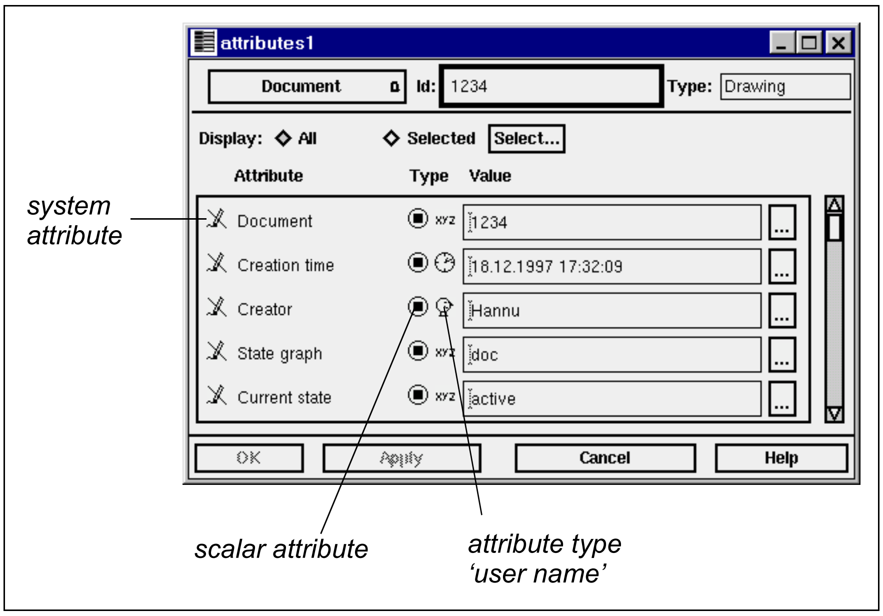
en.-.1

Representations of: main / fi.B.1

Name	Class	Status	Start	Compress	File name
rep	p				/u/users15/hpe/1234:fi.B.1:main.rep

Select document version or component, then a command from the menu

Figure 42. Version window in the old EDMS user interface



Document Id: 1234 Type: Drawing

Display: ◇ All ◇ Selected

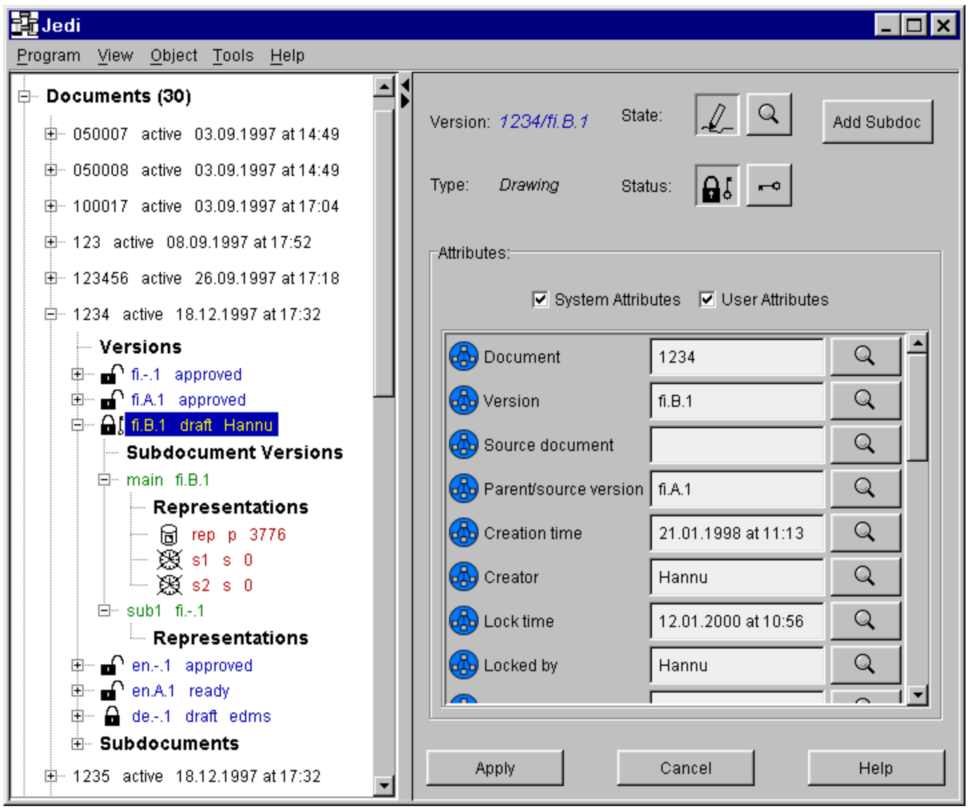
Attribute	Type	Value
Document	xyz	1234
Creation time		18.12.1997 17:32:09
Creator		Hannu
State graph	xyz	doc
Current state	xyz	active

Figure 43. Attribute window in the old EDMS user interface

12.2.3 Java User Interface

The main advantage of the Java user interface is that it runs on a large number of platforms, including Windows and various Unix environments. The new client is a Java application instead of an applet that could be started from a Web browser. The client is not an applet because the check-out and check-in operations must read and write files on the machine that runs the client program, and a Java applet is not allowed to perform local file operations. There were also doubts that it might be too slow to load the client as an applet over a network.

Although the object manager was only rewritten in Java for the new client, the new graphical user interface was written from scratch. The new interface has far fewer windows than the old one, and the main window uses the familiar "outline" presentation to display documents and their version, subdocuments, etc. Figure 44 shows the versions and subdocuments of the same document '1234' that was shown in figure 42 on page 158.



```
Documents (30)
  050007  active  03.09.1997 at 14:49
  050008  active  03.09.1997 at 14:49
  100017  active  03.09.1997 at 17:04
  123  active  08.09.1997 at 17:52
  123456  active  26.09.1997 at 17:18
  1234  active  18.12.1997 at 17:32
    Versions
      fi.-.1  approved
      fi.A.1  approved
      fi.B.1  draft  Hannu
        Subdocument Versions
          main  fi.B.1
            Representations
              rep  p  3776
              s1  s  0
              s2  s  0
          sub1  fi.-.1
            Representations
      en.-.1  approved
      en.A.1  ready
      de.-.1  draft  edms
    Subdocuments
  1235  active  18.12.1997 at 17:32
```

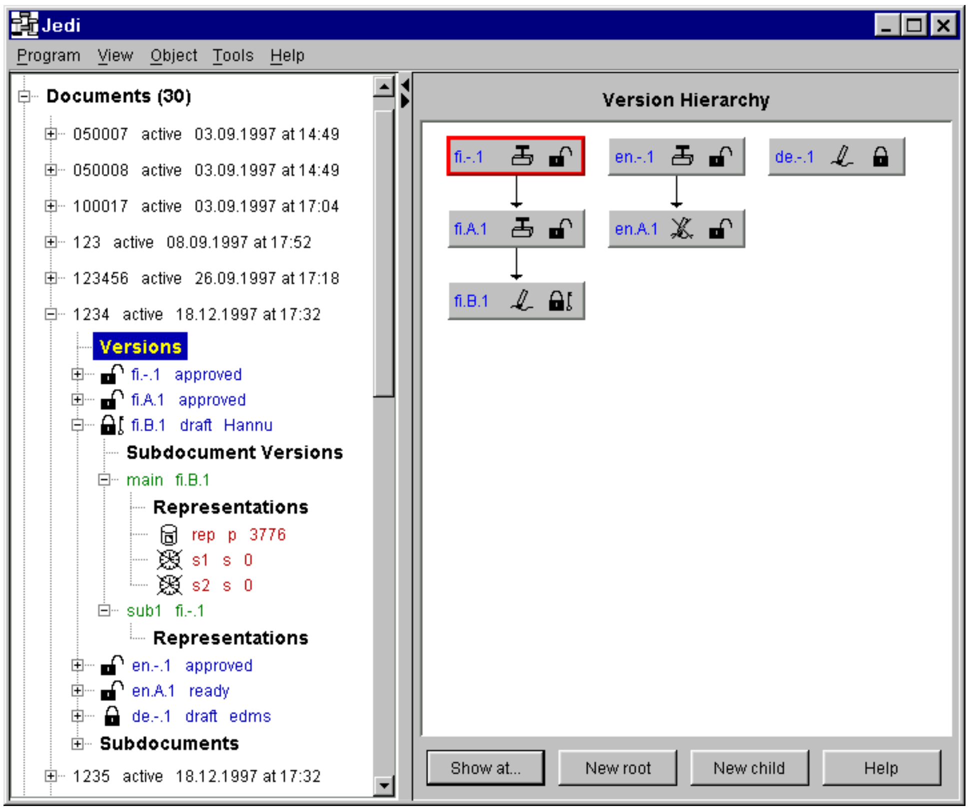
Version: *1234/fi.B.1* State:
Type: *Drawing* Status:

Attributes:
☑ System Attributes ☑ User Attributes

Document	1234
Version	fi.B.1
Source document	
Parent/source version	fi.A.1
Creation time	21.01.1998 at 11:13
Creator	Hannu
Lock time	12.01.2000 at 10:56
Locked by	Hannu

Figure 44. New EDMS user interface

The “outline” displays all versions of a document as a list on the same level. When the user presses the text ‘Versions’, which appears in bold above the list of versions, the right hand side of the window displays the actual version structure of a document (figure 45).



```
Documents (30)
  050007  active  03.09.1997 at 14:49
  050008  active  03.09.1997 at 14:49
  100017  active  03.09.1997 at 17:04
  123  active  08.09.1997 at 17:52
  123456  active  26.09.1997 at 17:18
  1234  active  18.12.1997 at 17:32
    Versions
    fi.-.1  approved
    fi.A.1  approved
    fi.B.1  draft  Hannu
      Subdocument Versions
      main  fi.B.1
        Representations
        rep  p  3776
        s1  s  0
        s2  s  0
      sub1  fi.-.1
        Representations
    en.-.1  approved
    en.A.1  ready
    de.-.1  draft  edms
    Subdocuments
  1235  active  18.12.1997 at 17:32
```

Figure 45. Document version display in the new EDMS user interface

Initially there was concern about the execution speed of Java programs. Although the Java implementation techniques are improving, the dynamic nature of Java may make it inherently slower than more static languages, such as C++ (Tyma 1998). Nevertheless, the speed of the Java client seems adequate on today’s powerful PCs.

12.2.4 User Interface Scripts

The X/Motif user interface was linked with the publicly available Tcl (Tool Command Language) interpreter (Ousterhout 1994). The administrator was thus able to write Tcl scripts for typical operation sequences within the user interface.

Tcl scripts could be executed by the user through menus. Some user interface operations automatically called functions that were defined in a Tcl file that was read by the user interface program when the program started. For example, when the user interface copied the contents of a representation into the database, the program tried to call the Tcl function ‘copy_in_callback’ that could be defined in the Tcl file. As mentioned in section 8.5.2, at KONE Elevators this feature was used for the automatic generation of secondary representations of documents created with a desktop publishing program.

The Tcl scripts of the X/Motif user interface cannot be used in the Java user interface. Instead, the EDMS administrator can write additional Java methods, which are called from the “main” user interface. The dynamic code loading mechanism in Java means that the administrator can add new methods to the user interface application without having access to the source code of the whole application.

12.3 Application Programming Interface

The EDMS Application Programming Interface (API) is a function library written in the C language for Unix and Windows NT environments. The API allows an application, such as a CAD program, to communicate with an EDMS server by calling C functions instead of sending and receiving protocol requests and replies directly.

The API is much simpler than the object manager of the graphical user interface. Most functions correspond directly to protocol requests. The library does have any cache mechanism, and at the moment there are no functions for schema queries, such as ‘get information on all attributes of document type XYZ’.

It is easier to call C functions than to use the protocol directly. As the parameters of the requests are represented as C data structures, the application does not have to convert data between the internal representation in a C program and the external representation in the protocol. Moreover, when API functions are used, the correct number of parameters and their types are checked when the application is compiled. If a program uses the protocol directly, this kind of error is not detected until the application is executed.

12.4 Web Server

KONE has written a Web server that allows users to view EDMS documents from a Web browser. Users can make queries to find documents and then view the attributes and contents of the latest approved versions of selected documents in different languages. The Web server accesses the EDMS server in the same way as other EDMS clients.

A tool-specific viewer program is only used for CAD drawings. Other documents, which are mainly made with FrameMaker or have been scanned, have a representation in Portable Document Format (PDF). This simplified the implementation of Web clients because usually only a PDF plug-in was needed in addition to the standard browser.

The EDMS Web server is implemented as CGI scripts written in the Tcl language. The present Web pages and scripts are partly based on the database schema at KONE and can only be used with a database that contains particular object types and attributes. The server will probably be rewritten in generic form to remove dependencies on any particular database schema. It is still unclear whether the new server will be based on the existing Tcl scripts or whether a completely new implementation will be made as a Java servlet.

12.5 Tool Integration in EDMS

The actual document contents (more precisely, the contents of representations) are manipulated with various tool programs (e.g., CAD and DTP). The term 'tool integration' refers to the means by which the document management system and the tools work together.

The basic mechanism for accessing document contents is to employ the check-out and check-in operations of the EDMS user interface. Check-out copies the contents of a representation from the database to an ordinary user's file which can then be manipulated with tools like any other file. Check-in is the reverse operation; data is copied from user's file the database as the new contents of a representation. After a file has been copied in, the original file should no longer be modified because the "master" copy of the file is now in the database. To prevent accidental modification of the file, the user interface can optionally remove or rename the original file after a successful check-in operation.

During a check-out operation the user can ask the user interface to start an appropriate tool for the document. Representations have a 'tool command' attribute for this purpose. After check-out the user interface executes a command formed by the value of the tool attribute followed by the name of the file to which the contents of the representation were copied. Typically the value of the tool attribute is a simple name of a command script that actually starts the tool program with proper options and environment settings.

It might be better to replace the tool command attribute with an attribute that would tell the file format of the representation contents. There would then be a separate mechanism for specifying which tool to start for a particular file format.

Once a tool program has been started a user should be able to perform check-in and check-out operations directly from the tool without having to switch between the tool and the EDMS user interface. In some tool programs it is possible to add new push-button and menu items that execute user-defined commands. These commands could for example be simple EDMS client programs for check-in and check-out operations.

Tighter integration between a tool and EDMS is possible by means of the EDMS API library (section 12.3), which was supplied to the company that has developed the CAD program used by KONE. The company then made a special version of the CAD program that communicates directly with the EDMS server.

Many attributes that KONE have defined for EDMS documents and related objects correspond to values that are already stored in CAD drawings. During check-in and check-out, the special version of the CAD tool also copies these values between the CAD drawings and the EDMS database.

One possibility for further integration between EDMS and document tools would be to add an ODMA interface (section 5.5.1) to EDMS.

13 Additional Applications Based on EDMS

KONE has built additional applications on top of the basic system. Although they are described very briefly here, they are very important because it is these kinds of applications that typically produce the concrete financial benefits from a PDM system.

13.1 Document Indexing

KONE has added a full text search capability to the system. A program regularly scans the database for representations with contents in the PDF format. The program creates a text file from the PDF file using publicly available tools and processes the text file with the publicly available Harvest system (Bowman et al. 1995), which creates a search index for the files. After the index has been created, all documents that contain a particular word can be found with the Harvest search program.

13.2 Document Subscription Service

A Web service allows a user to subscribe to documents. The system checks the document database at regular intervals selected by the user (e.g., once a week). If the database contains a new approved version of a document subscribed to by the user, the system sends an e-mail message to the user, who can then load the new document version via the Web if necessary.

13.3 Document Collection Application

Each delivery of a lift order includes a large amount of various documents. KONE Elevators are building a separate application that helps users to collect and print the documents for a particular order. The user still has to select the documents, but the application automatically finds the correct versions and representations from the database. In addition to printing the documents, the application also generates and prints a cover page, separator pages between sections, and tables of contents.

14 Evaluation of EDMS

This chapter contains a brief evaluation of EDMS. The evaluation is mainly based on the experiences at KONE and identifies strengths and weaknesses of the present system and suggests possibilities for its further development. The evaluation is written from the system developers' perspective and concentrates on technical aspects. A separate study would be needed to investigate properly how the EDMS has influenced the work of its users. As was already mentioned in the introduction, it would also be interesting to evaluate EDMS against other similar systems.

In general, the system has been a success at KONE. In spring 1999, the database contained about 300 000 documents. At the moment most documents are still legacy data from an old, much simpler document system and contain only attribute data. Almost all new documents that have been created after the introduction of the system (about 80 000 documents) also have a document file. The database contains 0.9 Gb of attribute data and 27 Gb document files (occupying about 12 Gb of disk space after compression). There are about 150 active users who update the data in the system. About 3000 users access the database through the Web tool.

The success has critically depended on the introduction of the EDMS Web tools and intranet as a document searching and viewing tool. It is also important that as an in-house system there are no license fees to be paid by users. This has encouraged occasional use of the system, which contributes to the increase of regular users.

14.1 Data Model

14.1.1 Document Model

The document data model has evolved according to the requirements of KONE. It remains to be seen how well the model fits the needs of other organisations.

It is conceivable that an organisation finds the present model unnecessarily complicated. For example, the multiple subdocuments or representations, or both, could be superfluous in some cases. Various ways to accommodate such needs are considered below.

One possibility is to remove the unnecessary concepts completely from the system. This would lead to four versions of the system: one with subdocuments and representations, another with subdocuments but without representations, etc. There would be considerable differences between the versions. For example, the database would contain different tables depending on whether the document contents were stored in document versions, subdocument versions, or representations. This alternative is obviously rather unattractive, especially to the developers of the system.

It might be better to make no changes in the actual database, and only modify the user interface to hide the unwanted concepts. For example, if multiple subdocuments are not needed, all documents would have exactly one subdocument, and the user interface would not show the single subdocument at all.

Nevertheless, rather than completely hiding unused features, such as multiple subdocuments, it seems better to build the user interface so that the unused features are visible but do not require any extra actions from the user. For example, if a document has a single subdocument, the user should never have to select the subdocument. This design principle is useful even at KONE because many documents have a single subdocument although it must be possible to have documents with multiple subdocuments.

14.1.1.1 Independent Subdocument Types

The treatment of document and representation types is somewhat arbitrary. The original use of subdocuments was to store the separate files of a document that consists of multiple sheets. In this usage it makes sense that all subdocuments of a document have the same type because the subdocuments are "similar". Nevertheless, subdocuments can be used for other purposes. For example, suppose that one subdocument of a document stores the "main" document and other subdocuments store figures used in the "main" document. In this case it might be more natural if the type of each subdocument could be specified separately.

14.1.1.2 Document Components

As explained in section 8.7, each combination of a document version and a subdocument (within a single document) corresponds to a "virtual" document component object. As the objects are not real objects in the database, it is impossible to make a query that finds all versions of a particular document that contain a particular subdocument version. More precisely, this kind of query is not available in the server protocol or the user interface. Internally the compositions of the document versions are stored in a single database table, in which it is easy to make the query.

14.1.1.3 Document Configurations

The present document model may also be too restricted for some companies. The lack of hierarchical subdocuments has already been mentioned. As another example of the limitations of the present subdocument model, suppose a document with separate text and graphics files also has versions in different languages. The document thus contains several subdocuments with the same text in different languages and several graphics files that are used in identical form with all texts. For example, a document could contain a Finnish text file, an English text file and a common graphics file.

To manage this situation, the model would have to be further extended with a new concept that could for example be called a configuration. Then it would be possible to say that the document has two configurations: configuration 'Finnish document' with subdocuments 'Finnish text' and 'graphics', and configuration 'English document' with subdocuments 'English text' and 'graphics' (figure 46). Furthermore, one would have to be able to directly create new versions of the subdocuments and combine subdocument versions into configuration versions.

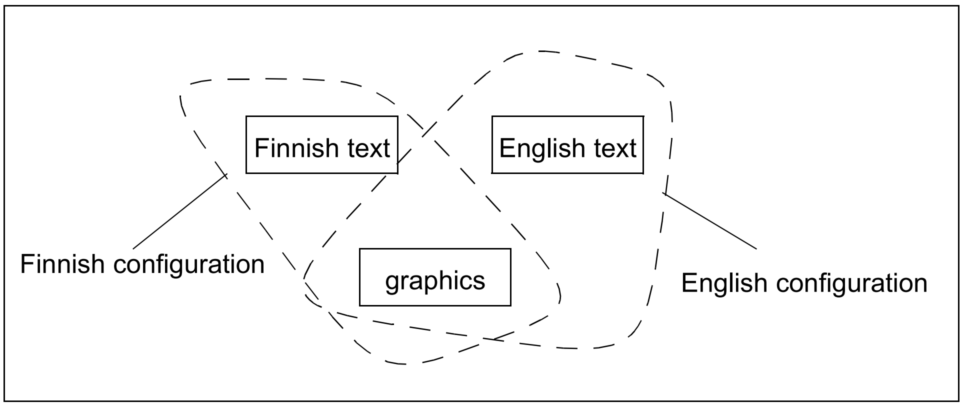


Figure 46. Document configurations

14.1.1.4 Modification of Document Version with Children

Document files associated with a document version cannot be modified after new versions have been created as its children. The users of EDMS at KONE, however, have found this rule too restricting. It is sometimes necessary to modify a document version that describes the current product in production although the database already contains a document version for the next product version. This kind of operation has not yet been added to the system because it is by no means obvious how the operation should treat shared subdocument versions. For example, consider the following situation:

document version	subdocument ‘s1’	subdocument ‘s2’
d/A	s1/A	s2/A
d/B	s1/A	s2/B
d/C	s1/C	s2/B

Suppose that it should be possible to modify subdocument ‘s2’ in document version B, which already has child C. This operation cannot create a new version B of the subdocument because such a subdocument version already exists. Nevertheless, if the existing subdocument version B is modified, the modification also affects document version C, which contains the same version of the subdocument.

One possibility would be to relax the rule that a subdocument version always has the same name as the document version in which the subdocument version has been created. For example, if a user modifies subdocument ‘s2’ in document version B of the previous example, the system could create a new subdocument version with the name 'Bx' (or something similar).

14.1.2 New Object Kinds

The set of object kinds (document, document version, product, project, etc.) is fixed in EDMS. Consider, for example, the potential new object kind 'document configuration' discussed in section 14.1.1.3. The new object kind would need many new operations in the system. It is difficult to imagine a mechanism by which the EDMS administrator, as opposed to the developers, could define the behaviour and the new operations for this object kind.

On the other hand, consider the object kind 'project' described in section 8.9. In the present system projects do not have any specific operations in addition to the generic operations available for all object kinds: the administrator can define common project attributes and project types with different attributes, and the users can create projects, retrieve and change attribute values, and make queries on projects. The system could be extended so that the administrator would be able to define new similar object kinds.

As an example of the need for new object kinds, consider 'access control groups', which are used at KONE as a basis for defining access rights to documents and other objects. Access control groups are now represented—rather arbitrarily—as a particular project type, although it would more natural to define a new object kind for this purpose.

14.1.3 User-defined Relations

At some time the developers of the system had thoughts about a generic mechanism that would allow the administrator to define new relations. The definition of a relation would include the object kinds that are associated with the relation and a list of attributes for the relation. The relations could be binary, in which case the definition would always specify exactly two object kinds, or general, in which case the definition would specify a list of two or more object kinds. The definition of a binary relation would also specify the cardinality of the relation as 'one-to-one', 'one-to-many' or 'many-to-many'. The operations provided by the system for user-defined relations could include 'create relationship', 'delete relationship', 'find all objects related through a given relation to a given object' and 'find all objects related through the transitive closure of a given relation to a given object'.

Nevertheless, there did not seem to be real need for this kind of extension. The mechanism is perhaps more appropriate as a part of a PDM Toolkit. Relations are then defined by the developer of a particular customised PDM system instead of the administrator of the PDM system.

14.1.4 Attributes

Figure 47 shows how many attributes of different value types are presently defined for document types at KONE. Many of the string attributes are supposed to have a value of a particular format. The value that a user tries to give to an attribute can be checked with the authorisation mechanism.

Base type	Scalar attributes	Sets	Sequences
string	36	6	2
list item	16	26	0
integer	1	0	0
date	15	0	0
time	0	0	0
user name	12	8	0
project name	3	1	0
multilingual string	12	not applicable	not applicable
text	9	not applicable	not applicable

Figure 47. Attribute value types at KONE

One useful extension to value lists and 'list item' attributes would be the idea of hierarchical value lists. A value list is now a flat list with all items in alphabetical order. A hierarchical value list could arrange the items in separate groups under appropriate headings. For example, consider a value list that stores names of countries. In a hierarchical value list the countries could be grouped under headings 'Europe', 'Asia', etc.

The attribute value types 'user name' and 'project name' make it possible to define attributes that store references to users and projects. It would be simple to add an analogous value type 'document name'. Nevertheless, these value types are used for creating relations between objects, and as was mentioned in section 3.2.3, it might better to represent relationships as entities of their own rather than as reference attributes. In some sense, the attribute types 'user name' and 'project name' should thus be replaced with user-defined relations (section 14.1.3).

14.1.5 Generalised Type Hierarchies

An object kind in EDMS has a set of base attributes and a number of object types, each with its own set of type-specific attributes. This model can be regarded as a class hierarchy with inheritance between two fixed levels of classes. It is natural to ask how this model could be extended to allow an arbitrary number of levels (Gunell 1999).

In fact, the extension to multiple levels should be relatively easy although it has not yet been implemented. In the present system an operation that applies to an object kind as a whole is carried out separately on each object type. For example, when a common attribute is added to an object kind, the corresponding column is added to all tables that represent the types of the object kind. Similarly, when a query is made on all objects of a particular kind, an identical query is made on all object tables.

The operations can be generalised in a quite straightforward way when any object type can have further subtypes. Each object type is designated either as abstract or concrete, and for each concrete type there is an object table with columns for the attributes defined in the type itself and in its supertypes. The attributes of an object instance are stored in the object table that corresponds to the type of the object.

When an attribute is added to an object type, the corresponding column is added to the object table that corresponds to the type itself (provided that the type is concrete) and to all object tables that correspond to the concrete subtypes of this type. Similarly, a query must examine the object tables of all concrete types.

This method can be used equally well with single inheritance and multiple inheritance. Multiple inheritance creates the usual problems with name conflicts but the solution does not affect the representation of the objects and their attributes.

14.1.6 More Flexible Attribute Definitions

So far it has been assumed that a query on objects of a particular type can only refer to attributes that are found in all instances of the type. In other words, if a query on an object type refers to an attribute, the attribute must be defined in the object type or in one of its supertypes.

Sometimes it is, however, useful to find all such instances of an object type in which some attribute has a particular value even when some instances of the type do not have the attribute at all. More precisely, an object instance is selected by the query only if the instance has the attribute and the attribute value satisfies the query condition.

These kinds of queries make it necessary to change the way attributes are defined. Consider first "ordinary" queries. If objects that are direct instances of two different object types have the same attribute, either one of the object types defines the attribute and the other object type is a subtype of this type, or the attribute is defined by a third type, which is a supertype of both object types that have the attribute. For example, in figure 48, object type T defines attribute 'a' with value type 'integer'. Since T1, T2 and T3 are subtypes of T, instances of all these types have attribute 'a'. Object type T2 defines attribute 'b' with value type 'integer', and object type T3 defines attribute 'b' with value type 'string'. The two attributes defined by T2 and T3 are two distinct attributes, which simply happen to have the same name.

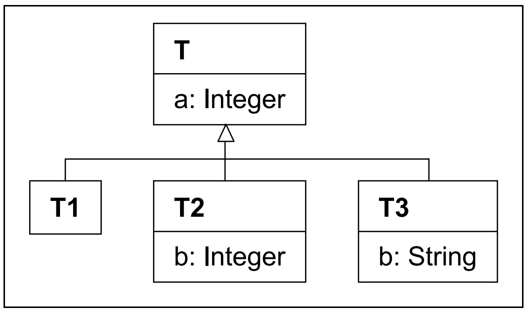


Figure 48. Different attributes with the same name

Now consider the kinds of queries considered useful for component management. A query could be something like 'find all instances of object type T which have attribute 'b' and in which the value of the attribute satisfies a particular condition'. This query does not make sense in the situation of figure 48. Although object types T2 and T3 both have an attribute with the name 'b', one cannot say that the object types have the same attribute 'b', which could be referred to in a query as a single attribute 'b'. In the example the attributes even have different value types, making it impossible to write a query condition that would be meaningful for the instances of T2 and T3 alike.

If it is necessary for object types T2 and T3 to really have the same attribute, there must be a single definition of the attribute with its name and value type. Component types T2 and T3 must then specify that they have this attribute, which is defined "globally" outside all component types.

One further question is whether all attributes must be defined in this way or can a component type still define directly those attributes that are not shared with other "unrelated" component types (i.e., with component types that are not subtypes of the component type that defines the attribute). If this is allowed, an object type can define its "own" attributes and contain references to globally defined attributes as illustrated in figure 49.

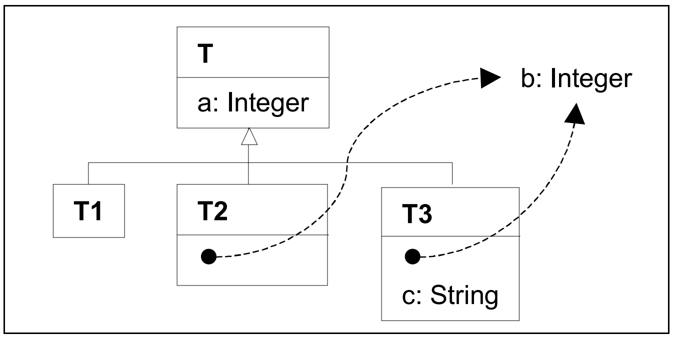


Figure 49. Global attribute definition

The situation is further complicated by the fact that some properties of the attributes can be meaningfully defined differently in different object types that include the shared attribute. For example, object types T2 and T3 in figure 32 could define different default values for attribute ‘b’.

Unrelated component types can also have the same attribute by means of multiple inheritance. If an attribute is to be added to a number of object types, the idea is to create a new object type that defines the attribute and then add this object type as a supertype to all component types that should have the attribute. Figure 50 shows how attribute ‘b’ is added to object types T2 and T3 through component type Tb, which defines the attribute.

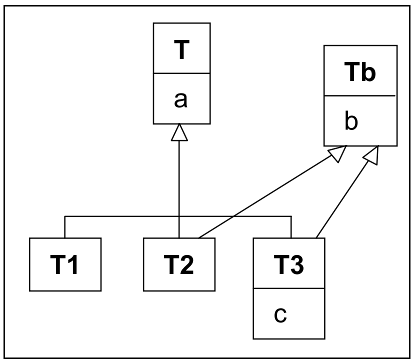


Figure 50. Shared attribute with multiple inheritance

Compared to the separate global attribute definitions, this technique may seem to lead to superfluous object types. Nevertheless, usually the attribute is defined for the object types because the object types have some common “property”, and this property implies that the object types have the common attribute. Even if the common “property” is originally represented with a single attribute, it is quite possible that the “property” will later be associated with more attributes. In this case it is only good that the common “property” is represented with an object type instead of an individual attribute. When a new attribute is added to the object type that represents the common “property”, all object types that have the object type as a supertype will automatically have the attribute.

14.2 System

14.2.1 Server Protocol

The server protocol defines a clear interface between the server and the client (i.e., the user interface). The interface has made it easy to divide the development work between members of the development team. As long as the protocol remains intact, the server and the user interface can be developed independently. When a new feature had to be added, it was often necessary to add new requests to the protocol. After the extensions were discussed and agreed upon by the team members, it was again possible to proceed separately with the server, which implemented the new request, and the user interface, which used the request to provide new functionality to the user.

Although more concise coding of protocol requests could be slightly more efficient, the "human-readable" (at least to EDMS developers and administrators) syntax has proved very useful. The access program allows a user to send service requests to the server directly from the keyboard or from a file. During debugging it is also very convenient that the clients and the server can directly print the requests and replies.

14.2.2 Storage of Document Files

The main architectural mistake was to store the contents of representations (i.e., the document files) in the relational database as Binary Large Objects (BLOBs). This decision was motivated by the advantage of having all data in one place under the control of the transaction mechanism of the database system.

Most PDM systems, however, store document files in ordinary files and only store references, such as the names of the files, in the database. The files are stored in a directory that cannot be accessed by ordinary users except through the PDM system.

Owing to the experiences at KONE, EDMS will also be changed to use separate document files. The main problem with BLOBs is that it is impossible to restore individual document files from a database backup. Now that the server stores document files as table columns in the database, the whole database must be returned to its earlier state from a backup tape. If the server stored document files as ordinary files, an individual document file could be restored from an ordinary file backup tape.

Another disadvantage of BLOBs is that although they are available in all widely used database systems, their manipulation is not part of the SQL standard. If the present EDMS server were to be ported to another database system, very little changes would be expected in the program code except in those parts that deal with BLOBs. When BLOBs are no longer used, all SQLprogram code in the EDMS server should conform to the SQL standard and be directly portable.

The change from BLOBs to separate document files does not affect the server protocol, and accordingly the client programs are not aware of this change at all.

14.2.3 Authorisation and Object Filters

Authorisation procedures are used extensively at KONE. User rights at KONE are based on 'access control groups'. Each group has rights to particular operations on particular objects, and each user belongs to one or more groups. As mentioned in section 14.1.2, access control groups are represented as projects.

One can argue that it would be easier to use a publicly available scripting language for the authorisation procedures. One obvious candidate would be 'Tcl', which was used in the original EDMS user interface as a scripting language (section 12.2.4).

Nevertheless, the authorisation system was built before the development team became aware of Tcl. If the system were to be written now, Tcl would probably be used for authorisation procedures, too. This would eliminate quite a complex component from the server, and the administrators would not have to learn a new language.

The present mechanism still has some advantages over Tcl. Tcl is a purely interpretative language and many errors, such as an unknown command or the wrong number of arguments for a command, are not detected until the program is executed. The present server, on the other hand, reads the authorisation program when the server is started and translates the program to an internal representation. If there are syntax errors in the authorisation program, the server reports the errors immediately and terminates.

Object filters (section 11.7) are implemented, but they have not yet been used at KONE. To some extent it is against the design principles of EDMS to write the filter conditions directly in the query language of the underlying database system. For example, the administrator can write filter conditions that use non-standard extensions of SQL and work only as long as EDMS is used with the present database system. Nevertheless, from the implementor's point of view it is much simpler to write filter conditions directly in the query language rather than to write the conditions in another language, which would then have to be translated to the query language.

There should perhaps also be a mechanism for hiding particular attributes instead of particular objects. For example, if the system stores product data, there can be attributes for costs and prices, and the management may want to hide these attributes from most users.

14.2.4 Flexibility of the User Interface

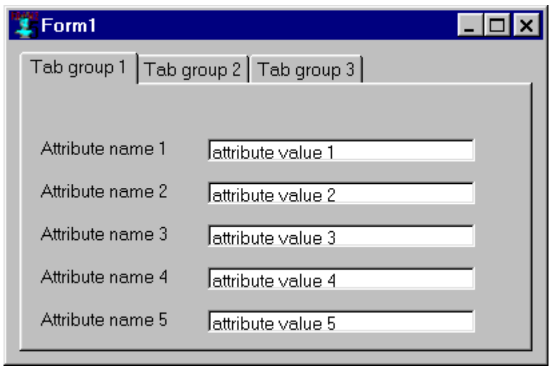
Both the X/Motif user interface and the newer Java user interface are in some sense very dynamic and flexible and at the same time static and inflexible.

The user interfaces are flexible because the database schema does not have to be described in the user interface. When started, the user interfaces read all schema data, such as object types and their attributes, from the server. The administrator can thus modify the database schema without changing anything in the user interface.

This kind of dynamic behaviour has been from the beginning a leading design principle in the EDMS user interfaces. On the other hand, it also means that the administrator cannot control how the attributes are displayed on the user interface. The system attributes, common attributes and type-specific attributes are always displayed in this order as a vertical list as shown in figures 43 (page 158) and 44 (page 159). The administrator can only specify the order of the common attributes and the order of the type-specific attributes in the database.

However, it might be more convenient for a user to manipulate attributes if they were arranged more freely on the screen. For example, related frequently used attributes could be grouped together, and attributes with short values could be displayed side by side.

One relatively simple way to improve the present user interface would be to allow each user to arrange the attributes in "tab groups" illustrated in figure 51. (The form in this figure has not been created with the same tool as the present user interface and only illustrates the general idea of a tab group.) Each user could define a number of tab groups and specify for each group the attributes to be shown in the group. To ensure that all attributes of the database are always shown, the user would have to designate one of the tab groups as the default group for attributes that have not been specified in any group.



Attribute name 1	attribute value 1
Attribute name 2	attribute value 2
Attribute name 3	attribute value 3
Attribute name 4	attribute value 4
Attribute name 5	attribute value 5

Figure 51. Tab group for attributes

14.2.5 Administrator's Tool

The system has no separate administrator's tool apart from the simple 'access' program by which the administrator can send protocol requests to the server. So far this has been enough because the administrators at KONE have been technically competent and have not minded using the protocol directly.

In the future a proper graphical administrator's tool is probably necessary. In fact, a prototype of such a tool was once built as a student project, but the tool was never actually used. The sophistication of the tool also depends on whether these kinds of administration tasks will be carried out by the personnel of the end-user organisation or—possibly in the future—by a company that sells the system and configures it according to the requirements of the end-user organisation.

14.2.6 Possibilities to Use Relational Extensions

As seen from section 11.9, it is rather complicated to implement inheritance hierarchies and set-valued attributes in an ordinary relational database. However, some new relational database systems directly support these concepts.

The EDMS server is implemented with an Informix database. This subsection examines if inheritance and sets could be implemented more easily with Informix

Version 9.1, which contains some of the extensions included in the coming SQL3 standard (Melton 1996).

With this version of Informix, a table can be created as a subtable of another table, called a supertable (Informix 1997b: 10-20…10-38). This means that the subtable automatically has the columns of the supertable in addition to the columns explicitly defined for the subtable. A subtable hierarchy can contain an arbitrary number of levels. A query on a table either only examines the rows of the specified table or examines the rows both in the specified table and in all its subtables.

Although the model itself provides exactly what is needed for EDMS, the present Informix implementation has a serious limitation. After a table hierarchy has been created, it is impossible to add or remove columns in the tables or modify the existing columns (Informix 1997b: 10-37). If document types were implemented with table hierarchies, it would be impossible to implement operations that add and remove attributes and modify attribute types in existing attribute types.

In Informix 9.1, the type of a column can be a *collection* (Informix 1997b: 10-14…10-19). There are three kinds of collections: sets, multisets and lists. Column types ‘set’ and ‘list’ correspond directly to set and sequence attributes in EDMS. Nevertheless, there are again limitations in the Informix implementation.

In Informix 9.1, the contents of a collection must not exceed 32 kilobytes (Informix 1997b: 10-15). It is also impossible to create an index on a column that has a collection as its data type (Informix 1997a: 1-140). These restrictions suggest that internally Informix may implement a collection column as an “ordinary” column. On each row, the column stores the elements of a single collection as a single data sequence of varying length.

In any case, the lack of indexing means that a query on a collection, such as ‘find all objects in which a particular collection contains a particular element’, is always slow. In EDMS, on the other hand, it is possible to create an index for a set or sequence attribute. The index is then created on the ‘value’ column in the table that stores the elements of the attributes.

14.2.7 Multiple Servers

So far, all of KONE has managed throughout with a single EDMS database and server for the whole company. The server is accessed from offices round the world (e.g., Finland, Italy, the U.K., China). Earlier in the project is was assumed that if EDMS were to be used outside Finland, it would soon be necessary to have multiple servers located closer to the users. Nevertheless, the speed and reliability of international data connections has advanced so rapidly that it is feasible to have a single server with global access.

Although EDMS now has a single centralised database, in the future there may still be a need for separate databases that are connected in some fashion. At the moment there are no plans to build a single logical database that would allow users to access any document without knowing its location. Instead, users are expected to usually access documents in their local databases. When a document or other data in another database is needed, a user must use specific operations to copy the data between databases.

There are many issues to consider, such as:

- Is the right to modify a document transferred along with the document between databases?
- If a document is moved for modification from a database to another database, is it also possible to create new document versions in the destination database or only to modify existing versions?
- Is it possible to modify different versions (e.g., different language variants) of a single document at the same time in different databases?

14.3 Development Project

14.3.1 EDMS Implementation

Towards the end of the project, the publicly available 'gnats' system was installed to submit and record error reports and change requests. It is clear that the system should have been introduced earlier.

Another tool that should have been made earlier is a server test program. Compared to the user interface, it is easy to test the server, which has a very clear interface. The server accepts requests, and sends a reply for each request. In spite of the usefulness of a test program, such a program was only written towards the end of the project. The input file to the program contains a list of requests and expected replies to the requests. The test program connects to the server, sends each request to the server and compares the actual replies from the server to the expected replies in the input file. In addition to requests and replies, the input file can contain commands for testing check-in and check-out operations. There are, for example, commands for creating files with random contents and for comparing the contents of two files.

The test files now contain about 750 requests that test the most important functions of the server. The test program can be run with a single command and this should be done after any changes to the server. The test program will be especially useful when the server is ported to a new environment. At the same time the test files must of course be extended.

The different components of the system were developed quite independently by different people. The developers should have agreed on coding standards, such as the capitalisation of the various identifiers in the C++ programs and indentation of the programs.

If the duration and extent of the project had been known when the project started, many things might have been done differently. Significantly more resources in particular should have been devoted to quality assurance (error reporting, systematic testing, regression testing, peer reviews). On the other hand, one can question whether a university is the proper place at all for a project so close to industrial software development.

14.3.2 Usability Test

The complexity of the system makes great demands on the design of the user interface. A usability test was conducted on the X/Motif user interface by a student group as an assignment for a usability course. During the test, end-users from KONE were asked to perform some typical tasks on the system while the students videotaped the sessions. The users also filled in questionnaires.

The test revealed a number of inconsistencies in the current user interface. For example, after entering text in a field, users must in some cases press the ENTER key on the keyboard while in other cases users click on a screen push-button with the mouse. On the whole, these problems were relatively easy to fix. Nevertheless, user interface can hardly change the fact that it is difficult to use the system without understanding the concepts behind the user interface. For example, the behaviour of sub-document versions remains mysterious for a user who is unfamiliar with the complete document structure.

The problems with the user interface are aggravated by the fact that the system is also used by people other than those that the developers originally had in mind. The developers believed that the system would be used mainly by the same people who use CAD programs and other tools to create and edit the documents that are stored in the system. Accordingly, the users were supposed to be familiar with the basic concepts such as documents and document versions. Nevertheless, the system is now also used by secretaries who work with detailed instructions of the form “first do this, then do that” without really understanding the meaning of the operations.

15 Conclusions and Future Work

There are many different PDM systems on the market. One reason for this heterogeneity is the lack of a "general standard model of products". If the STEP standard with its multitude of different and partly overlapping application protocols is any indication, such standard model is unlikely to ever emerge. Nevertheless, the first part of this thesis introduced a set of "core concepts", which are common to at least most PDM systems. Although the concepts were not presented in sufficient detail to serve as a specification for a PDM system, they constitute a minimal set of issues to be considered when evaluating or designing any PDM system.

Much further work is needed on configurable products and especially on the long-term evolution of configuration models and individual configurations. In other words, one must investigate the relations between versioning and configurable products. On a more practical level, one important question, which probably has no single "correct" solution, is the integration between PDM systems and other information systems, such as CAD tools, ERP systems and product configurators. For example, only time will tell whether PDM systems survive as separate systems or whether all their functions will eventually be included within ERP systems. It will also be interesting to see the effect of standards, such as STEP, on PDM systems.

The second main topic of the thesis was a document management system called EDMS, which implements some of the concepts discussed in the first part. Although the overall functionality of the system is relatively limited compared to many commercial PDM systems, the document model is elaborate and has served the needs of KONE quite well. The flexible schema manipulation operations and powerful authorisation mechanism have proved useful.

The experiences of KONE demonstrate how the wider acceptance of a PDM system depends on access through the Web. In the future, EDMS will be extended with product structures that will also support configurable products. To make it possible to use the system in other companies, the company-specific Web tools developed at KONE will be rewritten to work with the more general data model. The thesis also discussed different ways to generalise the present two-level object type hierarchy, for example, to support component and supplier management functions. Generalised type hierarchies may be implemented in the future.

Appendix A: Transitive Closure in the Object Constraint Language

The UML diagrams in this thesis are accompanied with constraints written in the Object Constraint Language (Warmer and Kleppe 1999). This appendix describes an extension to the language, which is used in some constraints. The extension makes it possible to refer to the transitive closure of an association that relates an object of a class to other objects of the same class.

Suppose there is a class and an association from the class to itself. As both ends of the association refer to the same class, the ends must be given role names. For example, figure 52 shows the class ‘City’ and the association ‘flight’. An association between a city in the role ‘source’ and a city in the role ‘destination’ means that there is a flight from from the former city to the latter city.

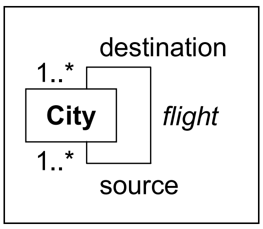


Figure 52. An association from a class to itself

The new construction

⟨*object*⟩.(⟨*navigation*⟩+)

refers to the set of all objects that can be reached from the given object by following the given navigation one or more times. In other words,

```
obj.(nav+)
```

means the same as

```
obj.nav->union(obj.nav.nav->union(obj.nav.nav.nav->union(…)))
```

For example, if ‘c’ is an object of class ‘City’ in figure 52, all cities that can be reached from city ‘c’ by one or more flights are found with the expression

```
c->(destination+)
```

Appendix B: Sample Commit Procedure

This appendix shows a real-life example of commit procedures (section 11.5). In this example it is assumed that both document and document versions have an attribute with the name 'main_title' and the type 'multilingual string'. The values of these attributes are thus sets of strings of the form 'lang:text' where 'lang' is a language code from the value list with the name 'languages'. All language codes are assumed to be two characters in this example.

The commit procedures should have the following effect: Whenever a new document version is created or the main title of an existing document version is modified, the version title is "added" to the main title of the corresponding document. If the title of the document version contains text in a language which does not appear in the document title, the text from the version title is simply added to the document title. If the document title already contains text in the same language as the version title, the text in the document title is replaced with the text in the version title.

For example, suppose the attribute 'main_title' of a document has the following value ('fi' is the code for 'Finnish'):

{ "en:elevator" "fi:hissi" }

A new version of the document is then created, or the attributes of an existing version are modified. The attribute 'main_title' of the created or modified document version has the following value ('de' is the code for 'German'—from the German word 'deutsch'):

{ "de:Fahrstuhl" "en:lift" }

The commit procedures should give the following value to the attribute 'main_title' of the document:

{ "de:Fahrstuhl" "en:lift" "fi:hissi" }

As can be seen, the German text has been added, the English text has been replaced, and the Finnish text has remained as it was.

A commit program to achieve this effect is shown below. The modification of attribute values and the creation of a new document version makes the server call the commit procedures 'changeAttributeValues' and 'createDocVersion', respectively. Since the main title must be treated identically in both cases, the commit program contains the procedure 'checkMainTitleUpdate', which is called from both commit procedures. Note that the second argument of 'changeAttributeValues' is a list of object identifiers, which is passed as such to 'checkMainTitleUpdate'. The second argument of 'createDocVersion', however, is a single object identifier of the new document version. The identifier is turned into a list with the list expression '{…}' on line 5.

```
(1)  event changeAttributeValues (user, objs, attrNames, attrValues)
(2)    checkMainTitleUpdate(objs, attrNames, attrValues);
(3)  end;
```

```
event createDocVersion (user, newVersion, parentType, parent,
                         attrNames, attrValues)
  checkMainTitleUpdate({newVersion}, attrNames, attrValues);
end;
```

The procedure ‘checkMainTitleUpdate’ first checks that the objects whose attributes are being examined are document versions (the first object in the list is extracted with the built-in function ‘element’ and its kind is examined with the built-in function ‘kind’). The attribute name list must also contain the name ‘main_title’.

```
procedure checkMainTitleUpdate (objs, attrNames, attrValues)
  if length(objs) = 0 or
     kind(element(objs, 0)) != "doc-version" or
     not ("main_title" in attrNames) then
    return;
  end;
```

The main title of the document version is then copied to the local variable ‘versionTitle’.

```
  foreach name, val in attrNames, attrValues do
    if name = "main_title" then
      versionTitle := val;
      break;
    end;
  end;
```

The languages of the version title are collected as a list to ‘versionLanguages’. (In this example the language is always in the first two characters of an element of a multilingual string.)

```
  versionLanguages := {};
  foreach text in versionTitle do
    versionLanguages := versionLanguages + sequence(text, 0, 1);
  end;
```

All objects, which are now known to be document versions, are examined.

```
  foreach version in objs do
```

Next, the procedure generates an object identifier for the document. Variable ‘version’ contains an object identifier for the document version, expression ‘version.doc’ gives the value of the system attribute ‘doc’ that stores the name of the corresponding document, and the built-in function ‘document’ gives an object identifier to a document with that name.

```
    doc := document(version.doc);
```

The old document title is retrieved to a variable. If this title contains all texts (the complete texts, not only the same languages) from the document version title, the document title need not be updated.

```
(25)      oldDocTitle := doc.main_title;
(26)      anyChange := 0;
(27)      foreach text in versionTitle do
(28)        if not (text in oldDocTitle) then
(29)          anyChange := 1;
(30)          break;
(31)        end;
(32)      end;
(33)      if not anyChange then
(34)         return;
(35)      end;
```

The new document title is formed into variable 'newDocTitle'. First the procedure copies all those texts from the old title that are written in a language that does not appear in the document version title. Then all texts from the document version title are added to this set.

```
(36)      newDocTitle := {};
(37)      foreach text in oldDocTitle do
(38)        if not (sequence(text, 0, 1) in versionLanguages) then
(39)          newDocTitle := newDocTitle + text;
(40)        end;
(41)      end;
(42)      newDocTitle := newDocTitle + versionTitle;
```

Finally the main title of the document is updated. The first 'end' closes the 'foreach' loop started on line 23; the second 'end' finishes the whole procedure.

```
(43)      update doc.main_title := newDocTitle;
(44)    end;
(45)  end;
```

References

Abiteboul, Serge, and Richard Hull. 1987. IFO: A formal semantic database model. *ACM Transactions on Database Systems* 12, no. 4: 525–565.

Aho, Alfred V., and Jeffrey D. Ullman. 1977. *Principles of Compiler Design*. Addison-Wesley.

AIIM (The Association for Information and Image Management International). 1997. Open Document Management API Version 2.0.

Allen, Wayne, Douglas Rosenthal, and Kenneth Fiduk. 1991. The MCC CAD framework methodology management system. In *Proc. of the 28th ACM/IEEE Design Automation Conference*, 694–698. ACM.

Arnold, Ken, and James Gosling. 1996. *The Java programming language*. Addison-Wesley.

Barghouti, Naser S., and Gail E. Kaiser. 1991. Concurrency control in advanced database applications. *ACM Computing Surveys* 23, no. 3: 269–317.

Barsalou, T., and G. Wiederhold. 1990. Complex objects for relational databases. *Computer-Aided Design* 22, no. 8: 458–468.

Bowman, C. Mic., Peter B. Danzig, Darren R. Hardy, Udi Manber, Michael F. Schwartz, and Duane P. Wessels. 1995. Harvest: A scalable, customizable discovery and access system. Technical report CU-CS-732-94. Department of Computer Science, University of Colorado – Boulder.

Buckley, Fletcher J. 1996. *Implementing configuration management: Hardware, software and firmware*. Second edition. IEEE Press.

Buffenbarger, Jim. 1995. Syntactic software merging. In *Software Configuration Management: ICSE SCM-4 and SCM-5 Workshops: Selected Papers*. Lecture Notes in Computer Science 1005, ed. Jacky Estublier, 153–172. Springer-Verlag.

CAD/CAM. 1998. Is Metaphase out of the box? *Product Data Management Report* 2, no. 11: 1–3. CAD/CAM Publishing, Inc.

Cagan, Martin. 1995. Untangling configuration management: Mechanism and methodology in SCM systems. In *Software Configuration Management: ICSE SCM-4 and SCM-5 Workshops: Selected Papers*. Lecture Notes in Computer Science 1005, ed. Jacky Estublier, 35–52. Springer-Verlag.

Casotto, Andrea, A. Richard Newton, and Alberto Sangiovanni-Vincentelli. 1990. Design management based on design traces. In *Proc. of the 27th ACM/IEEE Design Automation Conference*, 136–141.

Cattell, R. G. G. 1994. *Object data management: Object-oriented and extended relational database systems*. Revised edition. Addison-Wesley.

Cellary, W., G. Vossen, and G. Jomier. 1994. Multiversion object constellations: A new approach to support a designer's database work. *Engineering with Computers* 10, no. 4: 230–244.

Cleetus, K. J. 1995. Modeling evolving product data for concurrent engineering. *Engineering with Computers* 11, no. 3: 167–172.

Conradi, Reidar, and Bernhard Westfechtel. 1997. Towards a Uniform Version Model for Software Management. In *Proc. of the 7th International Workshop on Software*

Configuration Management (SCM97), Boston, MA, LNCS 1235, 1–17. Springer Verlag.

Conradi, Reidar, and Bernhard Westfechtel. 1998. Version models for software configuration management. *ACM Computing Surveys* 30, no. 2: 232–282.

Cook, Melissa A. 1996. *Building enterprise information architectures: Reengineering information systems*. Prentice-Hall.

Dong, Andy, and Alice M. Agogino. 1998. Managing design information in enterprise-wide CAD using 'smart drawings'. *Computer-Aided Design* 30, no. 6: 425–435.

Erens, Frederik. 1996. The Synthesis of Variety-Developing Product Families. PhD thesis, Eindhoven University of Technology.

Fowler, Martin. 1997. *UML distilled: Applying the standard object modeling language*. Addison-Wesley.

Grudin, Jonathan. 1994. Groupware and social dynamics: Eight challenges for developers. *Communications of the ACM* 37, no. 1 (January): 92–105.

Gunell, Kim. 1999. A Classification Model for a Product Data Management System. Master's thesis. Helsinki University of Technology.

Haag, Albert. 1998. Sales configuration in business processes. *IEEE intelligent systems & their applications* 13, no. 4: 78–85.

Hakelius, Cecilia, and Ulf Sellgren. 1996. PDM projects in Swedish industry—Experiences from six engineering and manufacturing companies. KTH/MMK/R-96/6-SE. Department of Machine Design, The Royal Institute of Technology (KTH), Sweden.

Hameri, Ari-Pekka, and Jukka Nihtilä. 1998. Product data management—Exploratory study on state-of-the-art in one-of-a-kind industry. *Computers in Industry* 35, no. 3: 195–206.

Harris, S. B. 1996. Business strategy and the role of engineering product data management: a literature review and summary of the emerging research questions. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 210, no. B3: 207–220.

Hull, Richard, and Roger King. 1987. Semantic database modeling: Survey, applications and research issues. *ACM Computing Surveys* 19, no. 3: 201–260.

IEC (International Electrotechnical Commission). 1997. International Standard 61360-4: Standard data element types with associated classification scheme for electric components-Part 4: IEC reference collection of standard data element types, component classes and terms.

Informix. 1997a. Informix Guide to SQL: Syntax. Version 9.1. Informix Software, Inc.

Informix. 1997b. Informix Guide to SQL: Tutorial. Version 9.1. Informix Software, Inc.

IPDMUG (International Product Data Management Users Group). 1995. Integrating/Interfacing PDM with MRP II.

ISO. 1994a. ISO Standard 10303-11: Industrial automation systems and integration—Product data representation and exchange—Part 11: Description methods: The EXPRESS language reference manual.

ISO. 1994b. ISO Standard 10303-203: Industrial automation systems and integration—Product data representation and exchange—Part 203: Application protocol: Configuration controlled design.

ISO. 1994c. ISO Standard 10303-21: Industrial automation systems and integration—Product data representation and exchange—Part 21: Implementation methods: Clear text encoding of the exchange structure.

ISO. 1994d. ISO Standard 10303-41: Industrial automation systems and integration—Product data representation and exchange—Part 41: Integrated generic resources: Fundamentals of product description and support.

ISO. 1994e. ISO Standard 10303-44: Industrial automation systems and integration—Product data representation and exchange—Part 44: Integrated generic resources: Product structure configuration.

ISO. 1995. ISO Draft International Standard 13584-10: Industrial automation systems and integration—Parts Library—Part 10: Conceptual model of parts library.

ISO. 1996. ISO Draft International Standard 13584-42: Industrial automation systems and integration—Parts Library—Part 42: Methodology for structuring part families.

ISO. 1997. ISO Draft International Standard 13584-1: Industrial automation systems and integration—Parts Library—Part 1: Overview and fundamental principles.

Katz, Randy H. 1990. Toward a unified framework for version modeling in engineering databases. *ACM Computing Surveys* 22, no. 4: 375–408.

Keim, Daniel A., Hans-Peter Kriegel, and Andreas Miethsam. 1993. Object-oriented querying of existing relational databases. In *Proc. of the 4th International Conference on Database and Expert Systems Applications (DEXA)*. Lecture Notes in Computer Science 720, ed. Validimir Marik, Jiri Lazansky, and Roland R. Wagner, 325–336. Springer-Verlag.

Kim, Won, Raymond Lorie, Dan McNabb, and Wil Plouffe. 1984. A transaction mechanism for engineering design databases. *In Proc. of the 10th International Conference on Very Large Databases (VLDB)*, 355–362.

Korth, Henry F., and Abraham Silberschatz. 1986. *Database system concepts*. McGraw-Hill.

Lee, Jintai. 1997. Design rationale systems: Understanding the issues. *IEEE Expert* 12, no. 3 (May/June): 78–85.

Light, Richard. 1997. *Presenting XML*. Sams.net Publishing.

Männistö, Tomi, Hannu Peltonen, and Reijo Sulonen. 1996. View to product configuration knowledge modelling and evolution. In Configuration—papers from the 1996 AAAI Fall Symposium (AAAI technical report FS-96-03), ed. Boi Faltings and Eugene C. Freuder, 111–118. AAAI Press.

Männistö, Tomi, Hannu Peltonen, Asko Martio, and Reijo Sulonen. 1998. Modelling generic product structures in STEP. *Computer-Aided Design* 30, no. 14: 1111–1118.

Mattos, Nelson M., Klaus Meyer-Wegener, and Bernhard Mitschang. 1993. Grand tour of concepts for object-orientation from a database point of view. *Data & Knowledge Engineering* 9, no. 3: 321–352.

McIntosh, Kenneth G. 1995. *Engineering data management: a guide to successful implementation*. McGraw-Hill.

Melton, Jim. 1996. SQL3 snapshot. In *Proc. of the 12th International Conference on Data Engineering*, 666–672. IEEE Computer Society Press.

Meyer, Bertrand. 1992. *Eiffel: The language*. Prentice Hall.

Miller, Ed, John MacKrell, and Alan Mendel. 1997. PDM buyer's guide. 6th edition. 2 vols. CIMdata Corporation.

Mittal, Sanjay, and Felix Frayman. 1989. Towards a generic model of configuration tasks. In *Proc. of the 11th International Joint Conference on Artificial Intelligence (IJCAI)*, 1395–1401.

Ousterhout, John K. 1994. *Tcl and the Tk Toolkit*. Addison-Wesley.

Owen, Jon. 1997. *STEP—An introduction*. Information Geometers.

Peltonen, Hannu. 1993. EDMS engineering data management system—Administrator's guide. Technical report TKO-C60. Laboratory of Information Processing Science, Helsinki University of Technology.

Peltonen, Hannu, Kari Alho, Tomi Männistö, and Reijo Sulonen. 1994a. An authorization mechanism for a document database. In *Proc. of the ASME Database Symposium*, ed. Peggy Bocks and Biren Prasad, 137–143. The American Society of Mechanical Engineers.

Peltonen, Hannu, Tomi Männistö, Kari Alho, and Reijo Sulonen. 1994b. Product configurations—An application for prototype object approach. In *Proc. of the 8th European Conference on Object-Oriented Programming (ECOOP '94)*, ed. Mario Tokoro and Remo Pareschi, 513–534. Springer-Verlag.

Peltonen, Hannu, Tomi Männistö, Timo Soininen, Juha Tiihonen, Asko Martio, and Reijo Sulonen. 1998. Concepts for modelling configurable products. In *Proc. of the Product Data Technology Days*, 189–196. Sandhurst, UK: Quality Marketing Services.

Peltonen, Hannu, Olli Pitkänen, and Reijo Sulonen. 1996. Process-based view of product data management. *Computers in Industry* 31, no. 3: 195–203.

Reichenberger, Christoph. 1995. VOODOO A Tool for orthogonal version management. In *Software Configuration Management: ICSE SCM-4 and SCM-5 Workshops: Selected Papers*. Lecture Notes in Computer Science 1005, ed. Jacky Estublier, 61-79. Springer-Verlag.

Richardson, Tomed. 1997. *Using Information Technology During the Sales Visit*. Cambridge, UK: Hewson Group.

Rumbaugh, James. 1987. Relations as semantic constructs in an object-oriented database. In *Proc. of the Conference on Object-Oriented Programming Systems, Languages and Applications (OOPSLA '87)*, ed. Norman Meyrovitz, 466–481. ACM Press.

Rumbaugh, James E., Michael R. Blaha, William J. Premerlani, Frederick Eddy, and William Lorensen. 1991. *Object-oriented modeling and design*. Prentice-Hall.

Sabin, Daniel, and Rainer Weigel. 1998. Product configuration Frameworks—a survey. *IEEE intelligent systems & their applications* 13, no. 4: 42–49.

Schönsleben, Paul, and Hendrik Oldenkott. 1992. Enlarging CAD and interfaces between PPC and CAD to respond to product configuration requirements. In *Integration in production management systems*, ed. H. J. Pels and J. C. Wortmann, 53–69. Elsevier Science Publishers.

Shah, Jami J., and Martti Mäntylä. 1995. *Parametric and feature-based CAD/CAM*. John Wiley & Sons.

Stefik, Mark J., and Daniel G. Bobrow. 1986. Object-oriented programming: Themes and variations. *AI Magazine* 6, no. 4: 40–62.

Teeuw, Wouter B., J. Reinoud Liefting, Roger H. J. Demkes, and Maurice A. W. Houtsma. 1996. Experiences with product data interchange: On product models, integration, and standardisation. *Engineering with Computers* 31, no. 3: 205–221.

Tichy, Walter F. 1985. RCS—A system for version control. *Software Practice & Experience* 15, no. 7: 637–654.

Tiihonen, Juha, Timo Soininen, Tomi Männistö, and Reijo Sulonen. 1996. State-of-the-practice in product configuration—A survey of 10 cases in the Finnish industry. In *Knowledge intensive CAD*, vol. 1, ed. Tetsuo Tomiyama, Martti Mäntylä, and Susan Finger, 95–114. Chapman & Hall.

Tyma, Paul. 1998. Why are we using Java again? *Communications of the ACM 41*, no. 6: 38–42.

Ungar, David, and Randall B. Smith. 1991. SELF: The power of simplicity. LISP and *Symbolic Computation* 4, no. 3.

van den Hamer, Peter, and Kees Lepoeter. 1996. Managing design data: The five dimensions of CAD frameworks, configuration management, and product data management. *Proceedings of the IEEE* 84, no. 1: 42–56.

van Veen, Eelco Anthonie. 1991. Modelling product structures by generic Bills-of-Material. PhD thesis, Eindhoven University of Technology.

Warmer, Jos, and Anneke Kleppe. 1999. *The object constraint language—Precise modeling with UML*. Addison-Wesley.