Development of a design history information system : capturing and Re-using the knowledge behind the product

DOI:
10.6100/IR526862

Document status and date:
Published: 01/01/1999

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Silvan Wiegeraad

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Druk: Universiteitsdrukkerij Technische Universiteit Eindhoven

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Wiegeraad, Silvan

Development of a design history information system : capturing and
re-using the knowledge behind the product / by Silvan Wiegeraad. -
Eindhoven : Technische Universiteit Eindhoven, 1999.
Proefschrift. -
ISBN 90-386-2641-X
NUGI 841
Subject headings: engineering design : knowledge management /
product data management / design history / design rationale /
design intent
Trefwoorden: ontwerpprocessen ; kennismanagement / product
data management / design history / design rationale / design
intent

Cover:
Teamwork supported by Mnemosyne, the mother of the Muses by Zeus and personification of the memory. The ancient Greeks already knew that a healthy memory is a prerequisite for intellectual and artistic activities. Long before the invention of book printing, the ancient Greeks practiced their 'Mnemotechniques,' i.e. methods and techniques to store and recollect things in the human memory.

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Capturing and Re-Using the Knowledge Behind the Product

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr. M. Rem, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op donderdag 30 september 1999 om 16.00 uur

door

Silvan Wiegeraad

geboren te Sittard

Dit proefschrift is goedgekeurd door de promotoren:

prof. dr. ir. R.F.C. Kriens
en
prof. L.J. Leifer, PhD.

Voor mijn oma, Riet Kreugel

Contents

Summary

The re-use of previously gained knowledge and experience in the development of complex mechanical products, like cars, planes and photo-copiers, is problematic. The documentation that generally remains from product development projects is aimed at providing just the minimum of information that is required to manufacture, use, maintain and disassemble the released product. This information is not aimed at supporting complex modifications or the development of the next product generation. Moreover, design processes are becoming increasingly complex. Design activities are performed in multidisciplinary design teams, which may be co-operating from distant locations. The increased complexity of the organisation hinders the diffusion of knowledge and experiences among product developers that share the same field of expertise.

To enable a more effective re-use of design knowledge and information, a *Design History* information system has been developed. A design history system enables product development organisations to record the steps in which a product is developed, including the underlying decision rationales, and makes this information available for re-use. By means of the design history information system, designers can retrieve the decision making that underlies particular design choices and play back the evolution of the product during its design process.

Based on a review of the related research on design history, design rationale, and design intent systems, the requirements were defined for the design history system presented in this thesis. Key features of the required system are an efficient and non-disruptive capturing strategy that has been validated in practice, a prototype system that allows integration with product information, and experimental evidence that the information that can be retrieved from the system enables a more effective re-use of design knowledge and information than current practices in documentation do.

To capture the design history, a new representation model and a new working method were developed. The design history is captured in a descriptive manner by an observant, or a designer with this role, who captures only group decision making. This approach was tested on three cases, two of which were in industry. The experiments showed that the reasoning that underlies a design can be effectively captured by recording design decisions. The used representation of decision making by means of Issue-, Proposal-, Argument- and Decision elements, proves to be a very useful format. In evaluation with the observed design teams, it was concluded that the captured design history gives a complete and accurate description of the major design problems, their alternative solutions and the supporting and objecting arguments.

A prototype design history information system was implemented within a commercial Product Data Management (PDM) system. This way, the capturing of design histories becomes a part of the organisation's overall information management strategy. Moreover, design history data can be directly linked to the 'real' product data in the organisation. Nevertheless, the capture and storage of design decisions imposes no burden or constraints on the actual product model or business process model that is used to manage product data. The prototype design history system was filled with an earlier captured design history and then evaluated with respect to the requirements. The evaluation shows that the prototype system offers the required functions for effective capture, storage, searching and retrieval of design histories.

Finally, more insight was gained in the capabilities of the developed design history system to improve the re-use of design knowledge and information. During two case studies, the information needs of designers were compared with the information sources that were actually available to them, and with the information that is provided by the design history system. Both case studies showed that the information sources that were available to the designers, like drawings and reports, didn't support an effective retrieval and re-use. For an effective re-use, the underlying concepts, functions, alternative solutions and their underlying rationale are just as important as the information that describes the finished product. These types of information can be found back in a design history. For one case study, it was demonstrated that an earlier captured design history actually contained the information, that was needed for the original product's redesign.

The results are encouraging, the prototype design history information system can be used for further research on the re-use of information from design histories and the effects on the design process.

Samenvatting

Hergebruik van de kennis die ten grondslag ligt aan complexe werktuigbouwkundige producten, zoals auto's, vliegtuigen en kopiëermachines, is moeilijk. De informatie die gedocumenteerd wordt tijdens een ontwerpproces, is in de meeste gevallen slechts gericht op de overdracht van de minimale verzameling informatie die nodig is voor productie, gebruik, onderhoud en demontage van een product. Deze gegevens zijn niet geschikt ter ondersteuning van complexe productmodificaties of de ontwikkeling van de volgende productgeneratie. Bovendien is de trend waar te nemen dat de ontwerpprocessen zelf toenemen in complexiteit. Ontwerpprocessen worden in veel gevallen uitgevoerd in multi-disciplinaire ontwerpteams. Grote teams bevinden zich vaak niet op één fysieke locatie. De teamleden moeten intensief samenwerken vanaf diverse plaatsen, die zelfs in een verschillende tijdzone kunnen liggen. De overdracht van kennis en ervaringen tussen ontwerpers door middel van persoonlijke contacten wordt hierdoor bemoeilijkt.

Om ontwerpteams in staat te stellen hun kennis en ervaringen effectiever uit te wisselen en te herbruiken, werd een *Design History* informatiesysteem ontwikkeld. Een design history systeem stelt een organisatie in staat, de stappen waarin een product ontwikkeld wordt vast te leggen voor hergebruik, inclusief de achterliggende besluitvorming en de bijbehorende argumentatie. Ontwerpers kunnen in het systeem niet alleen terug vinden hoe het produkt ontwikkeld is, maar ook waarom en door wie.

Op basis van een literatuurverkenning van Design History, Design Rationale en Design Intent systemen zijn de eisen voor het te ontwikkelen design history systeem opgesteld. Nieuwe elementen hierin zijn de onwikkeling van een methodiek waarmee de besluitvorming door ontwerpteams op een beschrijvende wijze kan worden vastgelegd, de bouw van een prototype informatiesysteem waarbinnen de vastgelegde ontwerpbeslissingen geïntegreerd worden met de productgegevens uit een ontwerpproces, en onderzoek naar de daadwerkelijke bijdrage van het voorgestelde systeem aan een betere beschikbaarheid en terugvindbaarheid van ontwerpkennis en informatie.

Voor het vastleggen van design histories werden een nieuw gegevensmodel en een nieuwe werkmethode ontwikkeld. De design history wordt vastgelegd door een observator, of een ontwerper in die rol. Alleen groepsbeslissingen worden vastgelegd. Deze aanpak is beproefd in drie case-studies, waarvan er twee plaatsvonden in het bedrijfsleven. De resultaten laten zien dat een design history van een product op effectieve wijze kan worden vastgelegd. Het gebruikte model waarbij ontwerpbeslissingen worden weergegeven als Issues, ('Ontwerpproblemen') Proposals, ('Voorstellen') en Arguments ('Argumenten') bleek zeer bruikbaar. Tijdens evaluaties met de geobserveerde ontwerpteams werd geconcludeerd dat de vastgelegde ontwerpbeslissingen een volledig en correct beeld geven van de belangrijkste ontwerpproblemen, hun alternatieve oplossingen en de argumenten ter acceptatie of verwerping van de voorgestelde oplossingen.

Voor de implementatie van een prototype design history informatieysysteem is gebruik gemaakt van een commerciëel Product Data Management (PDM) systeem. Door deze aanpak kan het vastleggen en beheren van deze histories geïntegreerd worden met de informatie management strategie van een organisatie. Bovendien kunnen de vastgelegde ontwerpbeslissingen direct gekoppeld worden aan de formele productgegevens die de organisatie beheert. Desondanks legt het vastleggen en beheren van ontwerpbeslissingen geen randvoorwaarden op aan de structuur en het beheer van de productgegevens. Het prototype design history system werd gevuld met de gegevens uit een eerder vastgelegde design history. Een evaluatie van de functionaliteit van het systeem demonstreert dat het systeem de vereiste functies biedt voor het vastleggen, opslaan en doorzoeken van design histories.

Tenslotte werd meer inzicht verkregen in de bijdrage van het ontwikkelde informatieysysteem aan een beter hergebruik van ontwerpkennis en informatie. Aan de hand van twee case studies werd de informatiebehoefte van ontwerpers vergeleken met de daadwerkelijk beschikbare informatie, en met de informatie die te vinden is in een design history. De informatiebronnen waarover de ontwerpers tijdens de case studies beschikten, zoals tekeningen en rapporten van een eerder ontwerp, bevatten onvoldoende informatie voor een effectief hergebruik. Uit een analyse van de benodigde informatie blijkt dat de onderliggende concepten, functies, alternatieve oplossingen en de achterliggende redeneringen, net zo belangrijk zijn als de informatie die het uiteindelijke product beschrijft. Een design history biedt deze informatie. Dit werd voor één case gedemonstreerd. Hierbij werd een herontwerp-proces geobserveerd, waarbij de design history van het oorspronkelijke ontwerp beschikbaar was.

Deze resultaten zijn bemoedigend. Het ontwikkelde en gebouwde prototype design history informatiesysteem kan gebruikt worden voor verdere onderzoeken naar het hergebruik van de informatie uit design histories en de effecten op het ontwerpproces.

1 General introduction

1.1 Products and their creation

A fundamental characteristic that distinguishes mankind from animals is, that man has the ability to create and use tools which aren't available in a natural environment (Eekels 1998). Humans have the ability to create artefacts that help them to successfully survive in world that is full of dangers and that is scarce of food.

Since our first prehistoric ancestors created their first 'products', like meat carving tools, utensils for hunting, and weapons, a lot has changed. Most of the products that surround the modern man aren't dedicated just to survival. Moreover, the modern man hardly ever creates his tools himself. Nowadays, products are created by a complex chain of researchers, developers, manufacturers, suppliers, distributors and sellers. Products are manufactured with other products, and these production products, on their turn, are created with the support of yet other products.

1.2 Trends in product development

Manufacturers of discrete products like cars, planes, copiers and video recorders, and their supply chains are engaged in a strong competition on product quality, product costs and time to market. The product's value that is perceived by the customer, the product's cost price and price of ownership, and the time at which the product can be launched onto the market, are being determined for a large part during the product's development stage. Therefore, an effective creation of new products is of the highest importance for manufacturers to compete and survive.

Approaches that are currently being considered as key-elements to an effective product development strategy are (Jami J. Shah 1996):

- Integration of all product life aspects, such as manufacturing, environmental and market aspects, into the early development phases. This is achieved by multi-disciplinary design teams and by *Concurrent Engineering,*
- Focus on core competencies. New forms of co-operation and co-development with suppliers are being established,

- The development of product families rather than products for which there is only one possible configuration,
- Taking into account local advantages on a global market. Products are being developed, produced and sold from locations that are globally dispersed,
- Establish a flexible workforce by working with co-developers and outsourcing development work,
- The application of extensive product modelling and simulation techniques to enable first-time-right designs, decrease the number of physical prototypes, and develop more 'on the edge.'

During the 1990's, computer technology has become increasingly involved in the support and organisation of these improved processes. Since the development of a new product is mainly an information-based process, tools that support the creation, exchange and management of this information have become of the highest importance to development organisations. They are often considered as the 'enablers' to the improved and accelerated design processes.

With respect to the emerging application areas of computer technologies in product development, the following observations can be made:

- Computers get every year faster, larger and cheaper. This makes computation a key facet of engineering design environments (Jami J. Shah 1996),
- Computer-based product models have become capable to handle both geometrical and functional information as well as analytical models to predict product performance. This makes that today's Computer Aided Design (CAD) systems' capabilities are far beyond that of an electronic drawing board (Pratt 1997).
- Computers are increasingly integrated into large computer networks. This offers many opportunities for communication and co-operation on a global scale.
- Database technologies, in combination with computer networks, enable the storage, management and distribution of huge collections of design information among widespread groups of engineering designers.

1.3 Problems with the re-use of design knowledge, experience and information

By means of the previously discussed strategies and tools, manufacturers of discrete products have been well able to increase product quality and accelerate the development of new products. However, the strive for integrated, fast and first time right design processes also introduces new problems.

Products have become increasingly complex. The final product is defined by innumerable goals, functions, constraints, interdependencies, conflicts and compromises. There is no one who really has a complete overview of all that plays a role in the conception of this very product. If the product must be modified, it is almost impossible to do this in a consistent manner. Sub-optimisations that do not contribute to the overall business goals can't be avoided.

Performing product development activities in multidisciplinary design teams enables the designers to take more product life cycle aspects into account in a earlier stage. However, such an approach makes the exchange of knowledge and experiences among persons in the same field of expertise difficult. This result is that identical problems are being solved in different manners and the 'wheel is being reinvented' in different projects. Moreover, the expertise that was provided by a co-developing supplier, is even harder to re-use in future design projects.

The current way of working in project teams requires that product developers must flow through the organisation and take their expertise from one project to the next. However, if a person is being promoted into a position in which he doesn't need to apply certain parts of his knowledge and skills, or when this person leaves the organisation, his knowledge and experience are lost. Moreover, the human memory is not always able to recollect the very reasoning of past projects. To be able to perform the same design activities, the organisation must re-acquire this knowledge, before it can learn any further.

Currently, more and more product developing organisations are becoming aware that knowledge and information are critical to effective product development, but that they are unable to manage it properly. Especially successful innovation and accelerated product improvements require that new knowledge must be quickly acquired and embedded in an existing level of competence. The effect of organisational measures, such as the appropriate culture and contact networks to exchange expertise, and an effective human resource management, are limited. Product development organisations currently lack the ability to effectively capture, store and distribute their knowledge among large groups of physically distributed people.

The documentation that currently remains from product development projects is unable to support an effective re-use of the experiences and knowledge that were gained during design projects. Formal product documentation just contains baseline information, needed to manufacture, use, maintain and disassemble the released product downstream the product life cycle. This information is not aimed at supporting complex modifications or the development of the next product generation. The quality of other documentation that remains from development projects, such as reports, memo's and notebooks, varies due to the personal style of their authors and due to time constraints. Moreover, even if certain information has been documented well, then it may be hard to retrieve this very piece of information from a library, filled with thousands of these poorly indexed paper based documents.

1.4 Objectives

Product developing companies are in need of a system that enables them to effectively re-use product development knowledge and experiences from past design activities. This system will support product developers to innovate their products more rapidly and prevent them from 'reinventing the wheel.'

Current practices for documentation and information management in engineering design do not support the re-use of design knowledge and experience very well. To build an effective *design memory*, a new approach to represent design knowledge and information is needed.

An very effective approach may be the capture and retrieval of *Design Histories*. A design history is a record of the various steps in which a product was developed, of the decision making that underlies these steps, and of the rationale behind the decisions. In a design history, product development knowledge is represented as design decisions and their underlying argumentation. A design history system enables a product development organisation to store product development information in a well-structured fashion. By recording design histories, the design process can be played back afterwards and the reasoning behind design choices can be recovered in its original context. Such an approach is far more structured than the collection of reports, meeting minutes, planning's, drawings and other documentation that traditionally remains after completion of a development project.

Problem statement

To develop better tools for design information management, the Section Automotive Engineering and Product Design at the faculty of Mechanical Engineering, and the Stan Ackermans Institute, (at that time known as the Institute for Continuing Education IVO (Trum 1995)), of the Eindhoven University of Technology defined the following problem statement for the research that is presented in this thesis:

> *Develop an information system that enables product development organisations to effectively capture and re-use Design Histories. The aim of this system is to accelerate design processes and increase product quality by means of the re-use of design information. Part of the design history system is an effective strategy to capture design histories and a representation that enables an easy retrieval of information from the system. Moreover, a prototype design history information system must be built and its user functions have to be verified.*

The research is aimed at the development of complex mechanical products, for example, aeroplanes, automobiles, and photo-copiers. The research result should be a generic approach, which isn't confined to a particular design project or a specific information system.

Research limits
Not part of the research are:

- A formal evaluation of the benefits of the developed design history information system in terms of product quality, time to market and development costs. (However, early insights in the use of the system and the observed opportunities for design process improvements will be collected and reported,)
- The implementation of software that meets quality standards for commercial release and sales,
- The development of a design history information system for area's other than those as described above. The application of a design history approach for, for example, the development of software, printed circuit boards, integrated circuits, logistic systems or governmental policies, is not discussed as part of the current research, and
- A deep investigation in human reasoning, logical thinking and communication. In these area's the actual foundations for a design history representation can be found. However, they are out of the scope for the development and implementation of an operational design history information system.

Audience for the research results
The work that is presented here is directed to the following audience:

- Researchers in the field of Engineering Design, for which this work presents new experiences and knowledge in the area of design history and design rationale,
- Researchers in the field of Information and Knowledge Management, for which this work presents a new knowledge representation and a discussion of the specific constraints for knowledge management in a product development environment,
- Consultants and vendors of (software) tools for product development, for which this work discusses a new direction in which future design tools will possibly evolve,
- Chief Information Officers (CIO's) of manufacturing industries, for which this work presents an alternative approach to knowledge and information management in engineering design, and
- Managers and group leaders in development departments, as future users of design history information systems.

1.5 Research approach

Figure 1.1 shows the approach that was undertaken to develop the design history information system. The development of the design history information system is founded on four separate research areas:

1) Literature survey of design history, design rationale and design intent systems,
2) Definition of a representation model and an efficient capturing method,
3) Implementation of an operational design history database system, and

4) Research on the re-use of design history information and the effects on the design process.

Various students who were in their final year participated in the research. Several manufacturers gave us the opportunity to perform case studies, the most relevant of which are reported in this thesis. A CAD/PDM vendor provided the software and necessary support for the design and implementation of the prototype information system.

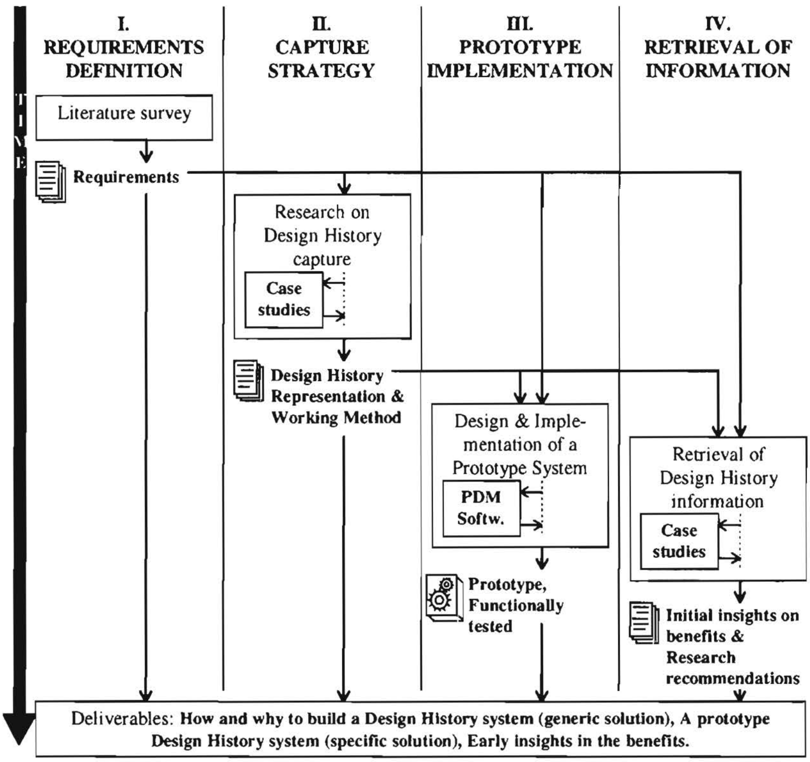


Figure 1.1: Approach to the development of a design history information system.

The literature survey of design history systems revealed that:

- There is no adequate capturing strategy that is fit for large organisations,
- The prototype information systems that have been developed for research purposes are stand-alone systems, they can't be integrated with other systems for information management in engineering organisations,
- More proof must be found that the re-use of decision information leads to large reductions in development time and an increase in quality.

Based on the experiences on design history capture which are reported in literature, a new approach for design history capture was developed. The approach is to capture design histories in a descriptive manner, capture only group decision making and let an observant, or a designer with this role, capture the design decisions. The approach was tested on three cases in industry.

To implement an operational design history system, it was decided to implement it as part of a Product Data Management (PDM) system. The integration of design history capture and retrieval with product data management has the following advantages:

- The capturing of design histories and their storage can be integrated with the overall information management strategy of the organisation,
- Design history data can be directly linked to the 'real' product data in the organisation,
- The re-use of design information in a PDM system is enhanced. Design histories enable new searching strategies for locating both product and decision information.

As far as the author knows, the current prototype design history system is the first system ever presented that integrates formal product information with the underlying reasoning.

Finally, this thesis addresses is the effects of using design histories. The aim of this part of the research is to gain more insights in the retrieval and re-use of information from the proposed design history system. This was achieved without using the implemented prototype design history information system. At the time the research on retrieval and re-use was undertaken, the prototype was still in an unfinished state. (See Figure 1.1.)

To address the re-use of design history information, clues were collected from three sources:

1) The claims for the effects on the design process as they have been reported by other researchers in literature,
2) An investigation on the re-use of a design history which was captured earlier, during one of the case studies on design history capture, and
3) A case study on the needs for design history information in a design project in industry.

This led to the first observations on how information from the developed design history system will be retrieved and (re-)used in practice.

1.6 Outline of this thesis

Chapter 2 is aimed at providing the reader with the necessary backgrounds on the subject of knowledge management for engineering design and its relation to design history. It starts with a discussion of state of the art approaches to information and knowledge management in an engineering design environment. This discussion is closed with the shortcomings of the current practices for an effective re-use of design knowledge and information. The second part of Chapter 2 introduces the subject of design history, design rationale and design intent systems. It discusses the opportunities to build a design memory which is based on recording design histories. Based on this discussion, the requirements for the design history system that is presented in this thesis are specified. The requirements are discussed at the end of Chapter 2.

Chapter 3 presents the research on design history capture. Chapter 3 starts with a discussion of the experiences in design history capture that have been reported by other researchers. Based on this discussion, a new approach is defined. The three case studies which were performed to test this approach are discussed in the remainder of Chapter 3. The conclusion of Chapter 3 summarises the representation model that was found to be the best for design history storage and the appropriate capturing method.

Chapter 4 describes the implementation of a prototype design history system. Input for the implementation are a set of objectively measurable specifications. They are based on the requirements from Chapter 2 and on the research on design history capture. The specifications are translated into a concept for a PDM system with integrated design history functions. After the presentation of the design history system, its functions are evaluated with respect to the specifications.

Chapter 5 describes the research on the retrieval of design history information. It starts with a discussion of the information requirements of engineering designers and the extent to which current information sources fulfil this need. Moreover, it discusses the benefits that are claimed for design history and design rationale systems and the proof that can be found for these claims. The discussion is closed with the implications for our design history system. This serves as background for the two case studies during which we investigated the need for information from a design history system and compared this with the information that was actually available to the observed designers.

Chapter 6 gives the conclusions of this thesis. It summarises the developed system and discusses the extent to which the system meets the requirements. Moreover, directions are given for future research and development activities.

This thesis is structured in such a way, that the reader mustn't necessarily read its chapters in sequence. In fact, it is possible to read Chapters 3, 4 and 5 independently from one another. Table 1.1 suggests alternative 'routings' for readers who are particularly interested in certain parts of the research.

Type of reader	Recommended routing through this thesis
Family, friends, students, apprentices, laymen	Chapters: 1 → 2 → 3 → 4 → 5 → 6
Researchers in Engineering Design	Chapters: 1 → 2 → (3 and/or 5) → 6, then the rest
Researchers in Information & Knowledge Mgmt	Chapters: 1 → 2 → 4 → 6, then the rest
Tool vendors and consultants	Chapters: 1 → 2 → 4 → 6, then the rest
Decision makers in industry (e.g. CIO's)	Chapters: Summary → 1 → 2 → Section 4.4 → 6
Managers and group leaders in industry	Chapters: 1 → 2 → 6 → 4, then the rest

Table 1.1: Alternative ways to read this thesis

2 *Requirements for a design history system*

2.1 *Introduction*

A design memory, that makes previously gained knowledge and experience available to the entire development organisation, is, if used in the appropriate manner, an enabler to a shorter time to market and accelerated innovation. However, one could ask, why does this necessarily have to be fulfilled by capturing design decisions? Aren't there other methods to improve the re-use of design information? Moreover, on what scientific foundations is an approach that captures decisions actually rooted? Is there scientific or practical evidence that such an approach will actually lead to organisational benefits?

This chapter is aimed at answering such questions. This is achieved by the following approach:

1) Explore what are the state of the art solutions to information and knowledge management in engineering design. Find out why these solutions apparently can't fulfil the need for a corporate design memory.
2) Explore the research and practical experiences by others on capturing and re-using design decisions, i.e. the research on design histories, design rationales and design intents. Assess the feasibility of such approaches to improve the re-use of design knowledge and information.
3) Define the requirements for a design history system that improves design re-use and organisational learning.

The requirements are used as a starting point for further development activities and are eventually used to evaluate the final result.

However, before the exploration of state of the art tools and methods for information and knowledge management in engineering design, first the 'raw material' for this work, i.e. data, information and knowledge, must be defined in the context of engineering design. Section 2.2 defines these concepts. Section 2.3 discusses the extent to which the state of the art methods and tools enable an effective re-use of design knowledge and information. Section 2.4 introduces design history, design rationale and design intent systems and discusses their feasibility as an enabling methodology for knowledge management. Based on this discussion, Section 2.5 draws the requirements for the design history system.

2.2 *Information and knowledge in engineering design*

2.2.1 *Data, information and knowledge*

The design process is an *information processing* process. It's input is information, for example a set of customer requirements or a product specification. The output of a design process is information as well. It is a plan that defines the actual product entirely, including the manufacturing processes and tools to build this product. By means of a complex process, designers translate the information that was originally given to them, into information that describes a product that meets the needs. This process involves the collection, creation, selection, transformation, evaluation and communication of an enormous quantity of information.

To a certain extent, the role of information in a design process can be compared to the role of materials in a production process. Like a production process transforms a given material into a product by adding, removing or forming material, a design process translates given information into a product by adding, removing and combining other information with this information. In a production process, machines transform the material. Intermediate products are transported from one machine to another by means of conveyor belts and other transportation devices. In a design process, information is processed by the brains of designers. Information is carried on to the 'next' designer by means of communication, which is either verbal or in some documented form.

However, a design process can't be as accurately prescribed and modelled as a production process. At the beginning of a design process, it can't be predicted what will be the actual flow of information that is necessary to translate the original requirements into a product. Intermediate results will strongly influence the course of action that is taken downstream the process. Moreover, many iterations will be required to bring a design process to a successful end.

Information is the 'vehicle' of the design process. It takes the product from its initial specification to a complete product definition. But what *is* information? And how is it related to data, communication, experience, knowledge and skills; terms that are often used in the same context? This must be defined before the tools and methods, that are meant to handle these entities, can be discussed.

Data are raw, unstructured and non-interpreted facts. Data are the raw material that are used for communication (Court 1995). Examples are sheets with numbers and characters and computer files, consisting of binary codes. A sequence of sounds, coming from someone's mouth can also be considered as a stream of data.

When a person receives data, reads it and interprets it, then data becomes *information*. Information is data that has a meaning to the receiver of this data. (Court 1995). For example, sounds become information when you can understand what someone says. Sheets with numbers and characters become information when you can understand the design alternatives that they describe.

To interpret data and understand its information content, the receiver of this information must have a certain frame of reference. *Knowledge* is this reference. It gives the receiver of information the ability to *understand* it. Moreover, knowledge gives a person the ability to *do* something with this information; to perform context and environment-specific tasks, based on this information (Weggeman 1997). For example, knowledge gives a person the ability to select the best design alternative or to identify missing information, or to identify the causes of malfunction and find a way to solve it. Knowledge cannot persist outside someone's mind. It is an absolutely personal asset. Moreover, knowledge is more than a set of rules or procedures for particular problems. It is the combination of explicit knowledge, like formal statements, and tacit knowledge, like individual experience, personal belief, perspective and meaning, that enables someone to apply knowledge to a specific task or situation (Nonaka 1995).

To acquire new knowledge, it must first be learned and practised. Individuals acquire new knowledge in different ways (Nonaka 1995):

- By practising tacit knowledge, e.g. by observation, imitation and training,
- By describing and modelling implicit knowledge, e.g. by articulating, reasoning, and modelling actions and behaviour,
- By combining more explicit bodies knowledge, such as rules, definitions, and models, and
- By bringing explicit knowledge into practice, to develop new skills and gain more experiences.

Knowledge can't be transferred directly from one person to another. Knowledge transfer requires *communication*, which is actually only the transfer of *data* between individuals. The 'knowledge emitter' must first express his knowledge, experiences, insights and arguments in information. Although this is information to the emitter, for the receiver it is only data. By interpreting this data, it becomes information and this new information might then result in new personal knowledge.

2.2.2 Knowledge management in engineering design

Knowledge Management in engineering design is concerned with the generation, collection, capture, management, co-ordination and utilisation of the constantly evolving collection of data, information and knowledge in an engineering environment (Prasad 1993). The aim of knowledge management is to assure that the right knowledge can be applied at the right place and at the right moment in a development process. Knowledge management comprises many strategies, methods and tools that cover long term as well as short term solutions, and organisational and human-centric measures as well as approaches based on advanced information and communication technology. This section discusses several state of the art approaches to knowledge management that are currently applied in product development organisations.

Organisational measures

An effective knowledge management strategy starts with organisational measures. Organisational measures take care that the right people develop the right knowledge, that they participate in the right projects and that there is the right culture for sharing and distributing knowledge and information. Some organisational aspects that may be included in the overall knowledge management strategy are:

- Human resource management, which may include career planning, employability and training,
- Product innovation strategies, from which the skills and competencies that are essential for success may be derived and planned to be acquired,
- Organising work in multidisciplinary design teams, which stimulates people to share and exchange their knowledge, and meet new people in every new project, and
- Cultural measures, aimed at achieving the right culture for sharing knowledge and information, and for stimulating the documentation of acquired knowledge and experiences.

The increasing complexity of product and process, the collaboration among multiple sites across the world, the intensified co-operation with suppliers and the increased amount of work that is being outsourced, won't allow that organisational measures in itself lead to an effective management of the organisation's knowledge. Moreover, the insight that knowledge is a corporate asset makes that organisation want to secure it by better formalising (describing), managing and controlling it (Korbijn 1999). Advanced information and communication technology offers new opportunities to improve organisational learning and to support the free flow of knowledge and information within the organisation.

Groupware

Groupware comprises tools that support communication and co-operation among people who are present in the same room, or distributed in time and place. A groupware tool can be relatively simple, such as e-mail, a discussion group on the Internet, or tools to exchange computer files. It can also be a technologically advanced tool, such as an Intranet site, (e.g. a shared project space, or a supplier database) or a collaborative engineering tool for sharing software applications and for video conferencing. Some groupware tools support live group processes, for example, a brainstorming tool or meeting software. Other tools facilitate asynchronous forms of co-operation, for example Workflow Management and electronic agenda tools.

Groupware tools are an opportunity for knowledge management because they can capture in-process discussions, communication and decision making (Feland 1997). Many groupware tools are supported by shared or distributed databases. The organisation can use this database technology to define structures in which it can manage all shared documents and data.

The technological opportunities of the Internet play an important role in groupware. Internet technology has become a standard technology for communication among computers (Laan 1999). This enables people to communicate, publish, distribute, exchange and retrieve information across the world, independent from the kind of computer or network they are using

Product data management

Whereas groupware is used for informal communication, a Product Data Management (PDM) system manages product information that has reached an official status. Each design process must result in a collection of information that fully defines the product, the processes that are required to produce it, and the tools needed to perform these processes. This information is used downstream the product life cycle, during manufacturing, distribution, sales, usage, service and recycling. The purpose of a PDM system is to guarantee the availability of this information at the right moment, at the right place, in the right representation, in the right version and for the right person (Pels 1997). This person is mostly a manager or an engineer from a product development or manufacturing department.

The basic principle of a PDM system is that there is only a single place in which unique occurrences of documents are stored and that this very document should be available to many users. This guarantees that all users have the right version of this document, when it's being changed. This principle is achieved by means of database technology. It requires that all products, assemblies and components are uniquely identified, classified and structured. In practice, this is mostly achieved by means of a hierarchical product structure that represents the released product, identifies its components and contains references to the documents that specify each component. The system uses this structure to keep track of versions of product information, product variants and alternatives, what product data is derived from what other product data, and the release level of each item in the database.

Chapter 4 will discuss the functions and architecture of PDM systems in more detail.

Artificial intelligence

Computer technologies that are based on artificial intelligence, such as knowledge based systems, neural networks, intelligent agents, rule-based systems, case-based systems and decision support tools, have capabilities that go beyond the structuring and retrieving of 'chunks' of human-interpretable data. Design support systems with artificial intelligence display intelligent behaviour and can perform tasks, based on information of the environment and the context of this task. These 'intelligent' systems perform activities such as diagnosis, planning, scheduling and giving advice. Real-world knowledge is formalised in these systems, for example in the form of rules. The knowledge is kept in a separate 'knowledge-base' and can be maintained and updated separately from the rest of the system. Based on data and information from the world outside the system, the system can derive new information and perform actions or make decisions based on this information.

Information systems for engineering design, that incorporate artificial intelligence technologies, offer very specific opportunities for knowledge management. They enable the organisation to formalise and externalise certain knowledge from one or more designers (mostly an expert or specialist in a certain field) and to build a system that can actually apply this knowledge. This leads to information systems that automate specific design tasks. (See for example (Adey 1997).) Major advantages of such an approach are that, once the knowledge-base is built, it can be easily distributed and put in action on multiple locations. Moreover, the organisation has become less vulnerable for the loss of this very expert who originally performed the tasks. For the expert, the intelligent information system can offer the advantage that he gains time to further develop his expertise (Wiegeraad 1999a).

However, many real-world design problems can't be formalised and modelled in sufficient detail to be solved by knowledge-based design systems. Therefore, the application of these systems is limited to design tasks that are dominated by routine work but which are so complex that their automation by means of 'traditional' software programs is problematic. Moreover, even in relatively stable knowledge domains, such as welding technologies or roller bearings, the knowledge and expertise evolves. Systems with a computerised knowledge base must, therefore, be continuously checked and updated. These activities require both an insight in the engineering design domain and methods for programming and knowledge modelling. Therefore, artificial intelligence is mainly applied in niches in engineering design, enabling and accelerating domain-specific complex tasks.

2.3 Re-use of design knowledge and experience

Despite the new opportunities and techniques for knowledge management in engineering design, development organisations have difficulties to preserve and make effective use of their corporate knowledge. This has a lot to do with the problematic characteristics of engineering design:

- Knowledge changes rapidly,
- New knowledge is acquired continuously,
- On a task level, activities are unpredictable,
- Design processes are highly iterative,
- Intermediate results determine the course of action downstream the design process,
- Decisions are dominated by incomplete information and assumptions, and
- Solving a complex real-world problem requires teamwork.

Organisational measures, as discussed in the previous section, are the starting point for the development of an effective knowledge capture, distribution, retrieval and re-use strategy. However, the effect of organisational measures is limited if people constantly move to other functions within the organisation or if they leave the company. Moreover, trends in development such as globally distributed development teams, increased co-development with suppliers, and working in multidisciplinairy design teams, make it more complex for designers to acquire the right information by means of their informal contacts and networks.

Design support systems that are based on artificial intelligence techniques enable organisations to describe, formalise, distribute and re-use their existing corporate knowledge. However, due to the instability and incompleteness of product development knowledge their application is limited to relatively small design domains.

Groupware offers interesting features for building a corporate memory. These kind of systems offer great opportunities to capture in-process information, reasons, discussions and rationales with a minimal effort. However, the structure and content of these systems aren't fit for the re-use of information over the borders of a project. The usability of such systems as an archive for development departments is comparable with placing all project documentation in a room without applying any control of the quality and organisation of this information (Conklin 1996). The use of indexing techniques may partly solve this problem. (See for example (Baudin 1993a, Baudin 1993b, Baudin 1992).) However, the indexing and filtering of information for later re-use is bound to require some extra effort.

PDM systems are currently the most effective solution for information re-use. Information is well structured, the quality of information is controlled and secured, and the availability of information is guaranteed for years after a project. The system hasn't intelligence by itself, but it provides a structure for all documents that were generated during the design process and for which it is important that they remain accessible and modifiable. However, currently, PDM systems only offer the *minimum* of information that is needed for processes downstream the product life cycle, such as production, distribution, use, maintenance and recycling. The re-use of information from PDM systems is mainly focused on the re-use of product geometry. More information underlying these parts, e.g. documents describing their purpose, the product functions and values that are related to this part and the selection processes and technical problems that surrounded it during its development aren't provided. The reason for this is that current PDM systems lack the ability to handle this background information. The management of information regarding operation, purpose and alternative solution concepts requires a structure that supports the unpredictable and iterative character of design processes (Kals 1998). An appropriate structure to handle this information does not exist.

It can be concluded that currently none of the state of the art techniques and methods are particularly well at supporting the distribution and re-use information, knowledge and experiences between parallel and subsequent product development projects. Neither artificial intelligence modelling techniques, nor product modelling techniques for PDM, or groupware techniques for sharing information, provide the right format for building a design memory. This raises the question how knowledge and information must then be modelled. A technique that combines the capture of more design information with a structure that is fit for group activities is *Design rationale.* It is based on the capturing and representation of 'clouds of information' around *design decisions.* The following section presents the approaches that have been developed so far in the field of design research.

2.4 *Design history*

2.4.1 *Design history, design rationale, design intent*

The documentation that normally remains from engineering design processes is largely product-oriented. It describes the final product, and sometimes some of the intermediate states that the product went through during its development. For example, the documentation may comprise not only the drawing of the final design, but also the initial specifications and some prototype designs. However, the process by which the final design and its intermediate states were achieved remains largely implicit. To capture and represent this process, several researchers have introduced the concepts of *Design History, Design Rationale* and *Design Intent.*

Lee (Lee 1991b) defines a design rationale as *an explanation of why an artifact* (which is any kind of product, for example a software product) *is designed the way it is.* The design rationale describes a dimension that is usually missing in design documentation, by augmenting the 'what' of the artifact's structure and function with the 'why' behind its design (Conklin 1991). A less abstract definition of a design rationale is that it is a *historical record of the reasons and the analyses that lead to the choice of a particular solution or product feature.* In this meaning, the term *design history* does also apply. Ullman (Ullman 1994) defines a design history as a record of the rationale behind design decisions and of the *intent* of designers. The design intent describes the designer's aims, goals, design requirements and constraints, used to plan and make decisions.

The design history (or the design rationale or the design intent) is a communication from the creator of an artifact to those who later must use or understand it (Conklin 1991). Design histories are particularly useful for that, because they include not only the reasons behind a design decision, but also the justification for it, the other alternatives considered, the tradeoffs evaluated, and the argumentation that led to the decision (Lee 1997). This makes them useful for supporting consistent designing, design modifications, design re-use, design documentation and learning.

The challenge for design history research is to find the most helpful and accessible representations of design reasoning for both developers and subsequent designers which minimise the non-productive effort required to create them (Shum 1994). The following sub-section discusses some of the representations that have been developed and evaluated in the past three decades.

2.4.2 *The origin of design history*

The original motivation for the development of design history, design rationale and design intent systems was the desire to make computer systems that would better support human thinking and reasoning processes. Computer systems that can well support these mainly mental and human-centric processes, could offer great opportunities for knowledge-intensive tasks, such as problem solving, collaboration, decision making and *designing*.

In the late fifties, the idea emerges that, in contrast to formal logic, many day to day problems are solved with insufficient information at the problem solver's disposal. Therefore, the problem solver must rely on heuristics, experience and intuition. Such problem solving processes are dominated by what is called *Argumentation;* semi-logical structures of possible solutions, criteria, evaluations, assessments, assumptions, trial and error experiences and iteration cycles (Shum 1994). If these 'argumentative' processes could be captured in a computer-supported model or notation, this would have great opportunities for creating useful tools for editing, merging, undoing and transforming in the problem solving process. Moreover, such tools could offer a means to understand what another has done.

An breakthrough in this research is achieved in the early seventies when Rittel develops the Issue-Based Information System (IBIS) in 1972 (Shum 1994). IBIS is a method for improved reasoning and problem solving. It uses a notation that represents the current state of a problem solving effort as a graphical network of problems, alternative solutions and arguments. The IBIS notation will become the 'mother' of many other semi-formal design rationale and design history notations.

Rittel, a professor in urban planning and design, describes intellectual work as the solving of problems. He distinguishes 'tame' problems and 'wicked' problems (Shum 1994). Tame problems are problems that can be solved with a high level of confidence, by virtue of the maturity of certain fields. For example, the selection of a roller bearing according to a set of well-defined requirements and according to the supplier's guidelines, can be considered as a tame problem.

In contrast to tame problems, wicked problems have the following characteristics that make their straightforward solution difficult. They;

- can't be easily defined in such a way that all stakeholders agree on the actual problem to be resolved,
- require complex judgements on the level of abstraction at which the problem must be defined,
- have no clear stopping rules,
- have better or worse solutions, no right and wrong ones,
- have no objective measure of success,
- require iteration,
- have no given alternative solutions - these must be discovered and
- often have strong, moral, political or professional dimensions, particularly for failure.

The resolution of wicked problems is dominated by communication, argumentation and negotiation. Often, this is done in multidisciplinary teamwork.

The IBIS method organises the resolution of wicked problems around 'Issues' (Conklin 1989a, Conklin 1989b), see Figure 2.1. Any problem, concern, or question can be an Issue and may require discussion in order for the design to proceed. Each Issue may have many *Positions.* A Position is a statement or assertion which resolves the Issue. Often Positions will be mutually exclusive for each other, but the method doesn't require this. Each of an Issue's Positions, in turn, may have one or more *Arguments* which either support that Position or object to it.

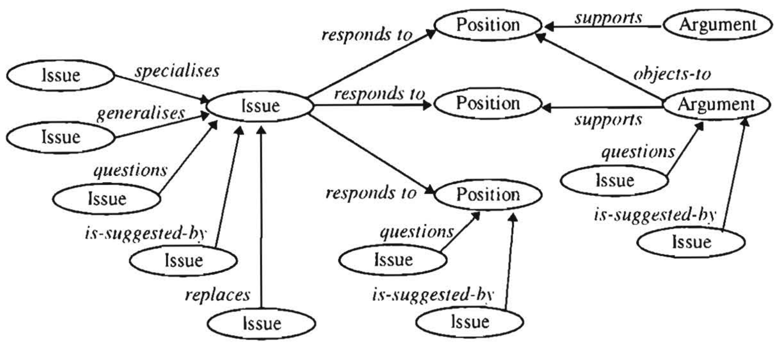


Figure 2.1: The nodes and relations of the Issue-Based Information System. (Adapted from (Conklin 1989b).)

Typically, an IBIS discussion begins with someone posting an Issue node, containing the main question to be solved. Then, the same person or someone else generates Positions, to which Arguments may be linked. In addition, new Issues, which are raised in the discussion, may be linked to the graphical network. Issues may *Generalise* or *Specialize* other Issues and may also *Question* or *Be-Suggested-by* other Issues, Positions, and Arguments.

Originally, working with IBIS was a paper-based activity. In the beginning of the nineties, the development of design rationale notations gets the attention of more researchers, due to the emerge of computer technologies such as hypertext, computer-supported collaborative work tools and large databases (Conklin 1991). By means of these technologies, the capture, analysis, restructuring, storage, retrieval and re-use of design rationales becomes feasible for the large development projects for which this information would be so useful. This results in several new design rationale notations for software and user interface design. See for example (Klein 1993, Lee 1990a, Lee 1990b, Lee 1991a, Lee 1991b, MacLean 1989, MacLean 1991, McCall 1986, McCall 1989, McKerlie 1993, Potts 1988). Chapter 3 will discuss the differences between these approaches.

Shortly after, the first design rationale approaches for mechanical engineering design are developed. These representations provide a coupling between the network of issues, alternatives and arguments, and a model of the product that is under development. See for example (Aasland 1993, Aasland 1995a, Aasland 1995b, Blessing 1993, Blessing 1994, Chen 1990, Sep 16-19, Fischer 1994, Fischer 1991, Lahti 1997, Malmqvist 1995, McMahon 1995, Murdoch 1994, Nagy 1992, Ullman 1991). Chapter 3 will give more details on the differences between these approaches.

The research on design history and design rationale systems hasn't lead to the application of these systems on a large scale in product development organisations. Nowadays, the organisations structure and store only the information that is being created in a design process anyway. Records with decisions and the underlying rationale can only be found back in unstructured sources such as designer's notebooks, meeting minutes and e-mails.

As far as the author knows, the research on design history and design rationale has lead to only one commercially available design rationale information system, called Questmap (Conklin 1998). This is a tool for the online structuring and representation of both individual and group discussions. It isn't particularly dedicated to mechanical engineering design.

2.4.3 Design history, an enabler to an improved design memory?

When combining the discussion on the 'roots' of design history with the discussion on the state of the art tools and methods for knowledge management in engineering design, earlier in this chapter, it can be concluded that the concept of design history offers new opportunities for knowledge and information re-use in engineering design. Organising product development information around the *decision making* that occurs during design is a new approach, which is not comparable with any other known approach to information and knowledge management. A design history enables a product development organisation to capture design information which currently remains tacit. Moreover, this information is probably essential for an effective re-use of designs and the underlying concepts.

A major advantage of a design history representation is, that it allows the capture of design knowledge and information in a purely descriptive manner. Decisions are such fundamental elements of the design process, that they can be detected and recorded, whether they are made spontaneously or in a very structured manner. For example, if a design team uses the Failure Mode Effects Analysis (FMEA) technique to analyse and improve a product's reliability and safety, then the improvements that are made to the product can still be represented as decisions that are augmented by the results of the FMEA analysis.

Another advantage of a design history representation is, that each 'cloud' of the goals, constraints, possible solutions and arguments, that result in a certain design decision, can be directly linked to the product information in which this decision is incorporated. For example, if a design team decides that two components will be glued together, then this will eventually result in a document, for example a drawing or list of materials, that prescribes that these very two components are glued together. The design history record that describes *why* the team has chosen this bonding technique, can then be directly linked to the document that contains the actual product information. This offers the opportunity to search *from* the final product to the underlying rationales.

However, a lot of issues need to be resolved first, before it can be concluded whether a design history approach is feasible or not. Although various representations and prototype systems have been proposed in literature, yet only few is known about the more practical aspects of these systems (Wiegeraad 1999b).

Regarding the capturing of design histories, a minor number of experiences have been reported in literature. Moreover, many potential capturing approaches haven't been explored at all. An important issue regarding the capturing of decisions is, in which the level of detail, or *granularity*, the decisions need to be captured. On the highest level in a design process, there is actually only one issue: 'What will our new product be like?' On the lowest level it is assumed that each individual designer makes a decision about every ten seconds. The best level of detail for a design history lies somewhere between. This is a compromise between capturing effort and richness and content of the recorded information.

Even less is known about the retrieval and re-use of design history information. A shared information base of design decisions seems as a very useful design tool. However, will designers actually use it, and be able to take advantage of the information that is offered to them? Moreover, if designers are taking advantage of the system, can the benefits be measured? More insight in this matter can only be gained by building a design history system and actually filling it with information and start working with it.

Moreover, new emerging technologies such as the Internet and Product data Management systems offer new opportunities to link decision information to product data and make this information accessible to a wide range of people. It should be considered whether these technologies can also be used to improve the effectiveness of a design history approach.

As a starting point for the further development of the design history system which is proposed in this thesis, a set of requirements were defined (Wiegeraad 1995, Wiegeraad 1996). The next section discusses these requirements in detail. Throughout the remainder of this thesis they will be used for the further deployment and evaluation of the design history capturing strategy, the prototype information system, and the re-usability of design history information.

2.5 Requirements

2.5.1 General aims

Requirement 1A - Main purpose

The design history system that is proposed in this thesis is aimed at an optimal re-use of design knowledge and information. The design history system will enable product development organisations to capture more of the reasoning and argumentation that underlies a product and effectively re-use it. This will be achieved by capturing, storing and retrieving information regarding the decisions that are made during design processes including the considered alternatives, and the underlying argumentation for the selected solution.

Requirement 1B - Users
The design history system is particularly aimed at large product development projects for the development of discrete, complex, mechanical products such as cars, planes, copiers and video recorders. Especially with these types of products, there exists an urgent need to capture and retrieve more detailed product knowledge and information. An effective solution currently isn't available yet.

The design history information system enables both engineers and managers to search, retrieve and learn the steps in which a product, or a family of products, was developed, including the underlying decision rationales.

In this stage, the application area of the design history system to be developed and its future users aren't specified in more detail. Our goal is to develop a generic solution that can be applied for the design of different types of products, in different types of industries and by different types of product development projects. Applications of design history systems which are dedicated to particular industries or design processes, are left for future research.

2.5.2 Design history capture and storage

Requirement 2A - Capturing method
The capturing method should be feasible in any product development organisation. The capturing of design histories should not impose a new way of designing, it should simply record the designers' reasoning. If an organisation uses specific design methods and tools to support their decision making, for example Failure Mode Effect Analysis and a brainstorming technique, then that should be recorded as well.

Although the design history *capture* must leave the design process unaffected, the *retrieval* will not. Shortly after it has been captured, designers will start re-using design alternatives and design argumentation for the resolution of new issues. So, from this point of view, capturing a design history *does* influence the design process. However, the methodology to 'capture and retrieve design histories' doesn't prescribe the design process. The organisation remains free to organise product development projects in the way it likes. The aim of the design history system is only to represent these processes as objectively as possible, the user must draw his own conclusions upon this information.

Requirement 2B - Content and representation of a single design decision
'Discussions' are the basic elements, a design history is built from. Each Discussion represents the process of solving a specific design issue or making a required design decision. Discussions are the basic chunks of design history information that the organisation captures, stores and retrieves. The actual information that designers will re-use, is stored *within* Discussions. To

ensure that each Discussion contains sufficient information, the following elements from the resolution of a single design problem need to be captured:

- The design issue or problem,
- The requirements (if any) to, or the intended effect of, the solution that is being sought,
- The proposed solutions,
- The way, the proposed solutions were evaluated. This might be an argument or a counter-argument, based on intuition, experience, calculations or experiments. It could also be a formal evaluation method where the alternative solutions are systematically evaluated against imposed requirements,
- The solution that was finally accepted and a record with the reasons for choosing this solution,
- References to other information and data that were used during the decision making. For example reports, drawings, handbooks, supplier documentation, measurements and calculations, and
- The persons that were involved in the decision making and the dates and times on which the problem was resolved.

A representation based on the IBIS model and its derives seems appropriate.

Requirement 2C - Representation of the relations between design decisions
The Discussions in the design history do not stand on their own. Each Discussion is related to other Discussions. An issue may require other issues to be resolved first. A decision may answer the originally stated issue not completely and leave new issues to be resolved next. A conflict with a previously made decision may arise and require that these decisions are reviewed and changed. Such interdependencies between discussions must be represented in the design history.

The relations between Discussions allow designers to retrieve chains of Discussions. This is important because the history of a specific part mostly isn't found in a single Discussion but is described by a series of decisions. Moreover, the relations between Discussions are needed to represent the actual design process. Like each step in the production of a product applies changes that contribute to the completion of this product (e.g. removing material, treating a surface or adding parts), each decision in the design process adds or removes information to the design. The relations between Discussions represent the flow of this process. They show what steps in the design process had to be made subsequently and what design work was done independently.

Requirement 2D - Integration with the documentation of other design information
Although product development organisations nowadays do not document the reasons behind design decisions, they do manage the product information that results from their decisions. Documents like specifications, measurement reports and drawings must be well managed for the effective communication and co-operation between designers. If the Discussions in the design history can be linked to this product information, then it enables the retrieval of design

decisions from product information and the retrieval of the product information that corresponds to what is discussed in design decisions.

The extension of the IBIS representation with a central product model seems appropriate and will be evaluated.

2.5.3 Retrieval and re-use of design history information

In an actual design situation, both the design histories from past designs and the incomplete design history of the product that is currently being developed, will be used by designers and their managers. The following requirements describe the various types of information needs that the design history system must fulfil. The requirements A to G are aimed at the re-use of design histories from previously developed projects. Requirement 3H, Requirement 3I and Requirement 3J are aimed at the use of the unfinished design history of the current design process.

Requirement 3A - Studying the reasons behind parts of the design
If a designer wants to re-use specific parts of a previous design, he wants to search for the sequence of decisions that have led to this part in the design. It is important for him to learn which functions a part fulfils and what requirements it meets. Other important information is to know what alternative solutions were considered on what levels of abstraction and what were, for the time being, the reasons for selecting the final solution. Based on this information, a designer can decide whether the considered part completely meets the current design problem or if some alterations or improvements must be made.

Requirement 3B - Searching for potential solutions
If a designer is faced with a problem, he might want to know how such a problem was solved in earlier situations. To extend the list with potential alternatives, the designer must be able to look for similar problems in the design histories of previous designs, retrieve all considered alternatives, including supporting or objecting argumentation.

Requirement 3C - Investigating whether a solution was previously proposed or not
Often, a totally different approach to a problem may seem better than the way it has been solved at present. For example, it may seem advantageous to use aluminium for a part instead of steel, because of its reduced weight. However, if this alternative material has been considered before, it is important to know why it was rejected at that time. In the case of the aluminium part, calculations may show that this will lead to an increase in production costs. If this information is not known, there is a substantial risk that the design team will again start working on aluminium and that they will find out that the part will become too expensive, only after having spent three weeks of work. On the other hand, the design history might reveal that no one ever choose aluminium because it was expected that it would become too expensive, although a proper calculation was never performed. In this case, the design history supports the decision to invest in the development of an aluminium part.

Requirement 3D - Retrieving specific documents which were used during the design process

For re-use in the current design process, a designer must be able to retrieve a document that was generated during a previous development project, for example a drawing, a calculation or a finite element model. By means of the design history, the designer must be able to play back a certain part of the design process, and retrieve the documents in the version as they were created at that specific moment in time.

Requirement 3E - Studying the lessons learned during the design process

When a development project is launched, it is important to know what were the most critical parts of the previous project. By means of an accurate analysis of the major iterations that occurred in a design process, effective measures can be taken for the next development project.

Requirement 3F - Studying the bottlenecks in the design process

By studying the design problems that delayed the design process, measures can be taken to improve the approach to such problems during future design processes.

Requirement 3G - Support for changes to the product

If a function or feature of a product needs to be changed, then this change may also affect other behavioural, functional, or aesthetic product aspects. Before a design team changes a part in the product, it must perform a thorough study of the new problems that such a change might introduce. By means of the design history, the designers can easily find the interdependencies between requirements, functions, components and their underlying decisions.

Requirement 3H - Consistent decision making

The most fundamental decisions, like the selection of the product concept, including its functions and desired behaviour, are made during the early stages of a design process. The later design stages must take these earlier decisions into account. However, as the product evolves, technical details may be conflicting with the original product concept. If the original product specifications are not taken in account well, the resulting product may be totally different from the product originally intended. A design history does not only contain the original product requirements, specifications, and concepts, but also the argumentation that underlies these choices. This supports the right interpretation of this information.

Requirement 3I - Support in conflict resolution

The teams in a design project mostly work autonomous. Each team has its own responsibilities and has the power to make decisions in its own specialist field. However, to achieve the desired product, which offers more than simply the sum of its sub-parts, excellent communication and co-operation between design teams are prerequisites. A design history enables design teams not only to share their product data, but as well the backgrounds and reasons behind it. This will support a more effective identification and resolution of design conflicts.

Requirement 3J - Control of project progress

The design history contains an actual description of the steps that were undertaken recently. By studying the incomplete design history of the current design process, more insight can be gained in the actual state of the product design. The design history enables a manager to observe the problems, that design teams are currently working on, which of these problems are currently delaying the process, and whether most decisions are founded on calculations or measurements or based on intuitive judgements. Moreover, the progress of raised, open and resolved issues can be compared with the progress of previous design processes.

3. *Capturing the design history*

3.1 Introduction

Problem definition
Before a company can use a design history, the company has to capture the appropriate information. 'Design History Capture' is defined in this thesis as *all recording, processing and structuring of data and information that an organisation must do to obtain design histories that are fit for use.* Capturing a design history does not only involve the recording of design decisions and their underlying rationales, but also the translation of this data into a clear and query-able structure.

The structured documentation of design decisions in a design history system isn't something that designers will easily do. If one would provide a design team with a design history system in which the designers can document all their reasoning and decision making, there is no guarantee that they will actually do this, and that they will keep doing it even when they are under time pressure. An organisation will only be able to capture design histories, if there are clear commitments on who is responsible for the recording, processing and structuring of the required knowledge and information. There should be guidelines that prescribe the required level of detail of the information. Moreover, it must be possible to make the capturing approach a part of an organisation's overall strategy on information and knowledge management.

Little research addresses the issues that are involved in capturing design decisions in practice (Ullman 1994). Most approaches in this research area prescribe only the format in which the information should be captured but not *how* the capturing should proceed. Little is known about the effort it takes to record a complete design history. It is unclear whether the capturing distracts designers from their actual work or not. No one actually knows how easily designers will adopt working practices that include the recording of design decisions.

This chapter addresses these issues. It describes the development of a capturing approach that is fit for application in practice. It is based on several case-studies which were performed in industry on real design processes.

Requirements
For the development of the design history system, a set of requirements was defined in the previous chapter. (See Section 2.5.) The following subset of these requirements is of direct importance for the development of an approach to design history capture:

- The *capturing* of a design history must leave the organisation-specific development process unaffected. (See ***Requirement 2A*** in Section 2.5),
- A basic element in a design history is a Discussion. It describes the process of solving a single design problem, or Issue. A Discussion is represented by a structure of the original issue, requirements on the solution, proposed solutions, the evaluations of the solutions, references to other information that was used during this decision process, and the final decision. (See ***Requirement 2B***.)
- The various relations that exist between Discussions must be represented. These relations must facilitate the retrieval of series of related decisions and must enable the (graphical) representation of the overall decision process. (See ***Requirement 2C***.)
- The Discussions in the design history must be linked to the actual product information that is created during the design process, such as documents describing conceptual designs, layout schemes, 3D models of the product and technical drawings. (See ***Requirement 3D***.)

Structure of this chapter
Chapter 3 presents the research that was carried out to find an approach for capturing design histories. The approach consists of two parts. The first part is the *model*, or framework, for collecting and structuring decision information. It can be expressed as a network of information elements, or entities, and their interrelations. It prescribes what types of information must be captured and how this is placed into a query-able structure. The second part is the capturing *method*. The method prescribes *how* the information must be captured. It prescribes who should perform the actual capturing and what activities must be performed before the actual data can be stored into a design history database.

The capturing method that is proposed in this thesis, is based on the descriptive recording of group decision making. This new approach was tested and evaluated by recording the design histories of real design processes for periods lasting up to six months. During these case-studies, the approach was refined and improved.

Section 3.2 investigates the related research on design history capture. The available models and methods for design history capture are discussed and evaluated against the criteria for the design history approach in this thesis. The section is concluded with the preliminary approach for design history capture.

Section 3.3 presents the empirical research. It presents the experimental method and the results of three case studies in industry.

Section 3.4 gives a final evaluation of the present approach for design history capture and presents the remaining research questions.

3.2 Approaches for design history capture

3.2.1 Representation models

A way to look at design history and design rationale representations is, that they represent our current understanding of human problem solving in engineering design processes. As discussed earlier in Section 2.4, design history representations find their roots in models of human thinking and reasoning. The purpose of a design history representation is to offer designers a means to structure and access the very different, but strongly related, elements that play a part in design problem solving, such as possible solutions, criteria, formal evaluations, assumptions, experiences and the lessons learned from iteration cycles.

A variety of models for design history and design rationale representation are proposed in literature. Apparently, some level of understanding in design problem solving has been reached, since all representations share the same basic structure of "Design Problem", "Alternative Solution", "Argumentation" and "Criteria" elements. Table 3.1 gives an overview of the different terms that are being used for basically the same concepts. It must be noted here that this difference in terminology is not without purpose. The different terms represent slight differences in the definitions of these element types and the types of information that the elements represent.

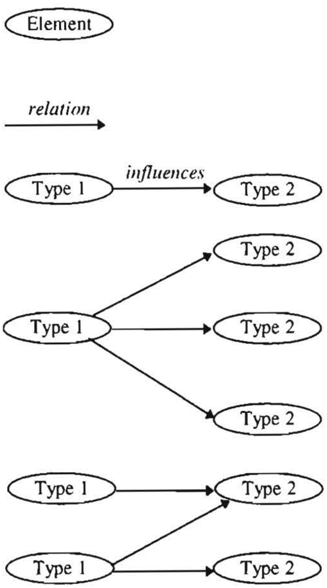
	'Design Problem'	**'Solution'**	**'Argument'**	**'Criterion'**	**'Decision'**
IBIS (Conklin 1989b)	Issue	Position	Argument		- -
DRL (Lee 1991a)	Decision Problem	Alternative	Claim	Goal	
PHI (McCall 1991)	Issue	Answer	Argument		- -
QOC (MacLean 1991)	Question	Option	Criterion		- -
Potts & Bruns (Potts 1988)	Issue	Alternative	Justification		- -
DHT (Nagy 1992)	Issue	Proposal	Argument	Constraint	Decision
Blessing (Blessing 1994)	Issue	Generate	Evaluate		Select
Aasland (Aasland 1995b)	Function	Solution	Evaluation	Specification	Selection

Table 3.1: Different terms for similar concepts in design history and design rationale representations

The various representations differ on the following aspects:

- The interrelations between proposals and arguments;
- The treatment of requirements, goals and constraints;
- The representation of the outcome of decision making in a separate decision element or not;
- The overall process structure that can be built from the captured design decisions;

The remainder if this section will discuss these aspects in more detail. For a comparison of the discussed models, they will be represented in the same way. Figure 3.1 provides a legend on this representation. The elements of a problem solving process are represented as ellipses. Each element represent a certain 'chunk' of information that can be identified in a design discussion. Eventually, an element will be represented by a set of attributes, for example, description, date, time, the source (name of a person) of this information, and the name of the person who captured it. The relations between these elements are represented as arrows. A distinction is made between 1:1, 1:n and n:m relationships.



Information Element, or entity, representing a type of object from the 'real world' and the information that is related to it.

Relation, representing a relation between two Elements.

Pronounced as: "Type 1 *influences* Type 2"

1:n relationship. An Element of Type 1 can be related to one or more Elements of Type 2

n:m relationship. One or more Elements of Type 1 can be related to one or more Elements of Type 2

Figure 3.1:Method used for the graphical representation of various design history models.

Proposal and argument interrelations

Most representation models express proposals and arguments on a single level. For example, in the Issue Based Information System (IBIS) (Begeman 1988, Conklin 1989a, Conklin 1991, Conklin 1989b, Yakemovic 1990), each Issue has only a single-level list of proposals and a single-level list of arguments. (See Figure 3.2.) The arguments are directly related to the proposals to which they refer.

However, the DRL *(Design Rationale Language*) model (Lee 1990a, Lee 1990b, Lee 1991a, Lee 1991b), allows that Claims (the Arguments) can support and deny other Claims. Moreover, in the DRL language, 'Questions' can be posed about Claims and 'Procedures' can be followed to answer them. (See Figure 3.3.) According to Lee (Lee 1990b) DRL was extended with Questions, Procedures and Claim-Claim relations to support discussions between designers on a *collaborative computer network.* On such a network, the users are separated both geographically and in time.

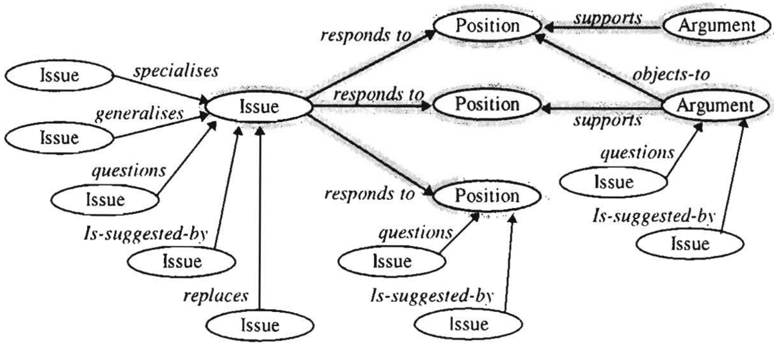


Figure 3.2: The IBIS model (Conklin 1989b).

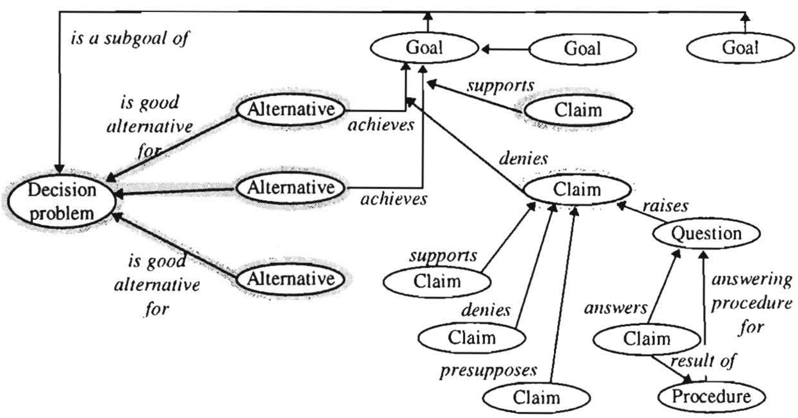


Figure 3.3: The DRL model (Lee 1991b).

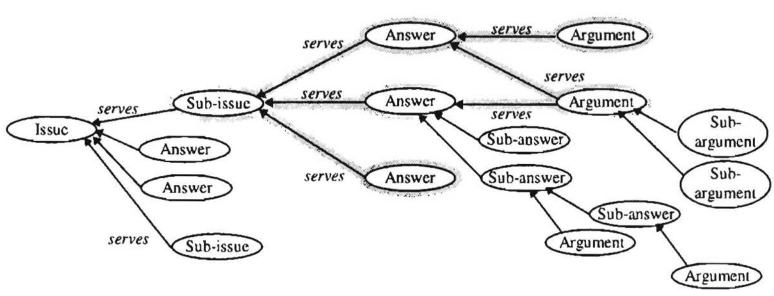


Figure 3.4: The PHI model (McCall 1991).

The PHI (*Procedural Hierarchy of Issues*) model (see Figure 3.4) extends in another way the expression of Proposals (called 'Answers') and Arguments. It allows the construction of a structure of sub-Answers under an Answer and a structure of sub-Arguments under an Argument. Each sub-Answer represents a more specific part of the solution than the parent Answer. Each sub-Argument further augments its parent Argument. The sub-relations express the levels of specificity and granularity (McCall 1986, McCall 1989, McCall 1991).

Requirements, goals and constraints

The IBIS model (Figure 3.2) hasn't a separate node for the requirements and constraints that are imposed on the solution, nor has it an element to express the goal that the solution is aiming at. In fact, these criteria are captured implicitly, in the Argument node. In most cases, two types of information can be found back in the description of an IBIS-Argument:

1) The constraint, goal or requirement, the related Position (i.e. Proposal) was evaluated upon, and
2) The reasons *why* the Proposal does, or does not, fulfil or comply with these criteria.

However, these two parts are not separated. They can be present in the same sentence. For example the argument description, 'My calculations show that the weight of this part will be much more than the required weight of 2 kg', contains both the goal (required weight 2 kg) and the reason why the proposal doesn't achieve it (based on calculations).

A separate node for the criteria which are used for the evaluation of solutions, might be useful for the representation of design discussions. For example, DRL (See Figure 3.3) has a separate 'Goal' element (Lee 1991a). The Goals have their own structure of sub-Goals, This collection of Goals makes is possible to see directly what is important for a good solution. In Sibyl, the design rationale system that is based on DRL, the Goals and Alternatives as represented in a matrix (see Figure 3.5). Each cell in the matrix is related to one or more Claims (i.e. arguments) that contain the reasons why the Alternative does, or does not, achieve the Goal. For each Claim, a user can give values for importance and plausibility. By means of these values, the Alternatives can be rated.

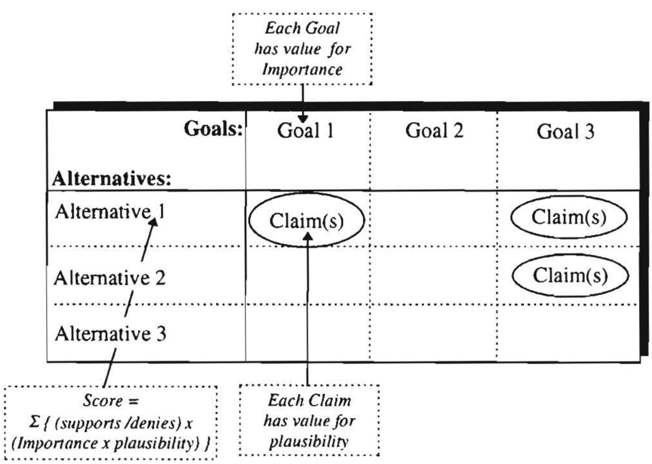


Figure 3.5: Claims, Alternatives and Goals in a Decision Matrix.

A step beyond DRL is to manage all constraints, goals and requirements that are used for decision making separately from the resolution of issues. This makes it possible to refer to the same constraint from different issues, and to manage the collection of requirements, constraints

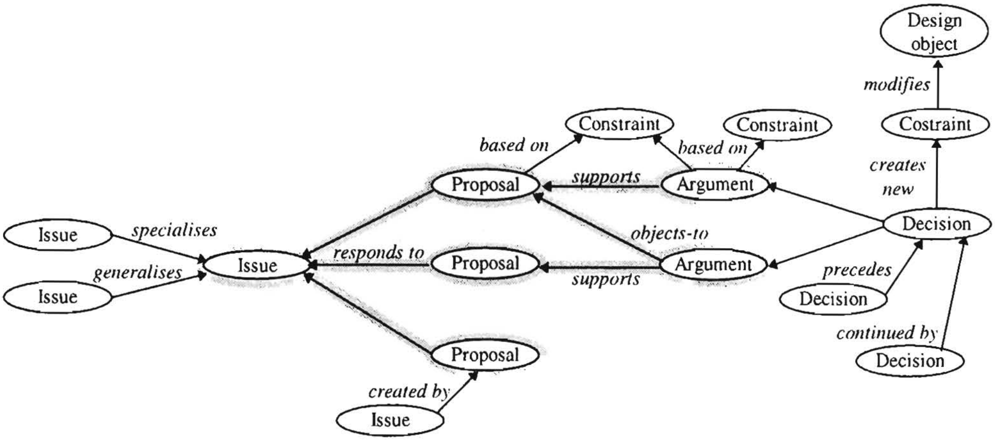


Figure 3.6: The DHT model (Nagy 1992).

and specifications throughout the design process. For example, in the DHT (*Design History Tool*) model (Chen 1990, Nagy 1992, Ullman 1991), there is a separate element, called 'Constraint.' (See Figure 3.6.) Constraints are defined as elements that 'identify all the values and the features' of the design (Nagy 1992). The constraint element is used for all information that *specifies* the design. Each decision results in one or more constraints. The resolution of other issues can be based on these constraints.

The decision

Most design rationale representations have a separate element for the final decision. When the decision is made, the original issue is resolved and the discussion is closed. The decision is made when the designers believe that they have collected sufficient information in the form of alternative solutions and arguments. The actual making of the decision is done by weighting the arguments and selecting the best solution.

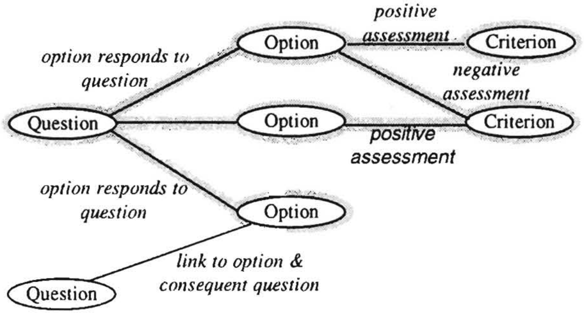


Figure 3.7: The QOC model (MacLean 1991).

The QOC model (Bellotti 1993, MacLean 1989, MacLean 1991, McKerlie 1994) doesn't contain a decision element. (See Figure 3.7.) Here, the final decision is a less important part of the rationale, because QOC is aimed as a tool for exploring the solution 'space' of Options and

Criteria. However, examples show that the best option is mostly marked by drawing a box around it (MacLean 1991).

Overall structure
Each design decision is related to other decisions. A decision may be based on the outcome of previous decisions, or an issue may require that another sub-issue is resolved first. These relations between the separate decisions are an important part of the design history. They enable the retrieval of related discussions and they provide a means to represent the process of raising issues and making decisions throughout the design process.

IBIS has an extensive set of relations to link Issues to Issues and other elements of the representation. (See Figure 3.2.) When a new Issue is raised, then this Issue is mostly linked to an existing Issue, Position or Argument. This way, the design process is structured in groups of related discussions. Figure 3.8 shows an example of a graphical representation of this network. Although the set of relation links provides an easy way to attach information to discussions that are still in progress, the IBIS representation is not fit for large amounts of Issues, Positions and Arguments. In these cases, the network becomes so complex, that the overview gets lost. In practice, this is solved by keeping more files of separate networks that deal with specific Issues (Yakemovic 1990). There are no guidelines for managing these files in a structured manner.

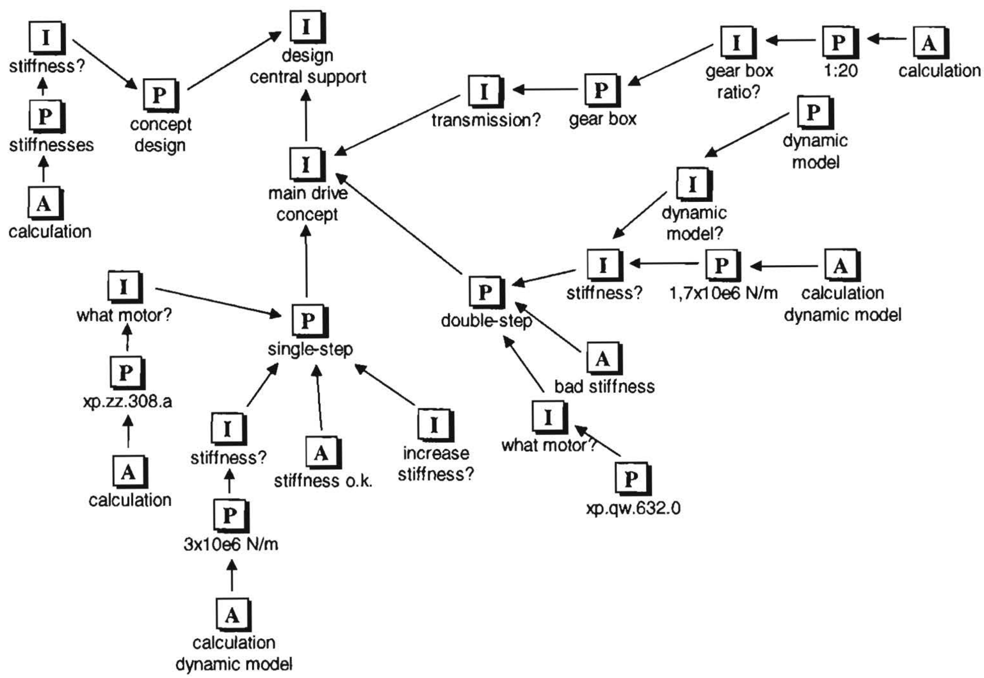


Figure 3.8: Graphical IBIS network. Adapted from (Abrahamse 1994).

PHI (see Figure 3.4) gives the user less freedom to link Issues to other Issues. There is only one relation type, the 'serve' relation, which is used to express the dependency relations between nodes. The serve relation is defined in the following way (McCall 1986): 'Issue A *serves* Issue B, if and only if the resolution of Issue A influences the resolution of Issue B.' Experiences show that, if a problem is solved using the PHI model, the serve relation is mostly used to express a relation of type 'is-a-sub-issue-of' (McCall 1991). The network of Issues has only one 'Root Issue' and can be graphically represented as a quasi-hierarchy (See Figure 3.9). This clear structure gives the user direct insight in what Issues are more important and what Issues are more detailed. However, the quasi-hierarchy does not show how it 'grew' in time. It shows the static, logical structure of all Issues that are involved for solving the Root-Issue. In most cases, the quasi-hierarchy is not built up in one time. The final hierarchy is mostly reached after several stages of re-structuring.

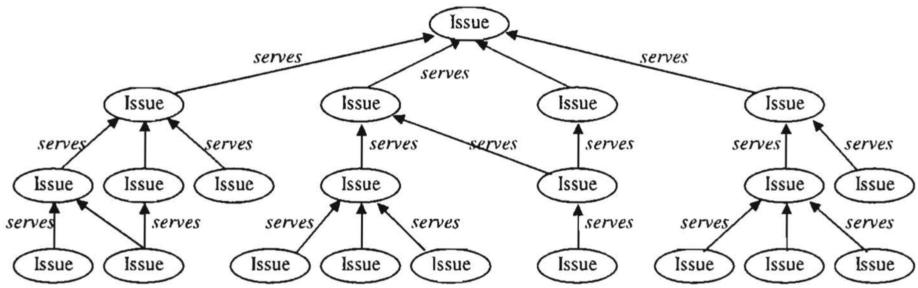


Figure 3.9: A quasi-hierarchical structure of sub-Issues according to McCall (McCall 1991).

IBIS and PHI do not take into account the actual product, that gets defined as a result of the decisions. Both in IBIS and PHI, issues start as a result of the discussion around other issues. The resolution of issues only results in newly raised issues. However, the origin of most issues is related to the *product*. During the design process, the product evolves as a result of decisions making. Every decision leads to new product information that is added to, or substitutes, parts of the design. The fact that the product is still in an intermediate state and that it doesn't satisfy all requirements yet, causes that new issues are raised and that designers start solving them.

In the Potts & Bruns model (Potts 1988), each Issue is derived from an 'Artifact.' (See Figure 3.10.) An Artifact represents a specification or a design document which contains architectural sketches, detailed designs, pseudo-code or structure diagrams. (The Potts & Bruns model was originally developed for software development.) The selection of the best alternative leads to new Artifacts, from which new Issues may be derived. This structure shows the interdependencies between product data and decisions. It represents the derivation path of all intermediate states, the product went through during its design. The Potts and Bruns model separates the design history in two kinds of documentation: documentation of the process (decision making) and documentation of the product (all intermediate design results).

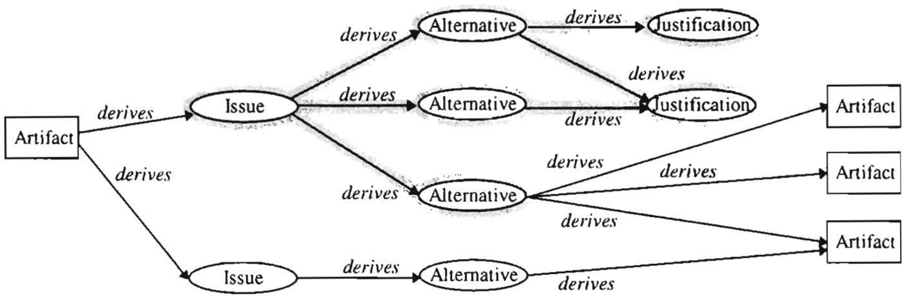


Figure 3.10: The Potts & Bruns model (Potts 1988).

More recently developed design history representations incorporate product models that are fit for mechanical engineering design. For example, Aasland (Aasland 1993, Aasland 1995a, Aasland 1995b) uses a 'Chromosome Model' to structure all product information. (See Figure 3.11.) The outcome of every decision is placed into one of three hierarchies. Every element in the hierarchy raises new 'Functions' (i.e. Issues) for which new 'Means' (i.e. solutions) must be found. Each hierarchy represents another view on the product. The Function Domain is for the functional decomposition of the product. The Organ Domain represents the decomposition of solution principles and concepts. The Construction Domain represents the physical structure. In Aasland's design history representation, the product model serves as the overall structure. Design decisions are linked to this information and contain information about the transitions between the separate domains.

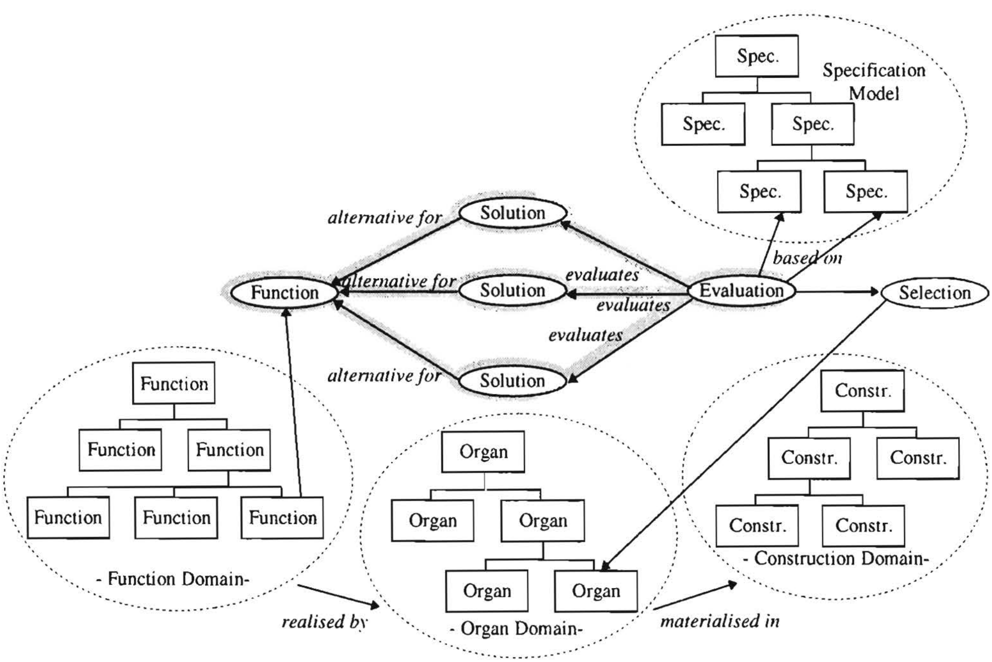


Figure 3.11: Aasland's Extensive Product Model for Design History Documentation (Aasland 1995b).

Another representation with a product structure as the overall model is PROSUS (*Process-based Support System*) (Blessing 1993, Blessing 1994). (See Figure 3.12.) Issues are grouped in 'Design Matrices', which contain all product and decision information that is related to an entire product, a (sub)assembly, a component or a standard component. (How this information is represented within a Design Matrix, won't be further discussed here.) All Design Matrices can be placed in a product hierarchy. The PROSUS structure is a placeholder for all information that is handled during design, including alternative solutions and their evaluation and selection. In contradiction to Potts and Bruns' and Aasland's representations, PROSUS-Issues are not represented as transitions between product data, but they are attached to the concerning product part. If a design team starts working on a new part, then this part must first be defined before Issues concerning the realisation of this part can be attached to it.

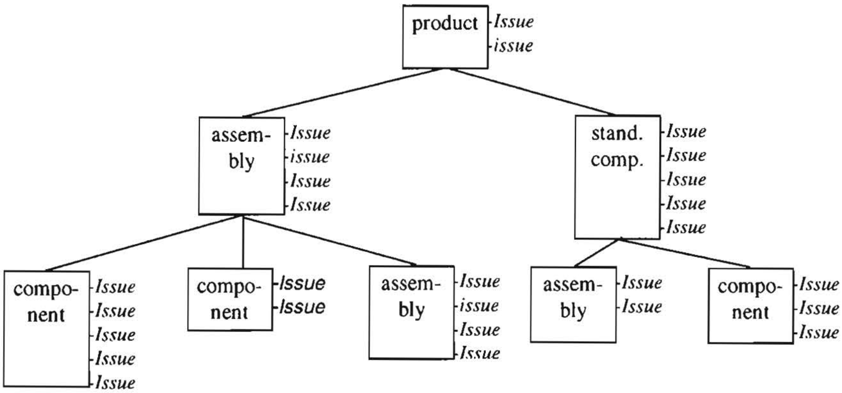


Fig. 3.12: The overall structure of PROSUS (Blessing 1994) as a hierarchical tree of *Product, Assembly, Component* and *Standard Component* nodes with related product and decision information.

3.2.2 Preliminary representation model

During some early experiments, we experimented with the previously discussed representation models (Beunis 1996, Doveren 1995, Doveren 1996, Maas 1995). For these experiments we used students who were working on a design assignment for a local company. We asked these students to record all their design issues, alternatives, and decisions in a logbook From the logbooks we reconstructed the design histories and represented them according to different representation models. Based on these early experiences, we specified the preliminary representation model which was used for the later experiments on design history capture. The model is partly based on the representation models that have been suggested by other researchers, and partly contains new elements to structure and represent design history information.

The core of our model is the following design cycle, which can be observed and recorded from every design process. (See Figure 3.13.)

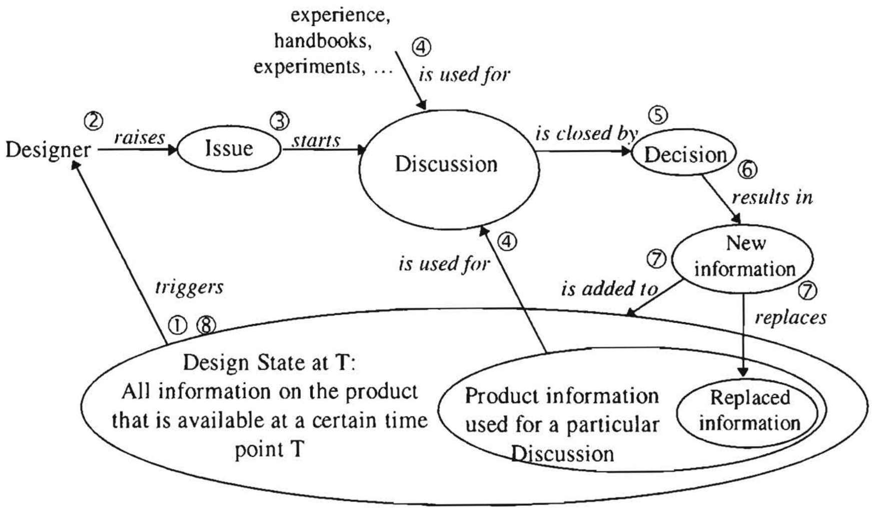


Figure 3.13: Basic cycle of decision making during a design process.

At a certain moment in time, a certain amount of information has been defined for the product that is under development. For example, the requirements have been defined, a function design has been made, and the product has been split up in modules, for which certain conceptual solutions have been proposed. We call this collection of information the *Design State* at that time point.

To proceed with this information, a designer or a design team must commit (1) to start working on a particular part or function of the design. This is done by raising (2) an Issue. The Issue describes the design problem at hand and the criteria which are to be met.

To resolve the Issue, the designer or design team starts (3) a 'Discussion' on it. During the Discussion, alternative solutions are worked out and are being evaluated. In this process, the involved designers use information from the current Design State, their minds and external sources (4), like handbooks, calculations and other designs. The Discussion is closed (5) when the designer or design team decides which solution will be used in the design.

When this decision is made, the Design State changes (7) because new product information (6) has become available. Moreover, old information may be replaced (7) by the new information. Based on this new Design State, new Issues may be raised (8) to proceed with the design.

Figure 3.14 shows the preliminary Design History representation model, which is based on this basic cycle of decision making. It consists of two sub-parts. A Product Model represents the product and its evolution during the design process. A Discussion Model is used to represent the decision making, by means of which the product evolves from its initial specifications into the final design.

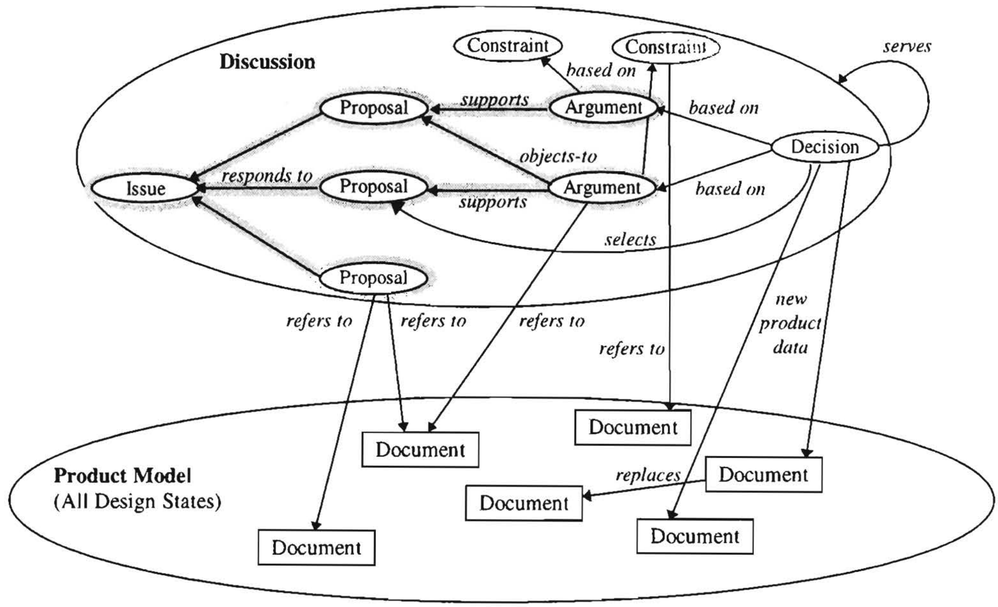


Figure 3.14: Preliminary design history representation model.

The basic representation of a Discussion follows the structure of problem solving in the IBIS model. (See Figure 3.2.) The Discussion starts with an Issue, which defines the design problem that must be resolved. To resolve this Issue, one or more Proposals are suggested. A Proposal describes a particular solution to the problem. In response to one or more Proposals, Arguments may be raised. Each Argument contains information that describes why, or why not, the Proposal that it refers to is a good solution, or why it is better or worse than another Proposal.

The design history representation will not provide Proposal-Proposal or Argument-Argument relations. For the approach presented in this thesis, it was decided *not* to support more levels of Arguments and Proposals under an Issue. The extensions in DRL and PHI improve the expressiveness of both representations but only when they are used as a *method* for structuring design decision making. For *descriptive* design histories, these approaches are not fit. Our early experiments in design history capture showed that it is difficult to interpret whether an argument is a sub-argument or not. Moreover, the networks of proposals and arguments tells us probably more about the chronological process of finding arguments and solutions, than that they contain more information about the reasoning that underlies the decision.

To represent the requirements, goals and constraints that are used for the evaluation of alternatives, a separate 'Constraint' element is used. The purpose of this element is to show directly what constraints are imposed on the resolution of a certain design problem and which criteria an acceptable solution has to meet. It may be difficult to capture this element objectively. Our early experiences showed that constraints and goals are mostly not stated explicitly, but that they are embedded in the occurring argumentation. Therefore, the explicit representation of the constraints that are imposed upon the solution is optional. Only if a goal, constraint or requirement is formulated explicitly, for example, a cost price target has to be met, or a construction may not exceed a maximum mass, then the Constraint element will be used.

The Discussion is closed by making the Decision. This element contains a time stamp of the actual decision and the final argumentation for the selected proposal. If a specific method is used for decision making (for example Value Analysis, or Quality Function Deployment), then the Decision element contains more information on this method and its deliverables (e.g. an evaluation chart, or a 'house of quality'). Our experience during the early experiments was that the Decision is the element that can be most easily observed and identified. The making of a decision is a clear event, it is the very moment that a designer or a design team judges that enough information about the design problem at hand has become available. Based on this information, a decision can be made about which all stakeholders feel confident.

Figure 3.15 shows the interrelations between Discussions and the product information in the Product Model. After an Issue has been raised, designers respond with Proposals, Arguments and Constraints during a certain period of time. Each Proposal, Argument or Constraint may refer to product information, for example, an earlier defined concept or a certain dimension. This is represented by means of the *refers to* relation. Since new product information may become available when the Discussion is still in an unresolved state, Proposals, Arguments and Constraints may only refer to product information that is part of the Design State at the very moment in time when this Proposal, Argument or Constraint was raised. When the Decision is made, new product information is added to the current Design State. This new information is related to the corresponding Discussion by means of the *New Product Data* relation.

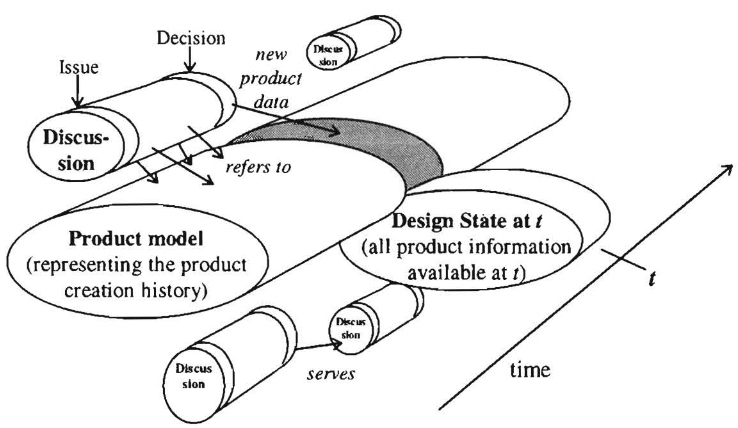


Figure 3.15: Interrelations between design decisions and the product structure evolution.

The actual content and structure of the Product Model will be discussed in Chapter 4. Although design decisions and their underlying rationale are currently not being captured, design teams in industry *do* manage their product information. Nowadays, most product development organisations use electronic archives like Product Data Management systems and shared hard disks to manage all their product information. Therefore, the capturing and the representation of the product information that is necessary to build the Product Model, will not be an additional activity. In the prototype Design History system, we will use an existing Product Data Management system for the storage and representation of product information.

To represent the interrelations among Discussions, *serve* relations will be used. (See Figure 3.14 and Figure 3.15.) The purpose of these relations is to capture the logical relations among Discussions. This will enable a user of the Design History system to track down the chain of related Discussions that lead to a specific feature or part of the product. (See for more details the requirements in Section 3.1.2.) The Serve relation is defined the following way: 'The Decision from Discussion A *serves* Discussion B, if and only if the resolution of Discussion A influences the resolution of Discussion B.' For example, there is a Discussion A, during which a design team selects a conceptual design, and there is a Discussion B during which the team makes a refinement to a certain component that is part of this concept. In this case, Discussion A *serves* Discussion B because another outcome of Discussion A would have influenced the outcome of Discussion B. Serve relations among Discussions can be expressed manually, when the Design History is being captured. However, in Chapter 4, an algorithm will be proposed by means of which the Serve relations among Discussions can be derived automatically from the interrelations between Discussions and the Product Model.

3.2.3 Capturing methods

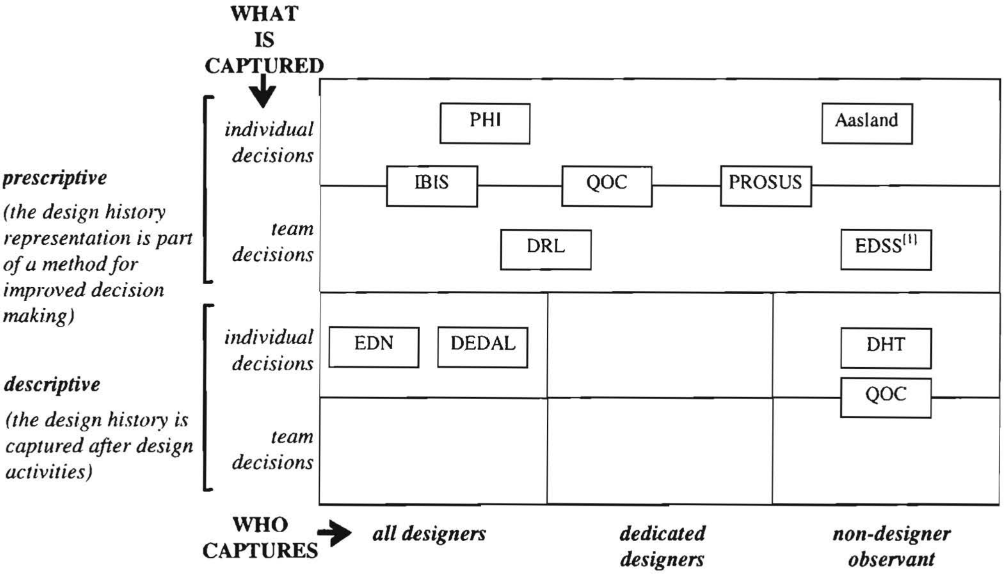


Figure 3.16: Design history capturing methods and experimental investigations.
[1]: EDSS is an IBIS-based method to improve design decision making (Herling 1995, Ullman 1997).

The actual capturing of design histories - or design rationales - is an unexplored area of investigation. Few practical experiences have been reported in literature. Moreover, not all possible approaches have been investigated yet (See Figure 3.16). To investigate which capturing method suits the approach discussed in this thesis best, the most related design history approaches by other researchers were categorised according to Figure 3.16. The corresponding papers were scanned for claims that support or object the various approaches for design history capture.

An approach is either *prescriptive* or *descriptive*. A *prescriptive* approach is a method that prescribes a format in which design decision making must take place. The aim of this method is an improved process of decision making. The design history is captured as a result of working according to this method. For example, the IBIS method is a prescriptive approach. Designers and design teams use it to express their decision making online in a format of Issues, Proposals and Arguments. This supports them in an objective evaluation of alternatives and helps them decomposing a design problem into sub-problems. A *descriptive* approach is aimed at the capture and documentation of design decisions for later re-use, and not at improving the decision process itself. The design history is captured by observation. This is done shortly after the actual decision making takes place. For example, to capture the design history according to the DHT model, designers were observed and video-taped. These records were then translated into a detailed design history.

Another distinction between approaches is *what* decisions are captured. The design history can be captured from group discussions, from individual decision making or from both. Capturing individual design decisions requires another approach than capturing the design history from teamwork. During individual work, all reasoning is present in the designer's mind and isn't verbalised.

If the design history is captured in a descriptive manner, then it is important to define *who* does the actual capturing. The design history can be captured by all designers, by several specific designers who capture the decisions for the rest of the group, or by a non-designing observant who's sole task it is to capture the design history. Combinations of these approaches are possible as well.

Prescriptive or descriptive

Most design history approaches are prescriptive. (See Figure 3.15.) The major advantage of a prescriptive approach is that the exploration of design problems is improved and that the design history or design rationale remains as a useful by-product. In literature, the following advantages are claimed for the use of a semiformal design history or design rationale notation.

In (Conklin 1991, Conklin 1989b, Yakemovic 1990), Conklin and others claim that IBIS makes meetings more productive. Team discussions do not wander from the original topic but are better focused on the issues. Teams can explore the set of unresolved issues and decide what will be the best sequence to discuss them or what issues should be resolved simultaneously. Moreover, the use of IBIS prevents that important unresolved issues are not forgotten downstream the design process.

More advantages of the prescriptive use of design rationale representations are given by McKerlie in (McKerlie 1994). The use of QOC for the exploration of design problems gives better insight in the problem and makes the problem more explicit. Moreover, QOC encourages designers to focus on a space of possible solutions, the use of QOC leads to an accumulation of design ideas.

Blessing (Blessing 1994) claims similar advantages of the use of PROSUS for methodical design. Experiments with designers that used PROSUS showed that the designers addressed more issues, generated and assessed more solutions and spent more time on the early design stages and on the documentation of their results.

However, the claim that the use of semiformal notations like IBIS and its derivatives improve the design process, is disputable. A major problem of these design rationale representations is that designers are unable to express their deliberations directly in terms of the semiformal node-link structures (Shum 1994). Conklin (Conklin 1989b) reports that designers experience difficulties to break their thoughts into discrete units, especially when the problem at hand is not well understood and those thoughts are vague, confused and shifting. New insights and ideas can't be captured as long as the problem is unstructured. When a breakthrough or point of understanding is reached, much that was deliberated previously may become incorrect and needs updated. It is reported that IBIS, QOC and PHI networks need restructuring during the design process (Conklin 1991, McKerlie 1994, Shum 1994).

Prescriptive design rationale models don't seem to 'speak' the language of the designers' thoughts (Shum 1994). To structure the problem into discrete units, identify their types, label and link them, requires prohibitive overhead (Conklin 1989b). Experiments by Davies (Davies 1995) during which designers that had to articulate their thoughts, were compared with designers that didn't articulate, show that the concurrent verbalisation affects design problem solving. The articulation of problems, solutions and arguments place an extra load upon the designer's mind. According to Davies, this leads to a less predictable and more opportunistic approach to design problem solving.

Other difficulties which have been reported on the use of prescriptive design history and design rationale approaches are:

- Schedule pressure leads to information not being captured. When the IBIS writer is in a hurry, he sometimes captures the bare minimum to record the essence of the issue, positions and arguments (Conklin 1989b, Yakemovic 1990),
- Sometimes, designers spend a lot of time on the exploration and evaluation of issues and solutions which are not very important and for which there is a good understanding and agreement anyway (McKerlie 1994), and

- IBIS needs learning and training. When working with others that don't use the method, the tools and its style of documentation must be abandoned (Conklin 1991).

A descriptive approach is not aimed at improving the actual problem solving processes, but offers a means to document design decision making in a format that is fit for retrieval and re-use. The design decisions are documented just *after* they have been discussed. A descriptive approach leaves the company- or department specific style of designing unaffected. It can be used in any environment, apart from the used methods and tools. However, for a descriptive design history capture approach, it should be noted that design decisions should be documented only shortly after they were actually made. If the time interval between the decision and its documentation is too long, then it may be very hard to include wrong turns or rejected alternatives into the design history. Moreover, schedule pressure may lead to information not being captured. There must be a clear commitment on who has the responsibility on the capture of what information.

A descriptive approach for design history capture, but which is not based in the IBIS representation, is the Electronic Design Notebook (EDN) (Hirose 1994, Lakin 1989, Leifer 1991). The Electronic Design Notebook (EDN) is an electronic version of the traditional paper-based notebooks of designers. It supports sketching and the quick and easy building of conceptual models. According to Lakin (Lakin 1989), explicit rationale and product models burden conceptual design activities. They require that too much attention is paid to details that can best be dealt with at a later stage. These details severely hinder the designer by being a distraction, by breaking chains of thought, and by costing more in productivity than can be simply measured by the amount of time it takes to do the formalisation. Therefore, the EDN prescribes no particular structure or working practice, the user himself must index the generated documents and connect parts of these documents by means of hypertext links. (See Figure 3.17.) In contradiction to a paper-based notebook, the generated sketches, calculations, models and comment can be *processed*. They can be easily searched, retrieved and shared with the other designers.

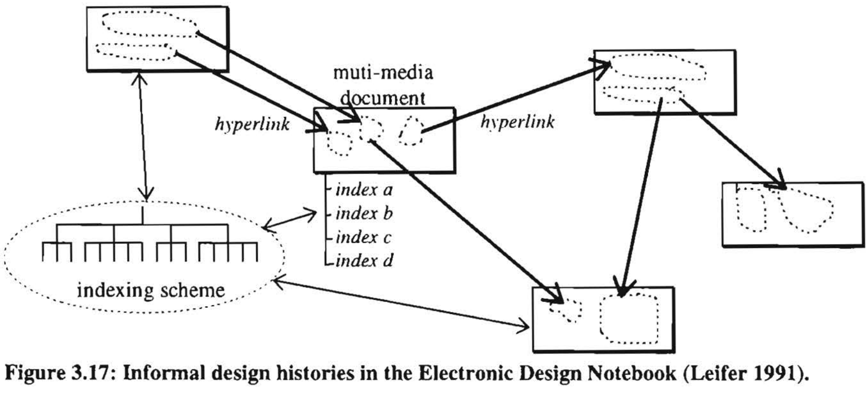


Figure 3.17: Informal design histories in the Electronic Design Notebook (Leifer 1991).

The EDN is probably the most easy and efficient way to capture information for a design history. However, the captured information is incomplete. Although the generated descriptions, sketches and other visualisations may well support designers to achieve their immediate goals, they are not fit for re-use by other designers. The usability of these records is comparable with that of the traditional paper-based notebooks. Moreover, the generated notebook information is too unstructured to allow easy retrieval of specific information. An intelligent indexing system, for example the DEDAL system which was proposed for the Electronic Design Notebook (Baudin 1993a, Baudin 1990, Baudin 1993b, Baudin 1992), enhances the EDN's retrieval capabilities. However, such a concept requires a product model and the indexing of a lot of information according to the model. After all, a substantial effort must be made to post-process the captured information.

Individual activities or teamwork

Design argumentation and decision making can be captured in the finest detail from individual design activities. This is where the actual design takes place; the generation of ideas, working out these ideas and the reflection upon the created solutions. On this level, the argumentation that *really* lead to the final solution can be found.

However, since all reasoning is still in the designers mind, capturing it for later re-use may be difficult. Ullman (Ullman 1991) performed experiments in which designers were observed during solitary activities. The designers were asked to speak aloud what they were thinking. The design history was handcrafted from video recordings of the designers. On average, one decision was captured from every two minutes of video. This was a very time-consuming process, it took approximately thirty minutes to extract and prepare each minute of video taped data.

Experiments by other researchers show that the capturing of design histories from individual design activities is feasible when a prescriptive approach is used (Bellotti 1993, Blessing 1994, Conklin 1991, McCall 1991). (See Figure 3.16.) However, as mentioned earlier in this section, the use of a design history representations as a method for individual decision making may burden conceptual design activities. Moreover, not all designers may be motivated to keep on using the representation for all their design problems, especially not when time stresses.

Design history capture from *group* activities is a prospective alternative. During group discussions, all problems, solutions and arguments are expressed in words. This makes them easier to capture and to write them down as text strings. Moreover, the work of individuals must first be discussed in a team meeting, before it is accepted and implemented in the design. A teamwork-based design history can thus also contain information that originates from individual design activities.

Several *prescriptive* approaches support teamwork and group decision making. (See Figure 3.16.) Examples of a *descriptive* approach for capturing group decision making and were not found in literature.

Who does the capturing

For prescriptive approaches to design history capture, it is clear who does the capturing. The designers themselves, who use the design history representation for structuring and expressing their design thinking and decision making, capture the required information.

For descriptive capturing approaches, there are more options. (See Figure 3.16.) Capturing the decision rationale shortly after the actual decision making will in most cases not immediately pay off. To ensure that the decisions are documented well and preserved for future retrieval, there must be a clear commitment on who captures what discussions.

The designers themselves could be responsible for the capturing of the design history. However, this may give rise to problems. Especially under time pressure, the documentation of design decisions and their underlying rationales is problematic. After resolving an issue, the designers will want to proceed with the next issues that are waiting, and don't want to spend time on the documentation.

If only the decision making that occurs in groups needs to be captured, then the design history can also be captured by an observant, who is not part of the design team. This person[1] gathers the required data by attending team meetings and by interviewing project engineers on a regular basis. The advantage of this approach is that the designers are not bothered by the documentation of their decisions. An observant can capture the design history in an objective and non-disturbing manner. Although proposed by other researchers(Carroll 1994, Hwang 1990), few is known about the opportunities and limitations of such an approach.

3.2.4 Preliminary capturing method

Figure 3.18 positions the approach for design history capture that was selected for further examination for the design history system that is proposed in this thesis.

The design history will be captured in a *descriptive* manner. No particular working method is imposed on the designers. The design decisions can be captured apart from any other method or tool that the organisation uses. Based on the experiences that have been reported by other researchers, our observation is that there is not enough proof for the claim that prescriptive design rationale approaches improve the design process. Most experiences show that there are advantages of these approaches, but that there are many problems as well. Although the approaches may be interesting for small, autonomous design teams, they are not fit to be used on a large scale, for example by an entire product development department. The best practice for the use of these design history approaches is *not* to use them for design episodes that require fluid thinking like creative design or brainstorming. Users should only start structuring

[1] Hwang and Ullman called such a person a 'design historian' (Hwang 1990) During this project, the more general term 'design history secretary' or simply 'secretary' was used.

their design problems after some problem understanding has been gained. This supports a descriptive approach that documents the design decisions just *after* they have been discussed.

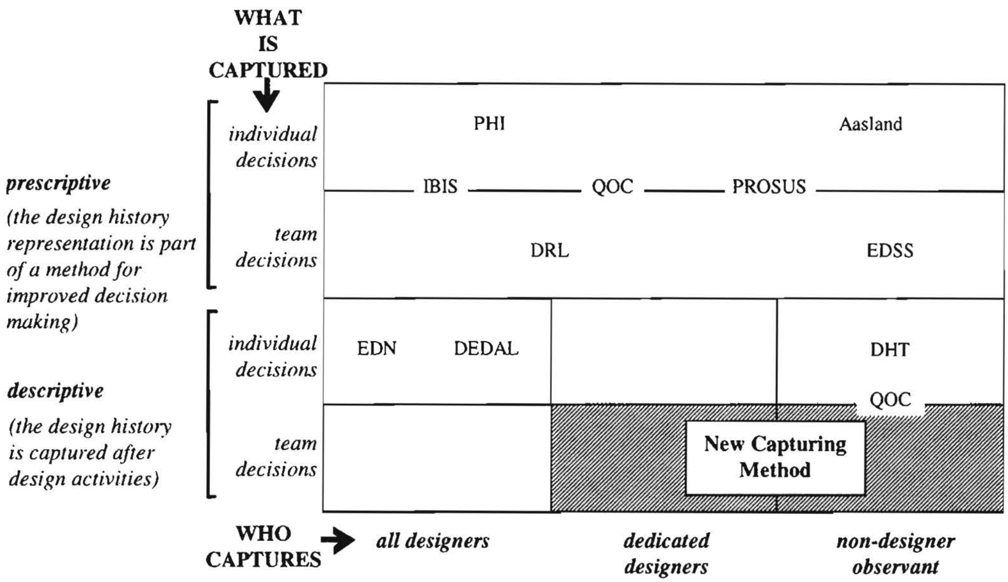


Figure 3.18: Preliminary capturing method.

Only group decisions will be recorded in the design history. During group discussions, all problems, solutions and arguments are expressed in words. This makes them easier to capture than individual decisions. Moreover, the capturing will be much more efficient because only the discussions between designers need to be observed. An approach that captures only group decisions may result in a less detailed kind of design history. The experiments will show whether this is a problem or an advantage.

To capture the design history efficiently, a combination of approaches seems best. Therefore, the design history will be captured by the following persons:

- An observant, called 'Design History Secretary,' who captures the major team decisions from team meetings, gathers more information by interviewing designers and stores the collected and structured information in the design history database,
- Designers in the role of Secretary, capturing the more detailed decisions from team meetings and other informal discussions, and
- Designers that review the captured design history episodes and add more in-depth information to it.

3.3 Experiments

3.3.1 Experimental set-up

The preliminary approach for design history capture was tested on three real-life cases:

- The development of a crash test-rig for vehicle components, which was performed by a team of seven persons, lasting six months,
- Three months of the work of a 4-person design team that worked on the mechatronic design of a printing unit for a high-volume copying system, and
- Four months of the work of a 3-person design team which was responsible for the conceptual design of the user interface of a product family, which consisted of copiers, scanners, printers and a network controller.

During these design processes, the design history was captured by an observant who attended team meetings and gathered additional information by interviewing the designers. The designers did not do any capturing activities themselves. During the experiments, the observant worked out the most efficient method for capturing the decisions. After the observation period, the observant evaluated the captured design histories with the observed designers. The observant questioned the designers about the correctness of the captured information, its usefulness for re-use and the differences with what the designers document traditionally.

For each experiment, the experimental setting, the best method for capturing and the results of the evaluation are discussed below.

3.3.2 Case 1: The development of a crash test-rig

The first case was at our university. We observed the development of a piece of test equipment by five students, an experienced technician from the laboratory's workshop and a university lecturer. Case1 is less representative for product development in industry than the other cases in this thesis. Most design activities were carried out by inexperienced designers and the project is, when compared with development projects in industry, of a relatively small scale. However, it has the following characteristics that make it particularly interesting for an experiment on design history capture:

- The *entire* design history can be captured, i.e. all decisions from the beginning to the end,
- The captured information isn't confidential, it can be used for later demonstrations,
- The deliverables of this project were used during a follow-up project. This follow-up project could therefore serve as a case to investigate the re-use of the captured information. (This case will be presented Section 5.3.2.)

Project
The Section Automotive Engineering and Product Design, Faculty of Mechanical Engineering, needed a piece of equipment for doing crash experiments. For the validation of their research, they wanted a test-rig for crash experiments with car body parts. On it, parts will be crashed under specified velocities. During each test, displacements, accelerations and forces will be measured. In a preliminary research project, the specifications for the test-rig were defined and translated into engineering requirements. A design concept was developed (see Figure 3.19) that fulfilled these requirements and which was realisable within limits of time and money.

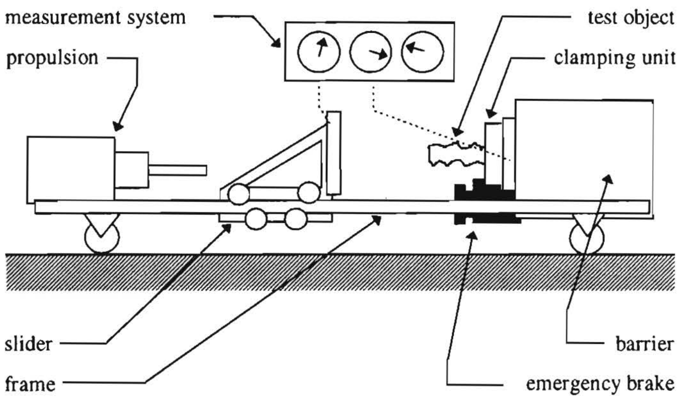


Figure 3.19: Concept for the crash test equipment

A design team was assigned to translate the concept into a detailed design that was ready for production. The team consisted of mechanical engineering students who were in their final year. The lecturer on vehicle crashworthiness supervised the project. A technician of the university workshop coached and advised the designers with respect to the production aspects.

The project started with a single student. After three months, the two other students were added to the team. One student was responsible for the frame and the propulsion system, one student designed the slider and one student worked on the clamping system and the emergency brake. At this point, we started to capture the design history. Another three months later two more students, both students in electronics, joined the team. They were responsible for the design of a measurement system. Three months later, nine months after the original start, the project was finished. Figure 3.20 shows the final design.

Capturing method
The observant performed the following activities to capture the test-rig's design history:

1) The observant attended the weekly team meeting. In this meeting, the team discussed the project's progress, planned further actions and made decisions. The observant made notes of the discussions and interrupted the conversation only if something was not clear to him. The meeting notes were unstructured. The best practice was to tag some parts of the notes with symbols for 'Issue,' 'Proposal,' 'Argument' and 'Decision' and to write in

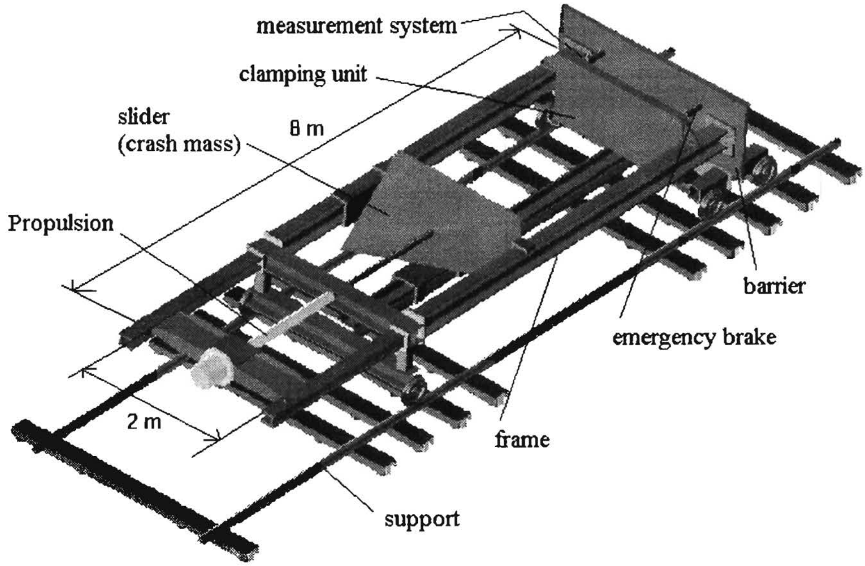


Figure 3.20: Detailed design for the crash test rig.

the borderline the names of persons who claimed something. A meeting lasted on average one and a half hour.

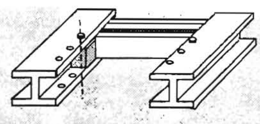
2) Directly after the meeting, the observant spent about a quarter of an hour asking some of the designers questions about specific Issues. Moreover, the observant collected the sketches, notes and other material that the designers came up with during the discussions. The observant made photo copies of the originals.
3) After this, the observant translated the notes into the format for design history representation. From his notes, he first identified the Issues and the parts of the discussion that were related to these Issues. Then he scanned the previously captured design history for similar issues that were in an unresolved state. If the discussion around an Issue was a continuation of an Issue that was previously raised, then this information should be placed under the former Issue. If an issue was new, then a new 'Discussion' was created for it. Finally, the observant identified the Proposals and Arguments for each Issue and documented the Discussions.
4) The Discussions were printed and stored in a file. Copies of the Discussions were kept in another file in the room where the designers worked.

Figure 3.21 shows an example Discussion in the design history. The Discussions were created in a word processor. The design history was one single file, which contained all Discussions in a sequence. Word processor macro's were available to (1) insert a new Discussion in the design history, (2) insert a new proposal in a Discussion, (3) insert a new argument in the Discussion or (4) to delete a proposal or argument from a Discussion. The document's front page contained a list of all Issues. A mark in front of an Issue indicated whether it had already been resolved or was still open. This ad-hoc tool worked fine for capturing design histories. Discussions could easily be generated by filling in the appropriate fields.

DISCUSSION 45 date: 12-3-97 persons: Leo Stool, Jerry Ice, Martin Barnings and Theo Svenson - captured by: S. Wiegeraad

Issue
What pin to adjust the propulsion-subframe?
date: **12-3-97** person(s): **M.Barnings** plan:
issues to be resolved first:

Proposal 1
Construction as displayed in picture. The calculation according to the handbook of our supplier shows that the pin diameter will be 65 mm. This is based on a pin of Steel-70 and a peak-force of 125 kN.

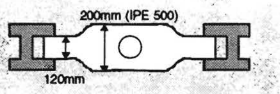


date: **12-3-97** person(s): **M. Barnings** refers to document: **REF45.1/Pin calculation**
issues to be resolved first:

Proposal 2
Use more, smaller pins which are placed in line.
date: **12-3-97** person(s): **M. Barnings** refers to document:
issues to be resolved first:

Proposal 3
Use a pin from hardened steel in combination with another beam. A beam of type HEM240 has a thicker flange (29 mm) than the beam of type HEB240 (17 mm).
date: **12-3-97** person(s): **J. Ice** refers to document:
issues to be resolved first:

Proposal 4
Custom-made beams will be used with a lower height and an asymmetric cross-section. The lower height reduces the bending stresses in the pin and the larger flanges allow a larger pinhole. The crossbeam will be adapted as represented in the sketch.



date: **19-3-97** person(s): **J. Ice** refers to document:
issues to be resolved first:

Argument 1
supports proposal(s): objects to proposal(s): **1**
The diameter of this pin is too large. The beam's fanges are not wide enough to bear a hole of 65mm. The maximum pin diameter that the constrcution allows is 25 mm.
date: **12-3-97** person(s): **M. Barnings** refers to document:
issues to be resolved first:

Argument 2
supports proposal(s): objects to proposal(s): **2**
The force will not be nicely distribute over more pins which are place in line. There is a risk that one pin will be loaded with 80% of the total force and the others with the remaining 20%.
date: **12-3-97** person(s): **M. Barnings** refers to document:
issues to be resolved first:

Argument 3
supports proposal(s): objects to proposal(s): **3**
Calculations show that the shear stress on a 25mm hardened pin is still too high.
date: **19-3-97** person(s): **M. Barnings** refers to document:
issues to be resolved first:

Decision:
selects proposal: **4**
final argument: This construction solves the pin-problem
date: **19-3-97** person(s): **M. Barnings, J. Ice, L. Stool, W. White**
issues to be resolved next:
new product data: Beams HEM 240, pin diameter 25mm, hardened steel.

Figure 3.21: Example of a Discussion

It took the observant one day a week to capture the design history. This day was used for attending the meeting, translating it into a design history record and distributing the updated Discussions across the team members.

Results

The captured design history covers a period of six months. During this period, the team had 17 meetings, resulting in 66 discussions. The average time from the moment the Issue was raised to the moment the actual decision was made, was 5,8 days. 27 of the 58 resolved discussions were solved during the same meeting as the Issue was raised. Eight Issues remained unresolved. The team recommended to explore them in more detail before building the test-rig. Figure 3.22 shows the opening and closing of the 58 resolved discussions in time.

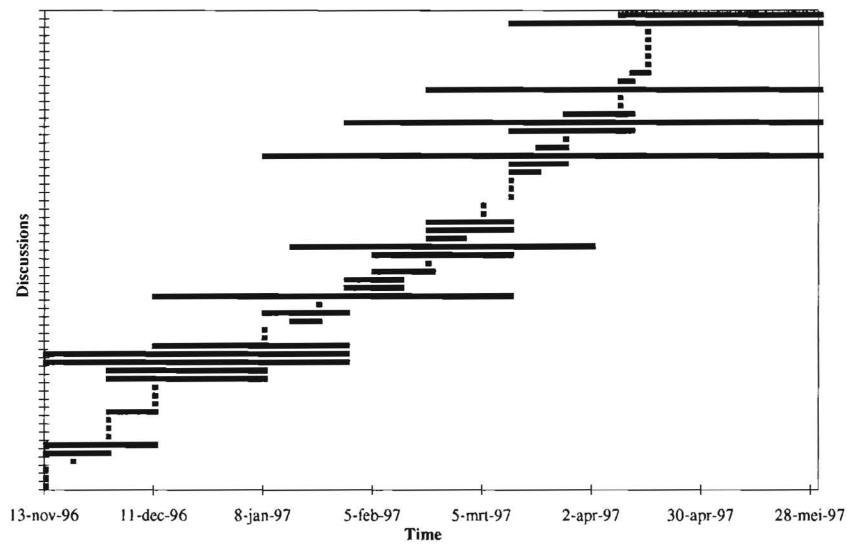


Figure 3.22: Opening and closing of Discussions during the project

On average, a Discussion contains 4,3 proposals, 3,9 arguments and 1,1 references. The complete design history file, including all references (sketches, calculations, extracts from component handbooks), consisted of more than 300 pages of paper.

Discussion

The test-rig's design history is a complete and correct record of the major design decisions and their underlying rationale. The only part of the design history that is less detailed, is the design of the measurement system. This part was designed by two students that worked relatively autonomous and who were not observed. We captured the parts of their design that were discussed with the other members of the group. As a result, the design history does only cover the definition of the measurement system's requirements, the presentation of the final design and the intermediate issues that were related with the placement and supporting constructions for sensors and other measurement devices.

Each student-designer had to write a report on his work. Compared with these reports, the design history contains all topics that are discussed in the reports and contains even more topics. Moreover, the design history contains more alternative solutions and more arguments on the rejected solutions. However, the reports contain better explanations of calculations. The design history contains these calculations as references, but at that moment in time, the calculations were still very sketchy. In the reports, they are described and explained in a better readable way.

As a matter of fact, the reports and drawing are also a part of the design history. After the project, a final Issue called 'what is the final design' was added to the design history. It contains references to all final documentation.

Little proof was found that the design history was already useful during the project. Although the captured paper-based design history was made available to all team members, they didn't access it very frequently. Only when they were writing there reports, they used the design history to remember what issues were addressed, what alternatives were considered and what were the arguments for accepting solutions.

Several times during the project, the designers re-discussed an issue which they had resolved a couple of meetings before. These discussions reoccurred because the designers didn't properly document their commitments. If they would have used the design history, they could have saved time because the final decision and the underlying rationale was properly documented in it.

The paper-based design history of the test-rig could not be easily queried. The design history file contained more than 300 sheets of paper, sorted in chronological order. For example, if you were looking at a Discussion on the concept selection for the clamping unit, it was difficult to find the subsequent Discussions during which the concept was worked out, or the previous Discussions about the requirements for the clamping unit. If this design history would be stored in a database system then the user is supported by far superior search and retrieval functions. The test-rig's design history is already for that. Each Discussion contains references to the product data it is based on and to the product data that was defined during the discussion. (See Figure 3.21.) Moreover, many Discussions contains references to the other discussions that they are based on. Later on, the test-rig design history was actually stored in a database and was integrated with a product model of the test rig. This is discussed in Chapter 4.

The observant captured the design history of the crash test-rig on his own. The designers didn't do capturing activities. The capturing of the design history did not disturb design activities, the design history is purely descriptive. It took the observant only one day a week to capture the work of the five designers who worked 5 days a week. This is a very low effort. However, this effort should be paid back by the improvement of the current design process or future processes. During the observed design process, only few improvements were gained by the representation of recently captured design processes. So most of the 17 days spent on capturing the design history, should be gained back in future. Chapter 5 discusses the re-use of design history information from this specific case in a follow-up project.

The crash test-rig's design history can be captured more efficiently if the designers do some capturing activities as well. For example, the meetings could have been captured by one of the designers. Probably this person would need less effort than the observant to capture this meeting because he would understand the reasoning better. If each meeting is recorded by another designer, a designer would only spend 1 day a month capturing the design history. This minimal effort is easily gained back. The designers will be more conscious of the information that is present in the design history. They will probably make more use of the records during the design process, for example to prevent redundant discussions. However, there is a risk that the designers will neglect the recording of their design decisions, for example when time stresses. This could be prevented from happening if the design history observant coaches the designers in their capturing activities and audits the captured discussions. In this case, the project manager could have fulfilled this role.

3.3.3 Case 2: The conceptual design of a printing unit for a copier

During two months, we observed a design team in industry. This enabled the evaluation and improvement of the suggested approach for design history capture and to gain feedback from professional designers. However, the observed project involved many more designers and spanned a longer period than what could be observed. Therefore, the we observed only one sub-team and during a period of two months..

Case 2 has been extensively reported in (Doveren 1996). See also (Wiegeraad 1997).

Project

The observed project was at Océ Research and Development in Venlo, The Netherlands. The project was aimed at the development of a new copier system, based on recently introduced printing technology. The new system had to achieve a higher resolution and printing speed than its predecessor. A year before the observant entered the project, it passed its predevelopment phase. The market introduction would take place within the next three years.

At the moment, the observant started recording the design history, the project consisted of 15 full-time engineering designers. Like all projects at Océ, it had a flat organisation (See Figure 3.23.) The entire project was located in several adjacent rooms. The project was sub-divided into design teams which were responsible for the development of a specific product part or function. Between the design teams, there was frequent informal communication. Design issues that required the commitment of more teams were discussed in special meetings with representatives from the design teams. The project was monitored by the project board, which consisted of the project manager and representatives from all design teams.

For the research on design history, our observant only observed the work of a single design team. ('Team A' in Figure 3.21.) The team consisted of an engineer in electronics, a physicist and two mechanical engineering designers. The team was responsible for the copier's printing unit. During the two months of observation, the team developed the unit's electronic working principle and its assembly concept, and started to build their first prototype.

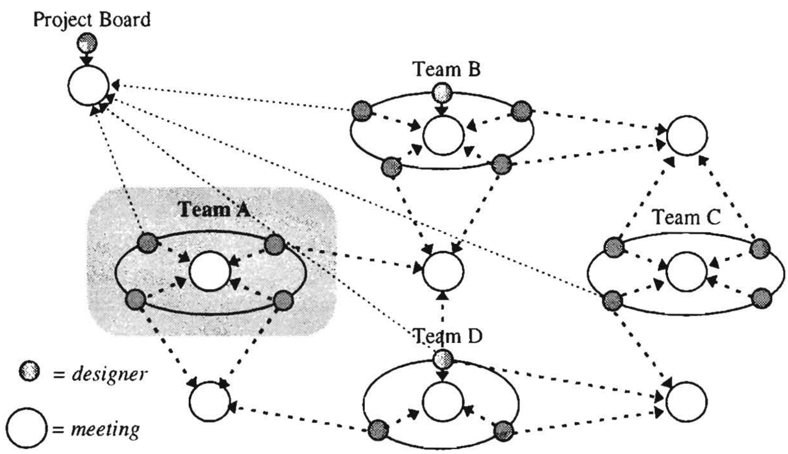


Figure 3.23: Project organisation

Capturing method

The observant captured the design history in a manner that was very similar to the approach for the test-rig. (See Section 3.3.2.) Regularly, the design team had a meeting. The observant attended these meetings, took notes from them and worked them out in design history format. The observant also observed meetings with members of other teams. On average, every two weeks such a meeting was held. The observant only recorded the issues which concerned the printing unit. The observant gathered additional information by interviewing the designers.

A substantial amount of deliberation and decision making was done during informal discussions. This was caused by the fact that the team worked relatively autonomously and the team members worked in the same room. To capture these discussions, the observant had to observe them or interview the designers shortly after the discussions.

Figure 3.24 shows an example Discussion in the design history. All Discussions were documented on paper and were kept in a file, sorted in chronological order. For reasons of confidentiality, the original information was adapted for this thesis.

After two months of observation, the observant stopped capturing the design history. During an evaluation session, the design team was questioned about their judgement of the accuracy and usability of the captured information. We questioned the designers about:

- the correctness and completeness of the captured information,
- the designers' judgement on the usability of the design history for themselves,
- the designers' judgement on the usability of the design history for future designers,
- whether the designers felt disturbed by the observant or not, and

- how the design history should be captured if the entire product development organisation would do it.

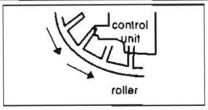
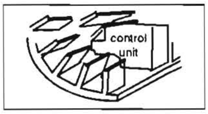
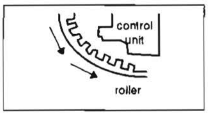
ISSUE 9 **description**	**19-10-96, M. de Vries, H. Jansen, B. Smit** We need more space for the control unit. How to create it? 
PROPOSAL 9.1 **description**	**19-10-96, M. de Vries** Mill away the cooling edges that will collide with the control unit. 
ARGUMENT 9.1 **description**	**19-10-96, B. Smit, + [ ], - [9.1]** The roller is an extruded part. Milling edges away will cause an increase in production costs.
ARGUMENT 9.2 **description**	**19-10-96, H. Jansen, + [ ], - [9.1]** Proposal 9.1 will cause an inhomogenous heat distribution on the roller surface.
PROPOSAL 9.2 **description**	**19-10-96, B. Smit** Make a roller with more (24), shorter (half height) cooling edges. 
ARGUMENT 9.3 **description**	**19-10-96, B. Smit, + [9.2], - [ ]** The roller can be extruded and needs no post-machining.
ARGUMENT 9.4 **description**	**19-10-96, M. de Vries, + [ ], - [9.2]** Production costs might increase due to the more complex form.
ARGUMENT 9.5 **description** **reference**	**19-10-96, H. Jansen, + [9.2], - [ ]** Calculations show, that if we halve the height of the cooling edge, we only need 4 more edges to let the roller have the same cooling capacity. See calculation X
ARGUMENT 9.6 **description**	**19-10-96, B. Smit, + [9.1], - [9.2]** There is no time to order a new roller. We planned to start testing the prototype next month. For these tests, the heat distribution on the roller is not important.
PROPOSAL 9.3 **description**	**19-10-96, M. de Vries** Use Proposal 9.1 for the prototype. test as well the heat distribution on the roller surface. Figure out the production costs of both Proposal 9.1 as well as Proposal 9.2
DECISION **rationale**	**19-10096, M. de Vries, H. Jansen, B. Smit, Accepts PROPOSAL 9.3** Due to time constraints, a provisional decision is made. The issue will be reviewed later on.

Figure 3.24: Example of a Discussion in the design history

Results

During a period of two months, the observant captured 19 design decisions and their underlying argumentation. To capture these decisions, 17 meetings were observed. 18 issues were resolved during the same meeting as they were raised. One issue was left open for 12 days. On average, each Discussion contains 1,7 Proposals and 2,8 Arguments.

An evaluation session was held four weeks after the observation period. The designers judged that the captured design history episode gives a complete and accurate description of the design team's deliberation during the observed period. The only information the designers missed, were their discussions about plans of actions. The designers suggested that the motivation behind planned work is important for future re-use as well.

The following event supports the claim that the discussions were accurately and correctly described. A few weeks after the observant stopped recording the design history, the design team had to review two previously made decisions, due to a design conflict. In the design history, the argumentation behind the original decisions was found back. During the evaluation session, the designers were well able to tell what was wrong with the original argumentation and what aspects they had overlooked.

The designers found it difficult to judge upon the usability of the captured information for future designers. They judged that the design history contains important experiences and reasons that are also valuable for other designers. However, to comprehend the argumentation behind a design decision better, more product information should be available to the user of this information. During this experiment, no detailed product information was added to the set of captured Discussions.

It wasn't possible to prove that the capture discussions already become useful shortly after they have been captured. The designers judged that the captured information might be helpful for reminding specific details. However, the records should not be used to control or manage design decision making because this might hinder informal communication between designers.

The designers claimed that their work was not influenced or disturbed by the presence of the observant. They judged that it improves the accuracy and objectivity of the design history when it is being captured by someone who isn't a stake-holder in the discussion. However, they felt that designers should have some responsibility in the recording of their design rationale for future designers as well. Therefore, not all capturing activities would have to be performed necessarily by an observant.

Discussion

The 'Printing-Unit Case' is an important experience in capturing design decision making and argumentation in real life. However, the case is limited in width and time. The captured design history contains only a cross-section of all decision making in the project because only a small team out of an entire project was observed. Moreover, we observed the team during a relatively short period of two months. The entire design process was planned to last three years.

The experiment showed that the proposed method for capturing the design history is objective, efficient in comparison with other capturing approaches and that it doesn't distract designers from their work. The resulting design history record contains the required information. The experiment shows that it is feasible to let an observant capture the design history. However, it is necessary that the effort that is needed for capturing a design history will be further reduced. During the experiment, it was necessary that the observant followed all what was going on.

Due to this, we estimate that an observant can only capture the work of a team up to 15 persons. Moreover, the observant must have enough background to understand all that is happening. It may be more efficient, to add an actual designer to a future design team than to add a person (with the same background as a designer) to a current design team to improve future design re-use.

The most efficient way to capture the design history in this specific case is much the same as the approach that was recommended in the previous section. The designers will record themselves their group decisions. For each project, one person (for example someone from the project staff) is assigned to coach and control the documentation of design decisions, to collect them and to make them accessible for others. The designers will comment and add information to the captured information. When these activities are integrated with other required documentation activities, this approach is probably much more effective than traditional ways of documentation.

It was difficult to evaluate the (re-)usability of the captured information. The current design history was paper-based and represented a limited period in time. Therefore, we could give the designers only a sketchy idea of the kind of information that they can expect in a design history and how they will be able to search for and retrieve it.

3.3.4 Case 3: The user interface for a family of office printers

The third case study was also performed at Océ-Technologies and was set up in the same way as Case 2. However, this time we did not capture a *mechanical* engineering design. The case study was aimed at capturing a part of the design history of a product's *user interface*. The design involved ergonomics, graphic design and software development. This enabled us to test the approach for design history capture in a different domain than mechanical engineering.

Case 3 has been extensively reported in (Beunis 1997). See also (Wiegeraad 1997).

Project
The observed design process was aimed at the development of a family of printers, scanners and network controllers that can be used in a local computer network. When the observation started, the project was in the transition between a conceptual and an engineering design phase. At this moment, the project had fifty full-time staff.

During the next four and a half months, our observant followed the design of the system's operating panels and their interaction with the user. This was performed by a small team, consisting of an industrial designer, a graphic designer and a software engineer. The team worked closely together with many other teams. This was caused by the fact that the user interface is functionally related to almost every part of the product. Moreover, the team co-operated closely with the department of industrial design so that the design would fit into the product line of the company.

Capturing method

The observant captured the design history from the meetings, that the team members attended. The observant took notes from the discussions and afterwards worked them out in a design history format. He gathered more information by interviewing the designers about the recorded issues. The observant did not capture user-interface related discussions which fell under the responsibility of designers from other teams. He only captured the design history of the user interface development.

Some meetings were less decisive than others. In these meetings, the actual decision was left to the responsible designer. These issues were more difficult to capture because the original discussion would not be continued in a subsequent meeting, nor would the responsible designer propose his most favourable solution to the other designers. Eventually, the responsible designer would describe his design in a report, which he would propose to the design team or the project management. The observant closed the underlying discussion when the team or the project management finally approved the report.

To represent the discussions, the observant used the same model as the one which was used in Case 2. Figure 3.25 shows an example. All Discussions were documented on paper and were kept in a file, sorted in chronological order.

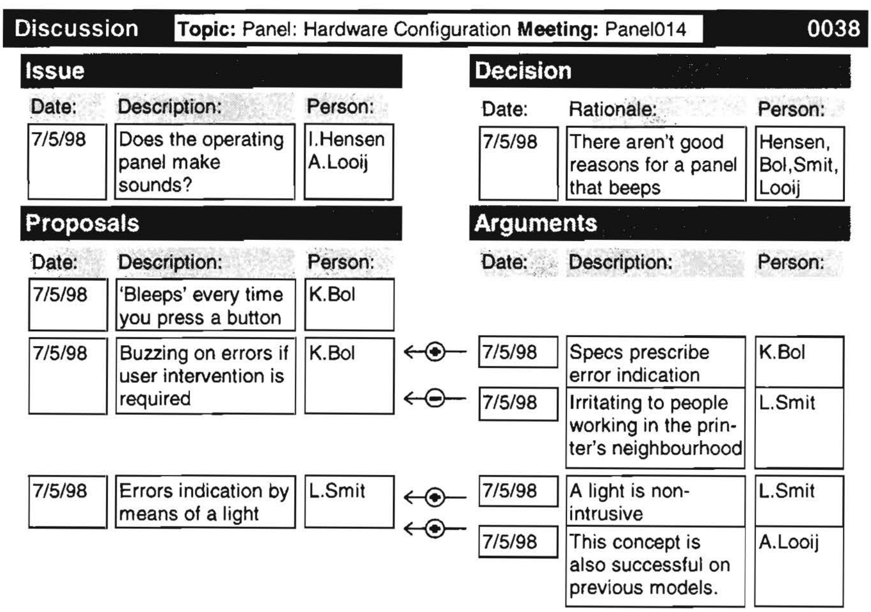


Figure 3.25: Example of Discussion on system-user interaction.

Although this case was in a completely different domain than the previous cases, the observant did not need a different approach for capturing the design histories. The resolution of the user interface issues could be observed and represented in the same way as we did in our previous cases. However, during Case 1 and Case 2, it was easier to map Issues to specific parts or functions of the product. The issues discussed in this case, were far more abstract and less related to some physical product part. For example, the design history contained Issues on what user actions would be necessary in case of a printing error and what actions the printer would perform automatically. This made it more difficult to group Discussions or to distinguish their interrelations.

After the observation period, the captured design history episode was evaluated with the observed designers. We questioned the designers about their judgement of the efficacy of the capturing approach and the usefulness of the captured information

Results

During the four and a half months of observation time, 33 Discussions were completely recorded (from Issue to Decision) from 17 meetings. The number of issues that the designers actually dealt with during this period, was approximately twice as much. However, the observant left the Issues that had already been raised before the observation period, and the Issues that were still in an unresolved state at the end of the observation period, out of the design history. On average, a Discussion contains of 2,4 proposals and 1,7 arguments. The Discussions' average resolution time is 22,5 days. However, about two-third of all Discussions were resolved in the same meeting as when they were raised.

An evaluation session was held a month after the observant stopped recording the design history. The designers judged that the design history contained correct descriptions of their decision making and that the Discussions covered the major proposals and arguments. However, they missed several issues on the subject of 'System Behaviour.' This part of their work covered the specification of the system's handling of jobs, errors and service requests, and the interaction with the user. This part of the design was performed in co-operation with many other design teams. Many of the occurring issues were not resolved on meetings, but during informal discussions between the concerning designers. Therefore, the observant could only record a subset of the issues that the designers had been dealing with.

The designers' general opinion on the captured information was that it contains useful information which can not be found back in the project documentation. They had the impression that design histories would be especially useful for new designers, joining the design project during its course, and for the re-use of product data as a starting point for new designs or design concepts.

A few times during the observation period, a designer asked the observant for recently captured information. In these cases, the design history provided arguments and details on proposals that the designers already had forgotten. Moreover, the designers sometimes seemed to forget what decision they made on a previous meeting and started the discussion again on the next one. In these cases, the design history provided useful as a memory of the agreements that were reached and on what arguments they were based.

The designers didn't feel disturbed by the presence of an observant, nor by his presence during meetings. The capturing did not affect the way in which they worked. However, the approach in which an observant captures the design history completely on his own, is not the most efficient approach. The maximum number of designers that, under the circumstances in this case, our observant could have recorded design histories from, is about fifteen people.

Discussion

Case 2 demonstrates that the approach for capturing design histories can be as well effective in other design domains than mechanical engineering. (This is not a surprise, semi-formal design rationale notations were originally developed for software development.) The capturing left the design process undisturbed. However, for use on a larger scale, the approach must be different. To make design history capture even more efficient, designers must do some capturing activities themselves.

Like Case 1, Case 2 is limited in time en depth. Discussions that spanned a longer time interval than the observation period, and discussions started before or ended after the design history was captured, were not represented in the design history. Due to this, the evaluation of the usefulness of the captured information is restricted.

3.4 Conclusions

A literature survey showed that there is limited experience in capturing design histories in real design projects. Moreover, a capturing approach that is efficient and that is descriptive so that it can be used in any design environment, was not available at that time. The three case studies, in which the design history from real design processes was captured, showed that the following approach to design history capture is optimal.

The reasoning which underlies the design can be efficiently captured by recording design decisions. The representation of design decision making by means of Issue-, Proposal-, Argument- and Decision elements, has proven to be a useful format. The elements can be well identified from actual discussions and conversations, and together, they give a complete and accurate description of the major alternatives and their pro- and counter arguments. A Constraint element can be useful, although we observed that we hardly ever used it during the case studies.

The information can be most effectively captured by recording only *group activities*. The case studies showed, that the major decisions and critical design conflicts are discussed in groups. Moreover, the results of individual work will only become part of the product if the team decides this. In all three case studies, the observed design teams made on average two decisions a week. However, to represent group decision making in the required level of detail, more information had to be gathered by interviewing designers afterwards about the alternatives and aspects that were not discussed in the team meetings.

Another advantage of design history capture from group decisions is, that the capturing leaves the design process undisturbed. The design history can be captured in a purely descriptive manner and apart from the organisation specific tools or methods that the designers use.

During the case studies, an observant did all capturing activities. In practice, this isn't the most efficient approach. Design must also take part in the capturing of group decisions. For every team meeting, the designers can assign one of them as their 'Meeting Secretary.' This person will take notes from the meeting and work them out in design history format. In advance of the next meeting, the other designer can review the captured decisions and add more information to it. For each project, one person will bear the end-responsibility for the captured design history. This person will collect the captured Discussions and will make this information accessible to other by storing it in a design history information system.

During the case-studies, it was hard to find proof that a record of design decisions is really useful for the designers. We observed that the recorded decisions were useful to prevent that the topics, the design team agreed upon previously, would be re-discussed in depth at another meeting. However, design history information will in most cases become useful to *other* designers, and *a longer period after* it has been captured, for example during the next project. The two cases that were studied for this research, only covered a single design team and only during a small period in time. Therefore, we were not able to study the re-use of the captured information.

An effective way to structure the decisions captured, is to link them to product data. The case-studies showed, that it was possible to determine what previously defined product data was used for the issue's resolution, and what new product data resulted from a discussion. The next chapter discusses the set-up of such a product model and how the user can search for design history data when it is linked to this product model.

The representation of the logical relations between decisions is not further discussed in this chapter. The cases in industry were too limited in time for that: Most Discussions were only related to decisions that were made before our observation period. However, from the first case, all Discussion-interrelations can be derived. This is discussed in the next chapter because the links with product data play an important part in the derivation of the 'serve' relations.

4 Design and implementation of a design history system

4.1 Introduction

Developing a design history system has similarities with answering the question 'What was first: The chicken or the egg?' An optimal design history system can only be built if it is exactly known how its users can take most advantage of the stored information. However, this can only be researched well by experimenting with designers that already use a design history system. In other words, one needs a design history system to implement a design history system.

The best approach to such a wicked problem is to solve it by making iterations. First collect as much information as possible without having a design history system, then specify a system based on this information, implement the system, test the system, and finally rewrite the specifications for the implementation of an improved system. This was the approach to the implementation of the prototype design history system. Based on the requirements for the design history system (Chapter 2) and the research on design history capture (Chapter 3), a system was specified that met the current insights. Then, a system was implemented according to the specifications. This system is to be used for further experiments on the capture and retrieval of design histories.

However, an additional requirement constrained the implementation. In practice, a design history system won't be a stand-alone system. The capture and retrieval of design histories must be a part of organisation's overall information management strategy. The storage and re-use of design decision is only a single aspect in this strategy. Therefore, the prototype design history system should be fit for integration with the state of the art on information management in engineering design.

This was achieved by implementing our prototype in a *Product Data Management* system, or PDM system. The result demonstrates how design history information can be integrated with product data management in engineering design. This chapter describes the translation of the original specification into the most realistic computer program that fulfils these specifications.

The prototype design history system was implemented in the following steps:

1) Translation of the requirements and the research results so far into a set of specifications;
2) Literature research on PDM systems to provide the required backgrounds for implementation,
3) Translations of the specifications into a concept design for the design history system,
4) Installation, customisation and implementation of the prototype system,
5) Filling the system with a previously recorded design history, including product data, and
6) Assessment to proof that the developed system offers the intended functions.

The implementation was performed within Information Manager (IMAN), the PDM product of Unigraphics Solutions. The development of a crash test-rig (see Section 3.3.4), which was observed previously, was used as a test case. From this case, both the recorded design decisions and all product data that the design team generated were available.

The next section presents the specifications for a prototype design history system. The specifications prescribe how design decisions are stored in the system and how they can searched and retrieved. The specifications that concern the storage of design information are based on the method for design history capture and the representation model that are proposed in Chapter 3. The specifications for the retrieval of design information are based on the requirements as they have been specified in Chapter 2.

The theory on Product Data Management (PDM) is presented in Section 4.3. It presents a definition of PDM systems, their architecture and their main functions and application areas. Based on this theory, Section 4.3 is concluded by the implications for PDM, if the storage and retrieval of design histories are incorporated in it.

Section 4.4 discusses the implementation of a prototype design history system within IMAN. It presents the extended data model and the functions for storage and retrieval.

To test the system, all product data that was generated during the development of a crash test-rig was stored in the IMAN database, as if IMAN had been used during this design process. Then, the previously captured discussions were added to the database. This is discussed in Section 4.5.

Section 4.6 evaluates the implemented system. This evaluation is only aimed at testing the system's functions. The system is evaluated with respect to the specifications from Section 4.2. For now, it is presumed that *if* the system fulfils the specifications, *then* the design history system leads to improved design processes. Whether this is really true or not, is further discussed in Chapter 5, on the retrieval and re-use of information from a design history system.

The last section draws the conclusions on the integration of design history and PDM, and gives directions for the improvement of the prototype.

4.2 Specifications

4.2.1 Design history capture

Specification 1A - Discussion representation model

The design decisions that will be stored in the system, will be structured according to the representation model in Figure 4.1. The fundamental object that contains design rationale information is called a *Discussion*. Each Discussion describes the resolution of a single design problem, from raising the problem, to making the final decision. A Discussion starts with an Issue, containing the problem definition, the person(s) that raised the Issue and the date on which it was raised.

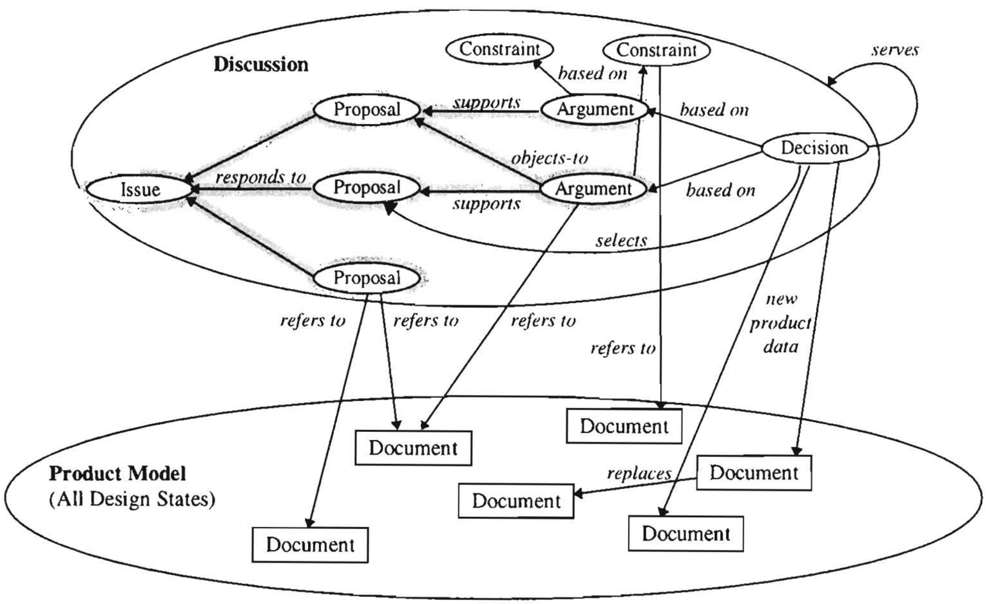


Figure 4.1: Model for design history capture.

One or more Proposals must be suggested to resolve the issue. Each Proposal contains a description of the suggested solution, the person that proposed it, the date and time this was done and, optionally, a reference to product data that contains more information, for example a sketch of the solution.

Arguments are raised in reflection to the proposed solution(s). An Argument supports one or more Proposals and can, at the same time, object to one or more other Proposals. It contains a description of the argumentation, the person who claimed it and the date and time at which it was claimed. An argument can refer to the product data, that it is based on. Optionally, an argument can refer to a Constraint. A Constraint is a requirement, customer wish or restriction which is imposed on the issue's resolution. It is characterised by a description of the constraint and an optional reference to product data that contains more information on the constraint, for example a list of requirements.

The final Decision is made by weighting the arguments and selecting one or more accepted solutions. It contains a description of the final argumentation, the persons that were involved in the decision making, and the date and time, at which the decision was made. Each decision has effects on the product. Mostly it results in new product data that is added to the current design state, but it can also result in changes to existing product data. The decision refers to the product data that is affected by the decision, by means of the *New Product Data* relation.

Specification 1B - Discussion Interrelations
Discussions are interrelated by means of the *Serve* relationship. (See Figure 4.1.) The Decision from Discussion A *serves* Discussion B, if the resolution of Discussion A influences the resolution of Discussion B.(See Chapter 3 for more backgrounds.)

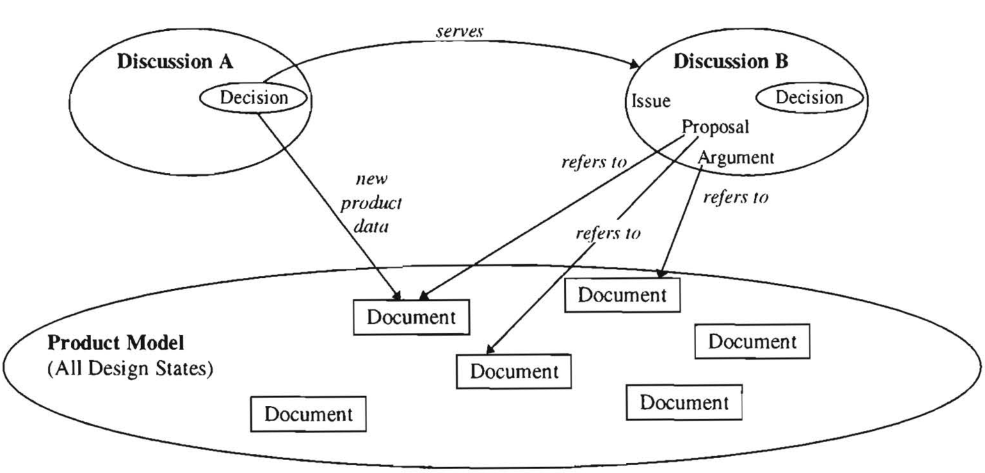


Figure 4.2: Serve-relations between Discussions.

The serve relations between Discussions are maintained manually. However, the system will suggest to relate Discussion A to Discussion B if Discussion B contains references to product data that was a result of Discussion A. Product information that is the outcome of Discussion A is linked to Discussion A by means of the *New Product Data* relation. (See Figure 4.2.)

Specification 1C - Product Model
Each Discussions references product data. This product data is kept in a separate part of the design history database, the *Product Model.* (See Figure 4.1.) The product model describes at any moment in time, the current state, the entire product is in. It covers the whole product in all levels of abstraction and from all points of view.

How the product will be modelled in a practical situation, depends on the type of product that is being developed. For a simple one-of-a-kind and mono-disciplinary product, a single product hierarchy that follows the product assembly structure will probably provide enough structure to organise all product information. More complex products need a more complex product model that, for example, supports multiple product configurations and different views, for example an assembly structure, a modular design structure and an electrical systems view on the product.

If a part of the product model is changed, for example by making a decision that concerns a specific component, then the old information must not be deleted, but must be stored as an older version. The entire history of the product model evolution must be kept in the database.

Specification 1D - Capturing procedure
Figure 4.3 represents the design history capturing procedure. It shows that design decisions are captured separately from product data. Decisions are captured during group activities, mostly team meetings. They are captured by a 'Design History Secretary,' which can be an additional person or a designer who has been given this responsibility. Product data is created by all designers during individual activities, for example by modelling on a CAD system or by performing simulations on a FEM system. During these activities designers build the product model by adding, modifying or replacing information in the product data base. Consequently, product data is owned by the responsible designer and Discussions are owned by the Secretary.

After the Discussions are inserted in the database they need to be reviewed by the design team. In this stage, designers can add more background information to it or comment the captured information. When all responsible designers approve the documented Discussions, the information can be released for re-use by others. This can be done in steps, for example, by giving at first only a few selected design teams access to this information, and by granting a wider group of users only access after project completion.

The design history system contains information on all projects that were recently done. To keep this huge amount of information manageable, it must always be possible to determine, for any piece of information in the database, of which development project is it a part. This is a prerequisite for effective database exchange, backup and maintenance.

4.2.2 Design history retrieval

Section 2.5.3 (in Chapter 2) defined 10 different 'modes' in which the use of the design history system contributes to an improved and accelerated design process:

- Information on the reasoning behind certain parts of an earlier developed product can be retrieved (***Requirement 3A***),
- Potential (earlier suggested) solutions to a particular problem can be found (***Requirement 3B***),
- Users can find out whether a particular alternative solution was previously proposed (and rejected) or not (***Requirement 3C***),

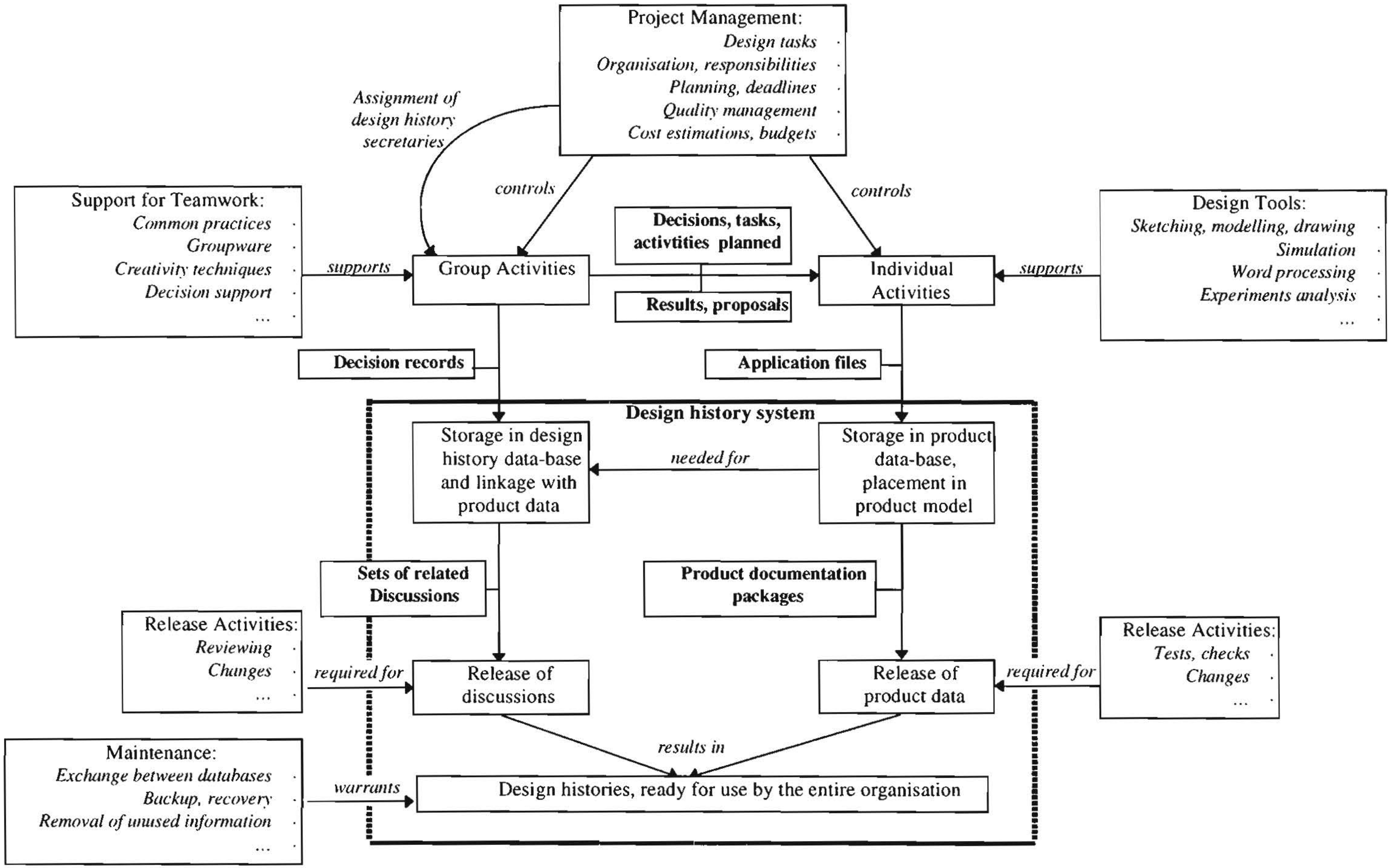


Figure 4.3: Capturing procedure.

- Specific documents, like calculations or sketches, that were used during a design process can be easily retrieved for re-use or review (***Requirement 3D***),
- The critical parts of a previously finished design process can be identified and studied to improve the current and future design processes (***Requirement 3E***),
- The issues that delayed a former design process can be identified and measurements for the future can be taken (***Requirement 3F***),
- If a user wants to change a product function or feature, then he can find out other aspects of the product may be affected by this change (***Requirement 3G***),
- Decision making that is consistent with earlier made decisions can be supported (***Requirement 3H***),
- The resolution of conflicts among design teams can be supported (***Requirement 3I***), and
- Project managers can use the system to monitor the progress of current product development projects (***Requirement 3J***).

Each requirement has been translated into a specification by defining the retrieval functions that are needed to support this requirement. Tables 4.1 to 4.10 show the specifications for retrieval of information from a design history system.

Specification 2A	**Studying the reasoning behind parts of the final design**
input	The part or sub-assembly in the final product, about which information is needed.
output	Sequence(s) of decisions that lead to the part's evolution in the design, including underlying rationales. All decisions, from requirements to approval of the part must be retrieved.
required function(s)	A function that represents the sequence of decisions after a component or (sub) assembly in the product structure has been selected.

Table 4.1: Specification 2A

Specification 2B	**Searching for potential solutions**
input	Aim of the required solution, e.g. the functions that must be fulfilled or the requirements that must be met
output	A list with potential solutions, including references to the Discussions during which they were proposed.
required function(s)	Searching Issue and Constraint descriptions on specific words and retrieval of the related Proposals; Selecting a function or requirement for the set of functions and requirements that were defined earlier in the design and then search for the Proposals that fulfil these functions or requirements.

Table 4.2: Specification 2B

Specification 2C	Investigating whether a specific solution was previously proposed or not
input	A description of the solution, the functions it fulfils and the requirements it meets
output	The Discussions during which a similar solution was proposed.
required function(s)	Searching Proposal descriptions for specific words; Finding in a similar product the Proposals that were suggested for a similar part in that product.

Table 4.3: Specification 2C

Specification 2D	Retrieving the documents which were used during the design process
input	The part, a document was generated for, during a specified period in time.
output	A list of Discussions, concerning the product part during the corresponding period in time and the documents used by these Discussions
required function(s)	Replay of the stages, the product went through during its development, selection of a part of the product and retrieval of the corresponding documents; Search documents with name, date and owner and retrieve the Discussions for which they were used.

Table 4.4: Specification 2D

Specification 2E	Studying the lessons learned during the design process
input	The selection of a project or a collection of Discussions.
output	Discussions describing the major iterations in the design process.
required function(s)	Searching for Discussions by which a large number of product parts are affected; Searching for product data that was changed after it was released for production; Searching for the Discussions with the longest period from the problem's identification to the final decision.

Table 4.5: Specification 2E

Specification 2F	Studying bottlenecks in the design process
input	The selection of a project
output	Discussions that slowed down the design process.
required function(s)	Searching for the Discussions with the longest period from the problem's identification to the final decision; Searching for Discussions that are served by many other Discussions that were raised and resolved within the time interval of the searched Discussion.

Table 4.6: Specification 2F

Specification 2G	Support for changes to the product
input	The requirement, function or component that needs to be changed.
output	The underlying Discussions that must be reviewed and the Discussions that might be affected when such a Discussion is reviewed.
required function(s)	Search for the underlying Discussions from product data, then represent the Discussions that are served by the originally found Discussions.

Table 4.7: Specification 2G

Specification 2H	Consistent decision making
input	The requirements, specifications or desired functions that must be taken into account while developing a physical solution.
output	The Discussions underlying these specifications, explaining why a specification is particularly important and how it was defined or derived.
required function(s)	Search for the chain of Discussions that lead to specified specifications, requirements or goals.

Table 4.8: Specification 2H

Specification 2I	Support in conflict resolution
input	The parts of the product that are conflicting (e.g. filling up the same space, or a part producing too much heat for an adjacent part).
output	The underlying chain of Discussions for each of these parts.
required function(s)	Searching for the Discussions that lead to the actual design, and the Discussions which serve them.

Table 4.9: Specification 2I

Specification 2J	Control of project progress
input	The current project and (optionally) the previous projects it must be compared with.
output	Management information on the progress of the current design process.
required function(s)	Searching for Discussions from the current and previous design processes that meet various criteria like dates, subjects, persons and product release levels.

Table 4.10: Specification 2J

4.3 Product data management

4.3.1 The origin of PDM

The result of a design process is captured in information. This information describes the plan for a product; its geometry, its structure and how it must be produced, assembled, operated, maintained and disposed. When a product is released for production, it is defined in a collection of documents, the *product documentation package*.

Traditionally, all documents that are necessary for the product documentation package, like drawings and bills of materials, are created on paper. Therefore, paper and microfilm are the traditional media on which the product documentation is stored (Schreur 1996). After the organisation has reviewed, approved and released this information, the documents are stored in an archive for later re-use. The manufacturing departments have their own copies and may add more information to it, concerning the ordering, processing and pricing of parts.

In the seventies, computers enter the manufacturing industries. Engineers start using word processors, 2D-CAD systems and software for production planning. The information that is generated by means of the computer systems, is first printed on paper before it is stored in the traditional paper-based archives. In this period, the large manufacturing corporations that are leading in the applications of computers to engineering, find their progress being seriously hampered by paper-based documentation systems (PDMIC 1998a). The translation of computer-based data into printed paper-documents and the management of these documents in a paper-archive imposes too much overhead on the business processes. These companies build their own 'home-grown' document management systems for the management of bills of materials, manuals and cost information.

In the late eighties, several software companies, mostly vendors of CAD, CAM and CAE software, bring the first generation Product Data Management (PDM) systems on the market (PDMIC 1998a). At this time, the main concern of manufacturing companies is to reduce their production costs and improve product quality. They achieve this by means of Just-In-Time production (JIT), Total Quality Management (TQM) and Activity-Based Costing (ABC). Therefore, the first generation PDM systems are especially focused on the exchange of information between engineering and manufacturing. The PDM systems consist of a database, containing records of all product parts and their related files, and a shell around the database for releasing information and for managing change orders.

Currently, product life cycle areas other than manufacturing are targeted for improvements. The main focus of manufacturing companies is to shorten the time to market and to respond more flexibly to changes in the market. This is achieved by means of the development of quickly configurable product families, by doing more development together with suppliers and to spread development activities over locations that are scattered over the world. Nowadays, PDM systems are used for the entire product life cycle, from initial concept to product obsolescence. However, the main focus is still the product information that has reached a level of maturity (i.e. data that is proposed to achieve a certain release level.)

Due to the fast evolution and growth of Product Data Management, it is difficult to give an accurate definition of PDM. Moreover, techniques as Engineering Data Management (EDM), Enterprise Document Management (also EDM), Engineering Data Interchange (EDI), Technical Document Management (TDM), Technical Information Management (TIM), Engineering Management Systems (EMS) and Workflow Management (WFM) have a lot of overlap with PDM or include aspects of PDM and vice-versa.

In this thesis, Product Data Management (PDM) is defined as the management of all product development information that is stored, retrieved and distributed, from the first conception through design, engineering, manufacturing, use and maintenance to disposal (Cornelissen 1995). A PDM system guarantees the availability of product information at the right moment, at the right place, in the right representation, in the right version and for the right person. Its users are managers, administrators and end-users. The end-users are in most cases the engineers from a development or manufacturing department.

4.3.2 The architecture of PDM systems

The basic principle of a PDM system is that each file or record is stored in a single location. Redundancy, i.e. there are copies of the same information that are stored in different locations, should at all times be prevented. However, the structuring of engineering data is rather complex. Engineering data is structured according to five orthogonal 'dimensions' (Hamer 1996):

- *Hierarchy:* A product can be broken down into smaller, related parts. For example, an orange juice press is assembled from sub-assemblies and components, and a software program can be split up in functions and sub-routines.
- *Views:* A product can be depicted in more than one representation. For example, a product may be represented by an assembly structure and an electric structure that refer to the same components.
- *Variants:* A product may actually be a family of strongly related products that use the same modules and components. This requires the management of the common and the different features of all possible product configurations.
- *Versions:* The steps that were performed during the design must all be backed up. This way, it is always possible to trace back the product to a previous state, for example when certain parts of the product need to be changed.
- *Status:* Some parts of a product may be ready for production, while others are still in an unfinished state. Therefore, each part or document that is related to a product can have its own level of quality and reliability.

Usually, there is the necessity to manage three or more dimensions concurrently in the product model. It depends on the characteristics of the product, the production process and the manufacturing equipment which dimensions are most relevant.

To manage the complexity of engineering data, the heart of a PDM system is a database. (See Figure 4.4.) It keeps records of all documents that are created and modified during the design process, including additional information about these documents. This information is also indicated as *Meta Data* (Cornelissen 1995). The documents themselves are stored on a separate medium, the 'Vault.' This is mostly a hard-disk which can only be accessed by the database.

On top of this database is the user interface of the PDM system. It enables the users of a PDM system to create, modify, view, search and retrieve product data. Typical functions that are incorporated in most PDM systems are (CA_Techniek 1998, Cornelissen 1995, McIntosh 1995, PDMIC 1998b, Pels 1995, Pikosz 1996, Schreur 1996, Schreur 1998):

- *Vaulting:* Basic functions for the storage of documents and their identifying meta-data,
- *Access control:* Protection of data to prevent from accidental loss or unauthorised access,

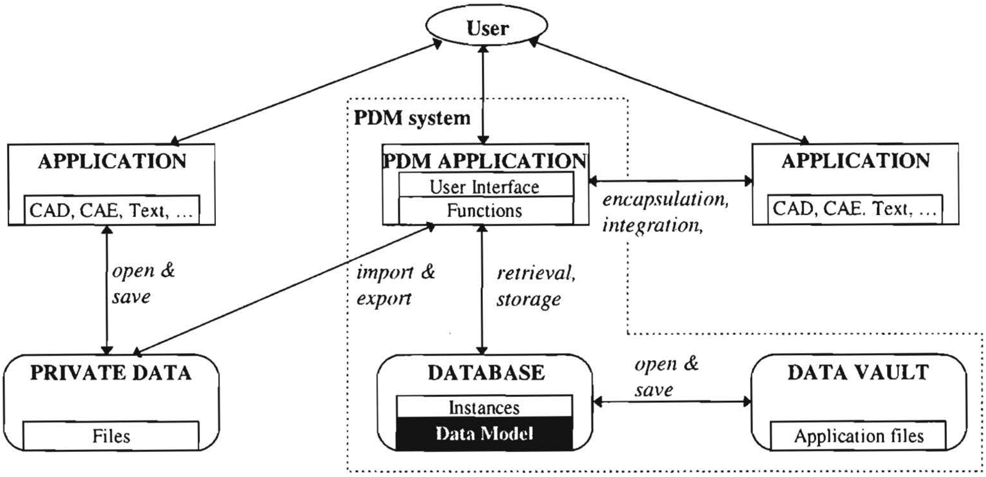


Figure 4.4: Architecture of a PDM system

- *Product structure management:* Functions to compose the complete product out of sub-assemblies, sub-systems and components. Product structure management mostly incorporates multiple views and the management of configurations, alternatives and variants (Erens 1996).
- *Release Management:* Functions to assign status levels to product parts and documents. An effective release management strategy leads to more variants and changes early in the design process, and less changes after the product's market introduction (Pels 1997).
- *Change Management:* Functions that support change procedures to change products after they have been released for production.
- *Workflow Management:* The activities that the designers perform on the data in the database can be modelled in a business process model. By means of workflow management, the tasks for activities can be created, assigned to persons, and monitored. For example, Workflow Management is used to support and automate certain release procedures.
- *Classification of components:* Additional functions to support the retrieval and re-use of (standardised) components.
- *System Administration:* Additional functions for backup and recovery, and for the interchange and synchronisation of product data between separate sites.

Most PDM systems are application independent. They allow the management of documents from a variety of applications, such as CAD systems, simulation software and office applications. The user has several ways to work with these documents (Breuls 1995):

The user can search, retrieve, create, modify and manipulate the data in the database directly from the user interface of the PDM system. To create, view or edit documents by means of an application, this application must be *encapsulated* by the PDM system. This means that the PDM system will temporally export the selected files from the database, then launch the required application with the exported files, and when the user ends its session with the application, re-import the created, updated or changed files.

If the application and the PDM system are *integrated,* then the user doesn't need the PDM system's interface to control its data. The user can directly search, retrieve, view, create and change his documents from within the application. For example, A CAD system, which is integrated with a PDM system, can automatically update the product structure in the PDM system when parts are added to or removed from an assembly.

The user will also work with data which is not stored in the PDM system. This is shown in Figure 4.4 on the left side. If this data should be managed in the PDM database, then it can be imported in the database by means of special interfaces that translate the generated documents into a structure that applies with the database.

4.3.3 Application of PDM technology

A PDM system enables companies to organise their product creation processes in a more effective and efficient way. Industries are currently implementing product data management for a number of reasons (McIntosh 1995, Miller 1998, Werf 1998):

- *Efficiency*: A PDM system replaces the traditional paper-based archive. This reduces the overhead for archive management, and increases the efficiency and effectiveness of information retrieval;
- *Product complexity:* The application of embedded software, product miniaturisation and product family thinking requires a more sophisticated management of product configurations;
- *Concurrent engineering*: The PDM system gives all participants in the design process access to the most actual information for manufacturing, engineering and marketing;
- *Quality management*: Quality standards, like ISO 9000 and the CE-mark, require that the most actual product information must be always available, that changes of this information must reach all the locations where the original information is used, and this information must remain available for years;

Most PDM systems are not fit for a straight forward installation and application in practice. Before A PDM system can be used in a design process, it must be customised to meet the organisation specific needs. Moreover, most product development departments are not fit for a straightforward introduction of a PDM system in their design processes. The introduction of a PDM system often requires another may of working (McIntosh 1995). Therefore, the implementation of a PDM system in a product development department is a complex process that must be carefully planned and executed (Pels 1995). It often involves a detailed *business process analysis,* which results in a model of the organisation from the viewpoint of information (Schreur 1996). Moreover, if the organisation wishes to optimise its information flows, then the PDM implementation may incorporate a *business process redesign* process (Miller 1998).

Product data management is a relatively young application of information technology for product development. Nowadays, the functionality of PDM implementations is mostly limited to the electronic archiving of CAD source files and product structure management for released products. To take full advantage of the technological opportunities that PDM systems offer, the following issues still need to be resolved.

Better integration between PDM and production planning systems: Nowadays, most companies have separate systems for their core business processes. For example, the engineering department uses PDM, and the manufacturing and logistics department uses an Enterprise Resource Planning (ERP) system. Although each system has its own purpose and content, there is an overlap. For example, both the ERP and the PDM system contain the product's final bill of materials. Currently, an integrated solution requires extensive customisation of both the PDM and the ERP system. Common methods for synchronising, exchanging and sharing data among PDM and ERP systems are just emerging. (Werf 1998).

More support for co-development and collaborative engineering: The amount of development work which will take place at geographically spread locations will increase. Distributed database concepts and interfaces to an intra- or internet will enable the organisation to manage their product data in a global environment (Huurne 1997). However, yet only few is known about the way in which distributed development activities should be organised and consequently supported.

More integrated support during all design phases: Although PDM may be used from the initial concept to the final design, the emphasis is currently on the later design stages. Product data management for conceptual design is complex, because a model of the physical product isn't available. Moreover, current product structuring capabilities of PDM systems are too rigid to support exploratory and iterative design activities (Kals 1998).

More support for Enterprise Knowledge Management: PDM vendors are aware of the fact that their PDM systems only contain the information that describes *what* the product is. The reasons *why* the product was designed in this particular way, and what would happen if you changed the product, is not managed by PDM. Current PDM-systems aren't able to handle more intelligent product models and more background information on the design process. Design history can be a core technology to improve the knowledge management capabilities of PDM systems.

4.3.4 Implications for design history

Figure 4.5 gives a graphical representation of the relation between product data management systems and a design history system. The horizontal axis represents the types of information that are stored in the different information systems. The vertical axis represents the user functions that are provided to manipulate this information.

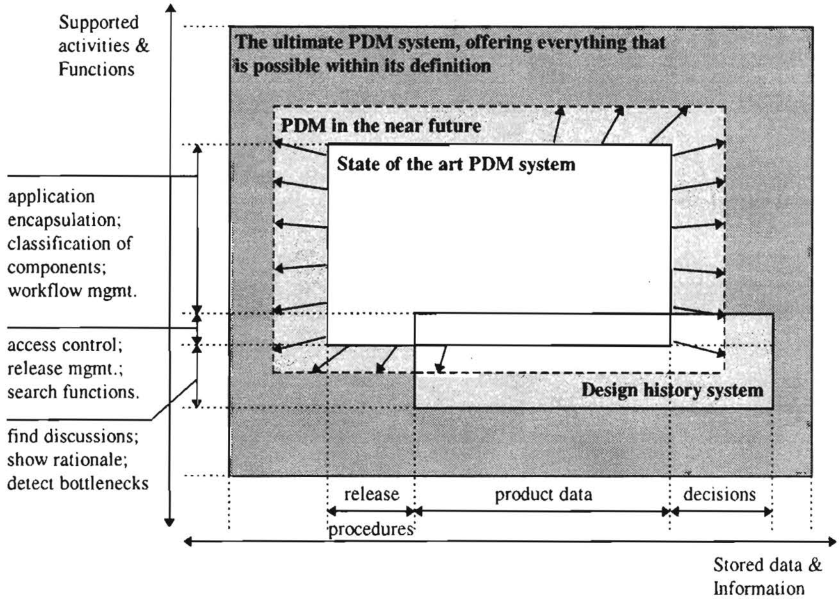


Figure 4.5: product data management *vs.* design history

From the point of view of the definitions of PDM and PDM systems, the capture and retrieval of design histories can be considered as *a part of* PDM. If the organisation considers the decisions, that underlie the product, as an essential part of product documentation, then the best location to manage design histories is within the PDM system. Although actual implementations are not known to the author, the PDM definition fully covers it. Figure 4.5 shows that a design history system lies within the definition of product data management.

However, there is a difference between product data management and the capture and retrieval of design histories. The main motives for the introduction of a PDM system, like concurrent engineering and control on the quality of information, are aimed at an unambiguous definition and representation of the final product. Therefore, the main goal of a PDM-system is to provide the user with the most *actual* product data that is relevant to him. In contradiction to this, the main goal of a design history system is to provide the user with the information that he needs from the *history* of the design process. The system will not only show the most actual information, but must as well be able to play back how the product evolved during the design process. This is a dimension that is hardly covered by state of the art PDM systems.

From the point of view of the data and documents which are currently being managed in state of the art PDM systems, the capture and retrieval of design histories is an *extension* of product data management. This is represented along the horizontal axis of Figure 4.5. For the retrieval of design histories, users need access to almost all product data that was generated during the design process. Additionally, the underlying decisions and their relations with product data must be stored in the system. This information is not stored in current PDM systems.

From the point of view of the functions that a PDM system provides the user with, a design history system has *overlap*. See the vertical axis in Figure 4.5. The basic PDM functions for the creation, storage and retrieval of product information are also needed for the capture, storage and retrieval of design histories. Both product data management and the capture and retrieval of design histories can be supported by the same functions for data protection, release management, data import and export, and backup and recovery.

However, a design history system requires additional functions for the retrieval of design history data. For example a design history system will incorporate functions to replay the product evolution and to search for the decisions that underlie specific parts of the product.

Based on this discussion, it can be concluded that the integration of a design history information system with a PDM system is, in theory, feasible. The result is a system that gives the user more than the sum of a separate design history and a separate PDM-system. The PDM-system supports an effective integration of decisions with the *real* product data to which these decisions are related. The design history functions enhance the retrieval capabilities of PDM systems. Moreover, the integration with a PDM system enables product development departments to manage the design history as a formal deliverable of a design process.

4.4 Design history information system

4.4.1 Information Manager (IMAN)

Within Information Manager (IMAN), the product data management software application of Unigraphics Solutions, a prototype design history system was implemented. This section describes the actual database structure of the system and the functions for design history storage and retrieval.

IMAN is a high-end PDM system, aimed at large, distributed product development organisations. Key features are application encapsulation, extensive product structure management, release- and change management, workflow management, and an integrated electronic mail system. Moreover, IMAN provides a direct tie to Unigraphics, a high-end CAD/CAM/CAE application.

A prerequisite for the implementation of a design history system within a PDM system, is that the PDM system must allow extensive customisations and adaptations. For extensive customisation IMAN offers a module termed the Integration Toolkit (ITK). The ITK is a large collection of functions that enables a programmer to write programs that have direct access to the IMAN database and which can be called from the IMAN user interface. By means of the ITK, the default IMAN functions can be replaced by functions that have another behaviour, or new functions can be written that perform entirely new tasks. Moreover, IMAN supports an extensive adaptation and customisation of the underlying database, as well as the modification of the IMAN user interface.

For the implementation of a design history system we used IMAN 3.4.2 in combination with Unigraphics 11.1. The software was installed on a Hewlett Packard 700 Series workstation with the HP-Unix 9.07 operating system. Our programming code was written in C and the user interface code in Motif UIL. The implementation of the design history information system has been extensively reported in (Linden 1999). See also (Wiegeraad 1998).

4.4.2 Data model

Default IMAN data objects

This section discusses the data model that was used to enable the storage of design history information in the database. Figure 4.6 shows the default IMAN objects that are relevant to this discussion.

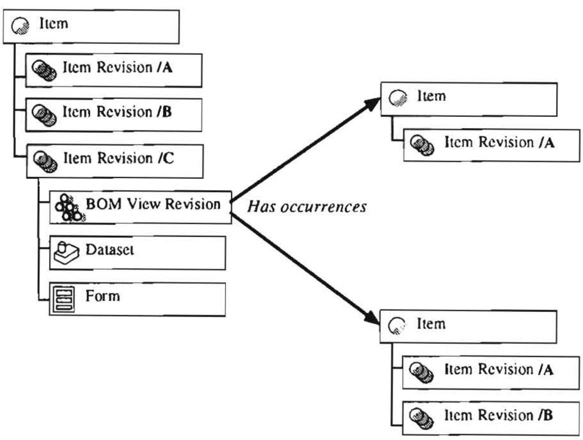


Figure 4.6: The basic IMAN data objects.

An *Item* is the fundamental object to manage information. Items represent physical or conceptual entities that an organisation uses to maintain, audit and change information (UGSolutions 1997). Typical uses of Items are parts, documents and equipment. Each Item has a unique identification code. This can be any sequence of characters, but in most cases a company has its own strict rules for identification and classification.

Each Item has one or more *Item Revisions.* If an Item needs to be modified, but you want to retain the original data for historical purposes, then you create a new revision of the item. In fact, this is the implementation of the *Version* dimension of product data. (See Section 4.3.2.)

The actual product data is stored in objects which are linked to the Item Revisions. A *Dataset* is an object that contains a collection of application files, for example pictures, drawings, CAD models and spreadsheets. By double clicking the Dataset, a suitable application is launched to view or modify the files' contents, or to create additional files that must be stored in the same Dataset. Each time the files are modified, the former files are copied and saved as backups.

A *Form* is another object to store data that is related to an Item Revision. A Form provides the ability to store customer defined attributes in a predefined template. For example, an organisation uses standard forms to store information on the components that are bought from suppliers. The contents of a Form are not stored in a file, but are directly stored in the database. The advantage of this approach is, that you can perform database queries on the contents of a Form, for example to find all components from the same supplier.

Each Item can be related to various other Items. For example, an Item that represents a certain sub-assembly may be related to the component Items that it consists of. Such relations are managed by means of the *BOM View Revision* object. It enables the user to build product structures, to manage different releases of the same product and to manage variant product configurations. In terms of the five dimensions of product data (see Section 4.3.2), the BOM View controls the dimensions *Hierarchy, Variants* and *Views.*

New data objects for design history

To be able to store *Discussions* in the IMAN database and to manage them in the default IMAN user interface, the original design history representation model was translated into a database structure that makes maximum use of data objects that are already present within IMAN.

IMAN provides two basic mechanisms to extend the database:

- The installation of new *types* of existing database objects and changing the behaviour of these objects by assigning new *properties* and *methods* to them. This approach leaves the actual database structure unaffected. The new object types are stored in the database class as the default object types, and new properties and methods are assigned during run-time. The advantage of this approach is that the newly installed types can be directly managed from within the IMAN user interface, because most IMAN functions work for all types within a default IMAN class.
- The creation of new database *classes* and their *attributes.* The advantage of this approach is that it enables the creation of entirely new objects in the database. However, IMAN can't deal with such objects by default. They require new programming code and new code for the user interface.

Discussions are implemented in the IMAN database as a new *type* of the object *Item.* This approach is entirely consistent with the definition of an Item. In the design history, *Discussions* are the basic objects that must be managed, like *Items* are the basic objects to be managed for product data. The main advantage of this approach is, that the release and access management of Discussions is exactly the same as for Items. Moreover, no extra programming code is required to create, search or modify Discussion objects.

Figure 4.7 shows the extended data model. Although Discussions are of the same type as an Item, their behaviour is totally different. A *Discussion Revision* is not defined by data in Datasets and Forms, like an Item Revision is, but contains only a *Discussion Master* and a set of *Proposals.* Both the Discussion Master and a Proposal appear in the user interface as new Form types. However, when the user opens a Discussion Master or a Proposal, a new window is opened, in which he can interactively view, create or modify the underlying information. The actual user interface that was created for creating, viewing and modifying the contents of a Discussion, will be presented in Section 4.4.3 and Section 4.4.4.

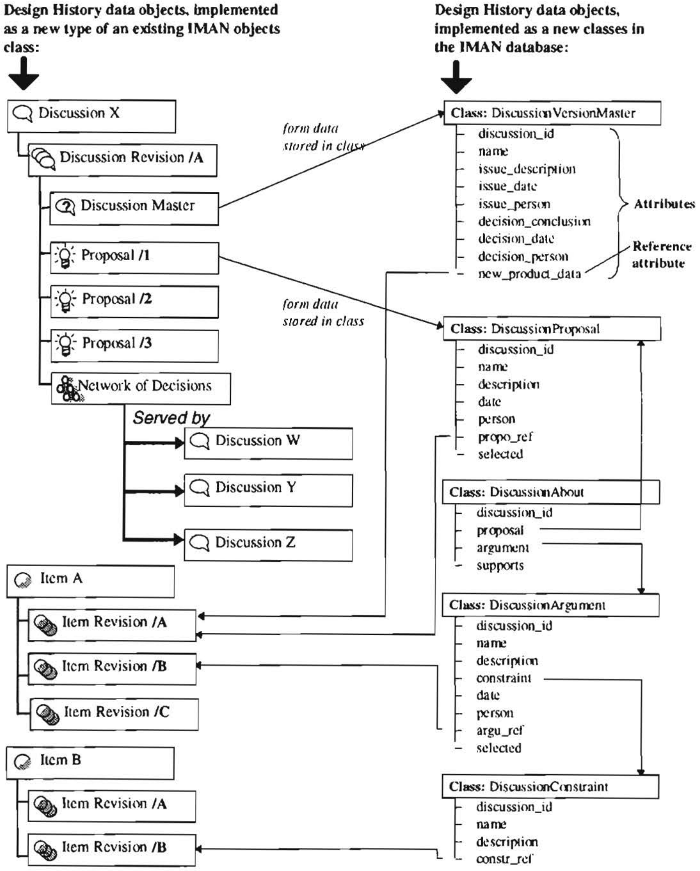


Figure 4.7: Data model for the storage of design history data.

The Discussion Master contains information regarding the original Issue, the Constraints imposed upon the Issue, and the final Decision. It includes a list of Item Revisions to which the Decision points by means of the *New_product_data* relation.

A Proposal contains all necessary information on the proposed solution, including a reference to the Item Revision that contains the related documents, like drawings, sketches or measurement results. Moreover, the user gets information on the arguments that support or oppose to this proposal.

The *serve* relations among Discussions are maintained in an object called the *Network of Decisions.* This object is a new type of the default IMAN object 'BOM View Revision.' The Network of Decisions contains references to the other Discussions that *serve* this Discussion. The main advantage of this approach is, that the part of the IMAN user interface, that is normally used to build product structures, can also be used to create, inspect and edit the relationships between Discussions.

4.4.3 Function for information capture

There are two different information flows that feed the design history system during a design process. (See Section 4.2.1; Specification 1.4.) Product data is created and modified by the engineers, during their design activities. Decision data is inserted by the person who is responsible for capturing the design history. This section discusses the implemented user interface for inserting Discussions and their contents into the database.

To create a new Discussion, the user selects the 'New Discussion' function from the 'Design History' pull down menu. (See Figure 4.8.) This function will open a dialogue that asks the user to insert the Discussion's ID, a comprehensive name and the description of the Issue. By pressing the 'OK' button, the new 'Discussion', 'Discussion Revision', 'Discussion Master' and 'Network of Decisions' data objects will appear in the IMAN workspace. Note that the descriptions of all data objects appear in a column next to the objects.

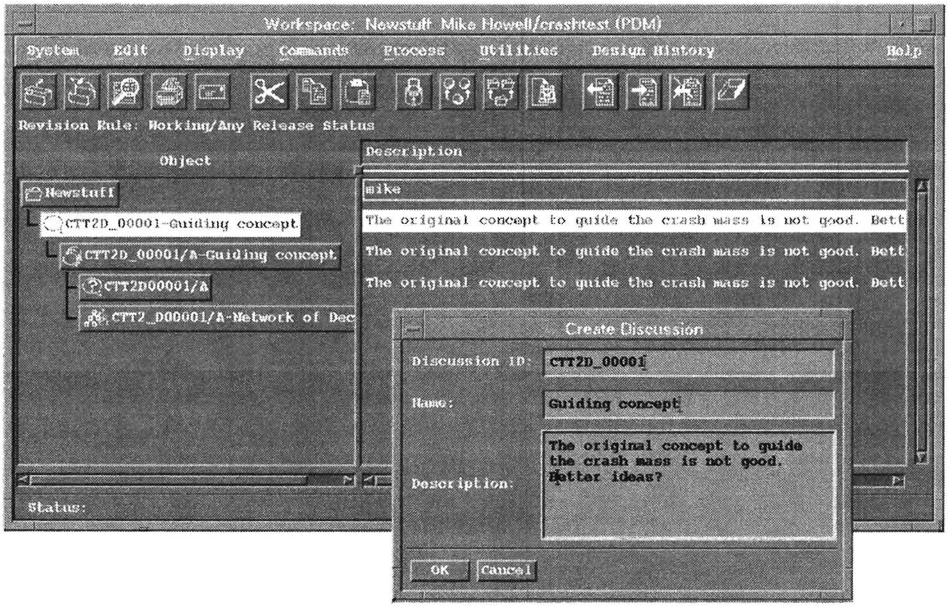


Figure 4.8: Creating a new Discussion.

By double-clicking the Item Master, which has the question mark icon, a new window called 'Issue&Discussion' will appear that contains the necessary fields to insert Issue and Decision information. (See Figure 4.9.) The first time, the user will only insert Issue information in the upper half of the window and then close it. Decision information can be inserted later on, when the final decision has been actually made.

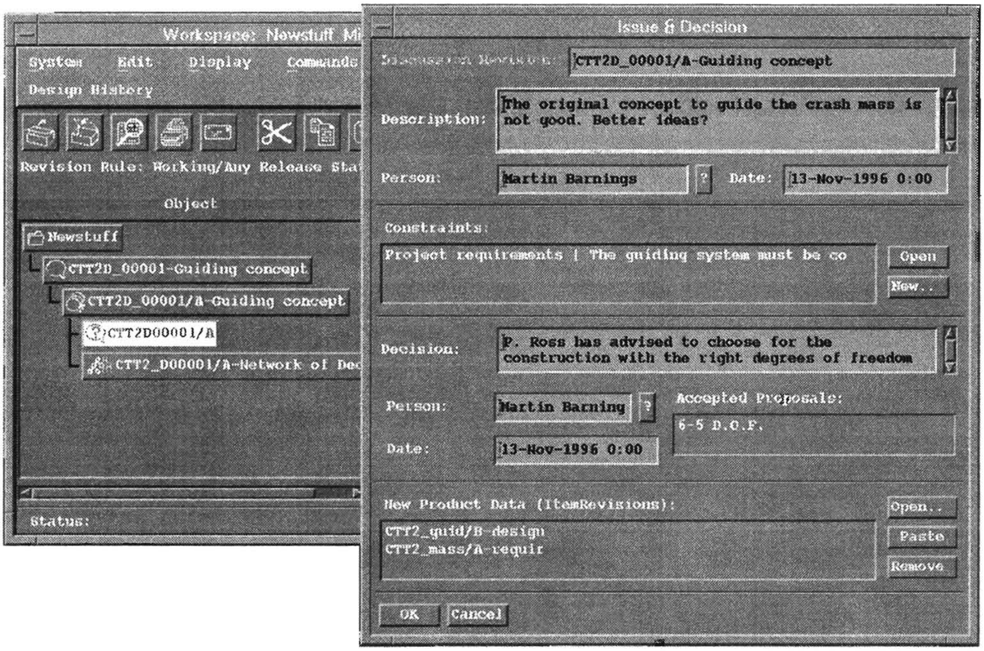


Figure 4.9: Entering Issue and Decision information

The 'Issue&Decision' window also displays the Constraints that are currently defined. This list is automatically updated when new Constraints are created from this window or from the Argument window.

By choosing the 'New Proposal' function from the 'Design History' pull down menu, a new Proposal object appears under the selected Discussion Revision. (See Figure 4.10.) By double-clicking this object, the 'Proposal' window opens. It shows all Proposal information, including the Arguments that are currently supporting or objecting to the Proposal. New Arguments can be created and linked to this Proposal by means of the buttons to the right of the list of Arguments.

Each argument is represented in full detail in a separate window, such as shown in Figure 4.11. This Argument contains a reference to the document that provides more background information. The user can view this document by pressing the 'Open' button.

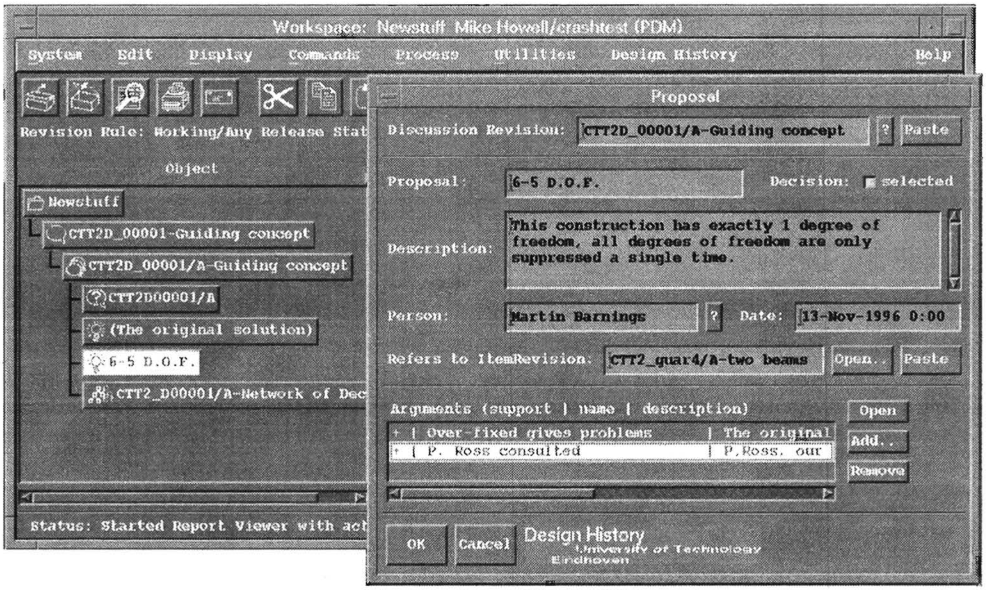


Figure 4.10: Entering a Proposal.

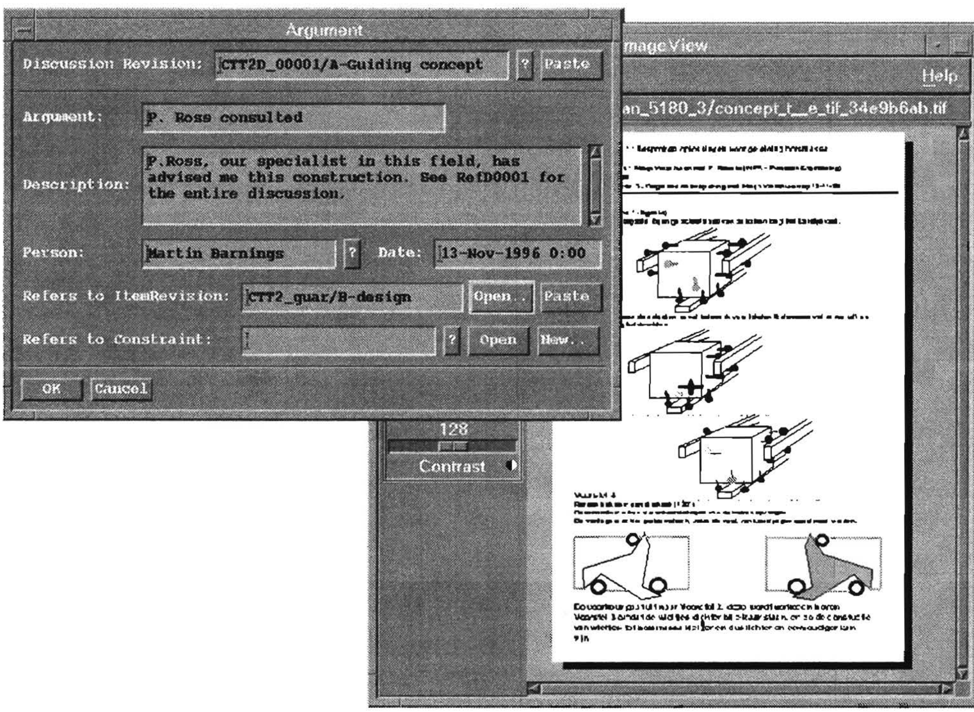


Figure 4.11: Creating an Argument that references another document

Finally, the user can update the relations that this Discussion has with other Discussions. By double clicking the 'Network of Discussions' object (see Figure 4.10), a new window opens, which displays a graphical representation of the Discussions that 'serve' the current Discussions. (See Figure 4.12.) This representation also shows the sub-sub-Discussions of the sub-Discussions, an so on. New Discussions are added by copying them from another window, and pasting them in the Network of Discussions.

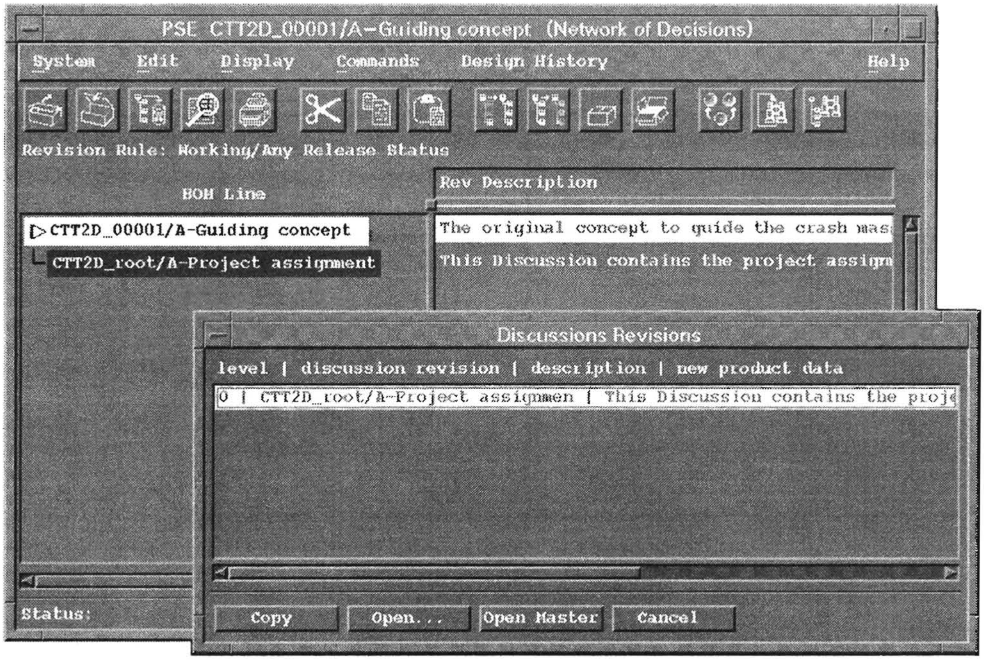


Figure 4.12: Adding the previous Discussions that serve the current one.

An easier approach is to query the system to search for potential Discussions that might serve the current one. This function will give a list with Discussions that can be added to the Network of Discussion by copying and pasting. (See figure 4.12.) The user can start the search by choosing the 'Suggest Discussions' option from the 'Design History' pull down menu. Figure 4.13 shows the method that the function uses to find such Discussions. First the function will retrieve all product information that the current Discussion is based on. Secondly, it will retrieve the other Discussions that are related to this product information by means of the *New Product Data* relation.

For the example in Figure 4.12, the system finds only one Discussion. The Discussion that is found is the very first one of the design process, the 'root discussion.' It represents the proposal and acceptance of the project assignment. The current Discussion is indeed served by the root Discussion because it takes requirements into account that were accepted in the root Discussion.

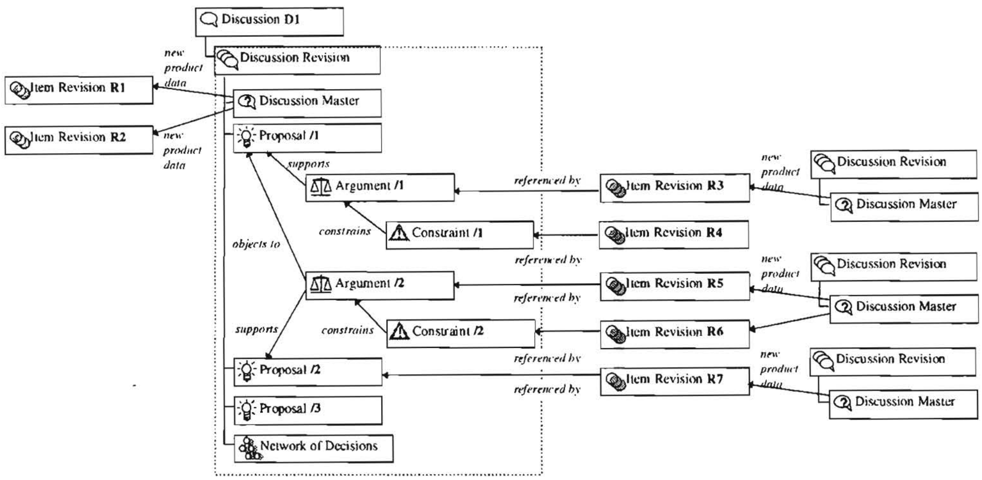


Figure 4.13: Retrieval of serving Discussions

4.4.4 Functions for information retrieval

The following functions enable the user to search for design history information.

Functions to find product data

Before the underlying decision making can be retrieved, the user will first search for the product data, *about* which he wants to retrieve the underlying decision information.

IMAN offers several functions to search on the attributes of product data. The *Find Item* function can be used to find any Item that meets criteria like ID, Name, Description, Owning user, Owning group and Dates for creation, modification and release. The *Find General* function works in the same way for other object types, like Folders, Forms and Datasets.

The disadvantage of these IMAN find functions is, that you have to know what you are looking for. If you don't know how the product's parts are called, you will not be able to effectively retrieve the right appropriate of product data. This problem is solved by looking at the product's *Product Structure.* The product structure shows the sub-Item Revisions of an Item Revision, the sub-sub-Item Revisions of a sub-Item Revision, and so on. By loading the root object of a product, all Item Revisions that are part of the product can be viewed. From this structure, the user can easily identify the part about which he wants more information.

The default IMAN product structure user interface is aimed at providing the user with the *latest* information. However, a user who is interested in the design history, would also want to see how this structure evolved in *history*. In the current implementation of the prototype design history system, the product can be viewed during its previous states, by setting a *Revision Rule.* As a result of setting this rule, only the parts will be loaded that have received a certain status level. For example, if product data is released after the project definition phase, the conceptual phase, the detailed design phase, and finally for production, then the product structures that resulted from these respective stages can be easily reconstructed.

A more sophisticated approach to represent the product evolution during the design process would be to make an actual *reconstruction* of the product structure at a certain moment in time. Based on the creation and modification dates of Item Revisions, this function would enable the user to actually see the separate steps in which the product was developed and play back this evolution forward as well as backward in time. This function hasn't been implemented yet in the current prototype.

Functions to find Discussions

The direct way to retrieve certain Discussions, is to search for their attributes. For example, a user might want to see all the Discussions with an Issue that contains the word "roll", or the Arguments that designer 'Peter' claimed in January or in February. Figure 4.14 shows the dialogue that was implemented to perform such queries. It allows various combinations of the attributes of Issues, Proposals, Arguments, Constraints and Decisions.

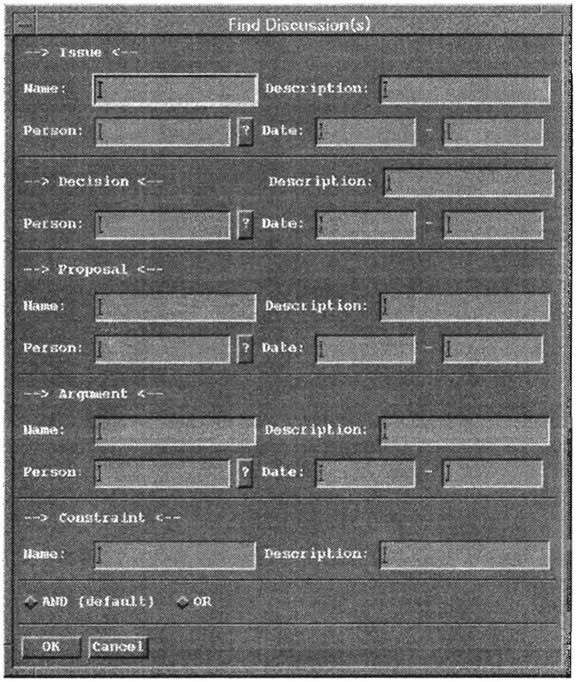


Figure 4.14: Find Discussions on attribute.

Another search method is to *find Discussions on Item Revision*. By means of the this function, the user can query the database for the Discussions that have led to a particular Item Revision. This function enables the user to actually retrieve the underlying rationale behind specific parts of the product.

Figure 4.15 shows the method that is used to search for the Discussions that underlie an Item Revision. After the user has selected an Item Revision, the *Find Discussions on Item Revision* function starts searching for Discussions that are related to the selected Item Revision by means of the New Product Data relation. (1.) The Discussions that are found have directly resulted in the selected Item Revision. Therefore, they will very likely contain the underlying rationale for this part. However, earlier considerations may also have influenced the design of the selected part. Therefore, the function also searches for the Discussions that are linked to previous revisions of the selected Item Revision. (2.) After the function has finished this search, it will continue to search for the underlying Discussions of the Item Revisions that have the selected Item Revision as a component in their product structures. (3.) The function will repeat this search for the previous revisions of these Item Revisions (4.) and for their parent assemblies. The query will stop when ten Discussions have been found, or when it has reached the top of all product structures that is has searched through.

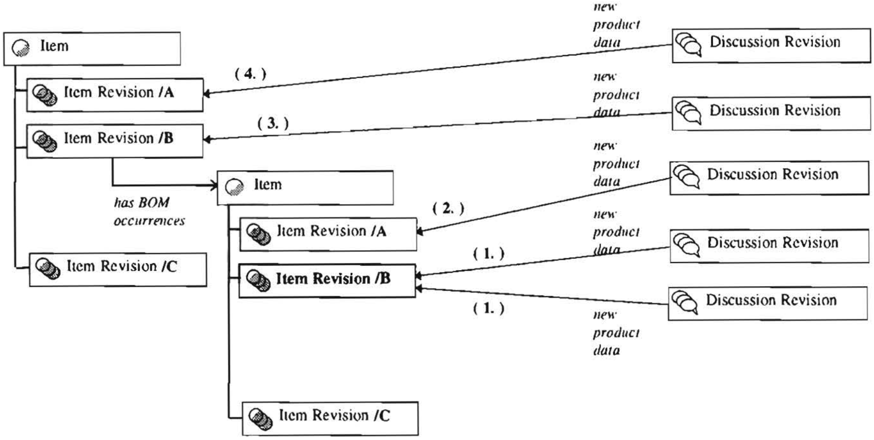


Figure 4.15: Find Discussions on Item Revision.

When the user finds a Discussion, he can immediately see on what previous Discussions it is based. This is shown in the *Network of Decisions*, which represents the Discussions that *serve* the root Discussion. The network gives a clear overview to the sequence of decisions that lead to the current Discussion. The main window in Figure 4.12 shows this network.

Instead of searching for the Discussions that underlie a certain Discussion, i.e. searching back in time, the user can also retrieve the Discussions that this very Discussion serves. This way, the user can retrieve the later Discussions that have been influenced by the selected Discussion. For example, suppose Discussion "X" is related to other Discussions as in Figure 4.16. The Network of Discussions only shows the previous Discussions that influence the current one. However, it may also be interesting to know, what later Discussions are influenced by the current Discussion.

The user performs such a query by means of the *Where Used*-function. This function gives a list of Discussions that have the current Discussion in their Network of Decisions. The user can choose whether he wants to search for the Discussions that the current Discussion serves directly, or the Discussions that are at the end of the networks in which the current Discussion is present.

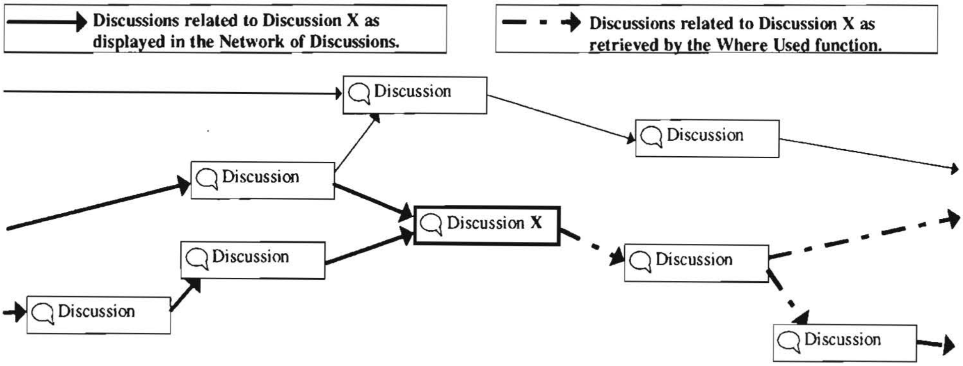


Figure 4.16: Retrieval of interrelated Discussions in the Network of Discussions and by means of the Where Used function.

Functions for design process analysis

The main purpose of a design history system is to provide designers with a useful tool for capturing and retrieving the knowledge that underlies a product design. However, once captured, we believe that a design history system can also be very useful for reviewing design processes. By analysing the episodes in a design process that were extremely successful, or which led to major problems, much can be learned for future design processes. To demonstrate and explore some of our ideas, we implemented three functions to analyse the design histories of completed design processes.

The *Longest Living Discussions* function retrieves the five Discussions which have the longest time interval from Issue to Decision. These issues may have been very hard to tackle and may have decelerated the design process.

The *Bottleneck Discussions* function retrieves the five Discussions which have the largest number of sub-Discussions. A sub-Discussion is a Discussion which serves its parent Discussion and which was started and closed within the period of time that its parent Discussion was open. A Discussion with many sub-Discussions may indicate that this issue needed many other issues to be resolved first before it could be resolved, and therefore slowed down the design process.

The *Discussions With Most New Product Data* function, retrieves the five Discussions that have the largest number of links to Item Revisions by means of the New Product Data relations. The idea behind this function is that Discussions, which result in many new, or modified, Items, have a large impact on the product design. These Discussions may have been very critical in the design process, or may represent large iterations.

4.5 Case: The development of a crash test-rig

4.5.1 Product data considerations

An actual design history database was set up and filled with a previously captured design history for the purpose of evaluation, demonstration, and further experiments. During the earlier research on design history capture, we observed the development of a test-rig for vehicle component crashes. (See Chapter 3.) Both the product data and the underlying decision making were available from this design process. However, the designers didn't use a PDM system to manage their product data. So before the prototype design history system could be filled with decisions, first all product data had to be stored in the system *as if* the original designers had worked with IMAN. This section describes the customisation steps that we performed to set up the product data base for the development of a crash test-rig. More details can be found in (Houben 1998, Houbolt 1998).

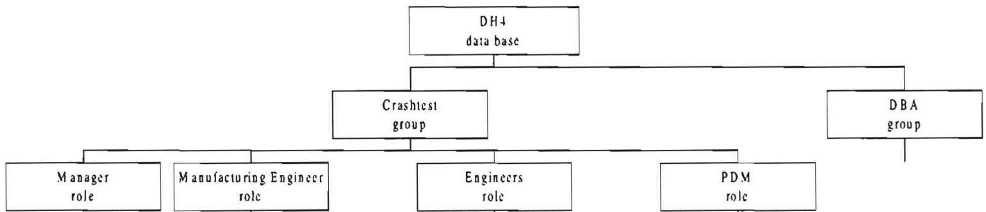


Figure 4.17: Users of the database

The first step was to set up an organisation that represents the design team. Figure 4.17 shows the users of the product data base. There are two groups. The Data Base Administration group (DBA) is responsible for system administration. The group 'Crashtest,' is the design team that is responsible for the 'Crash Tester 2' project. The Crashtest group has a manager, a manufacturing engineer, and four engineers. This is just like the organisation of the original design team, except that the two students who developed the measuring system, are represented by a single person. (See Section 3.3.2.) The group has an additional member, who has the role 'PDM'. This person is responsible for the management of all product data in the system. He has the privileges to perform group administration activities. Moreover, he is responsible for the capture and storage of design decisions.

By default, each group member has read and write access to all data that is owned by the group. A user can only delete data or change its protection settings, when he is the owner of the data. Other users, that are not a member of the Crashtest group, have no access to the data.

The users can work with various applications from within the product data base. The CAD system, which is used for 3D modelling and the generation of drawings for production, is integrated with the database. Moreover, a finite element analysis system, an application for simulations and several tools for editing and viewing text and graphic files were encapsulated by the database.

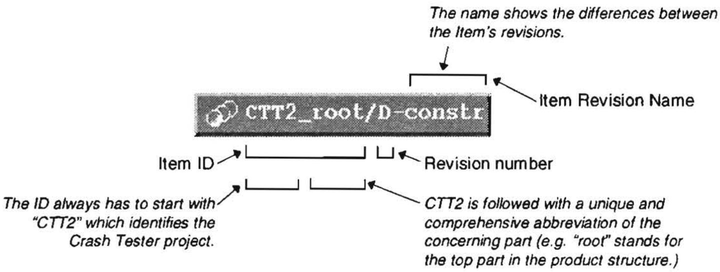


Figure 4.18: Naming conventions for Item Revisions.

Each Item in the database must have a unique ID that is named according to the convention in Figure 4.18. The name of an Item Revision is used to express the differences between the various Items. For example, an Item can have a set of Revisions named 'Requirements', 'Concept', 'Design', and 'Final.'

The product structure is a single-view hierarchy. This provides enough structure to manage all product data for the crash test-rig-product. Figure 4.19 shows the product structure at the beginning of the project, Figure 4.20 shows the product in its final state.

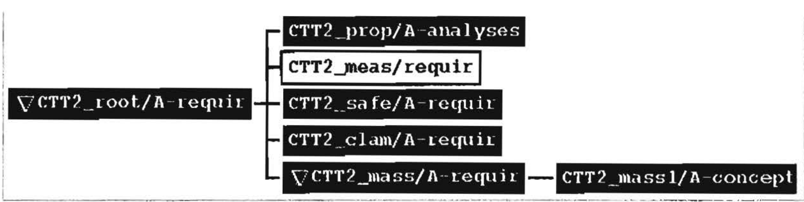


Figure 4.19: Product structure at the beginning of the design process.

Product data reaches one or more of the following status levels:

- *Accepted Requirement:* For product data that has been accepted by the design team as a requirement for the crash test rig. All product data that was known at the beginning of the design process, has the Requirement status.
- *Accepted Concept:* All product data that describes the accepted conceptual solutions for the various parts in the product. This data serves as a specification for further in-depth design activities.
- *Accepted Design:* All information that defines the final design. It contains the main product dimensions and geometry, although the representation form is not important.

- *Released for production:* Final product data, in the representations that are required to build the crash test-rig.

The collection of product data from the test-rig's design process consists of 105 Items, 133 Item Revisions and 210 Datasets. The final product structure is built from 70 different Item Revisions. The database vault contains approximately 600 application files.

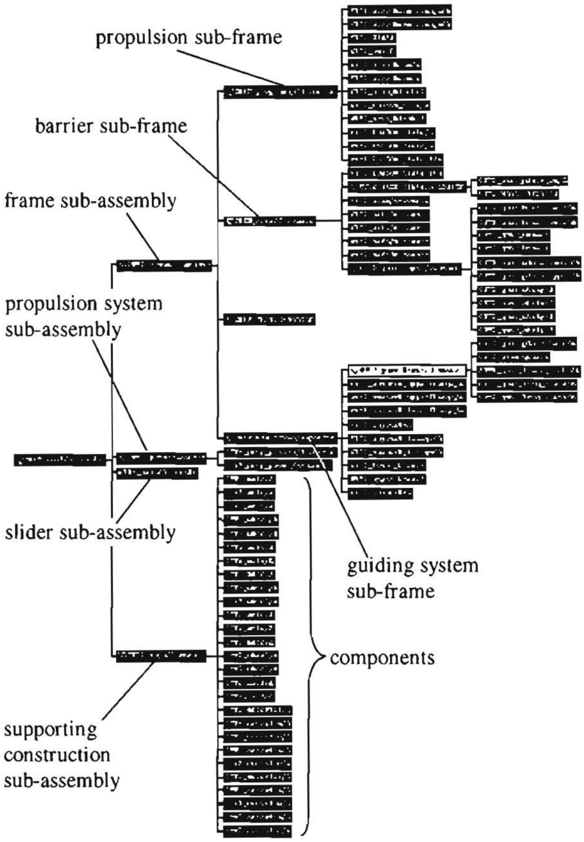


Figure 4.20: Product structure at the end of the design process.

4.5.2 Design history data considerations

The input of design history requires no customisation steps. The design history was inserted in the database simply by creating new Discussions and filling their contents. For the input of information, we used the design history records from the experiments on information capture. (See Section 3.3.2.)

The PDM-officer (see Figure 4.17) creates and is the owner of all Discussions in the database. By default, all group members can view and edit the captured data, or add more Proposals and

Arguments to it. Discussions can only achieve a single release status, termed *Reviewed.* After release, the data can not be modified anymore and the users of all other groups can read the data as well.

Often, a Proposal or an Argument references a document that isn't stored in the database. For example, many Proposals are explained by sketches on paper. In such a case, the new information is stored as a reference under the appropriate Item revision and the Item Revision is referenced by the Proposal.

4.6 Assessment

This section evaluates the prototype design history system. This evaluation is aimed at testing the system's functions with respect to the specifications from Section 4.2. For now, it is presumed that *if* the system fulfils the specifications, *then* the design history system has the ability to improve design processes. Whether this assumption is right or not, will be further discussed in Chapter 5.

4.6.1 Information capture

Specification 1A - Discussion representation model
The current implementation entirely covers the specified data model for design history storage. All data objects, including their attributes and interrelations, can be stored in the database in an unambiguous manner.

Specification 1B - Discussion interrelations
The interrelations between Discussions can be well managed in the Network of Discussions. The *Suggest Discussion(s)* function is available to help the user to find potential Discussions that serve the selected Discussion. However, the user interface only represents hierarchical structures. The Discussions that serve Discussions in different branches in the discussion tree, are represented in both branches.

Specification 1C - Product model
The design history system can contain all product data that is created during a design process. This is achieved by implementing the design history module within a PDM system. The design history implementation doesn't affect the PDM system's default functions for product data management. The Product data isn't captured as a part of the design history capturing procedure. It is created and modified directly by the designers.

Specification 1D - Capturing procedure
The design history system enables an organisation to capture both product information and the underlying decisions and their rationales according to the approach shown in Figure 4.3. Each

Discussion has its own access protections. Moreover, Discussions can be released according to an appropriate release procedure.

4.6.2 Information retrieval

Specification 2A - Studying the reasoning behind parts of the final design

The decisions that underlie a specific part, function, or feature of the product can be retrieved by selecting the corresponding Item Revision and calling the Find Discussions function. The Item Revision can be easily selected from the product structure. The user can select whether he wants to see the most actual product structure or the product during previous design stages.

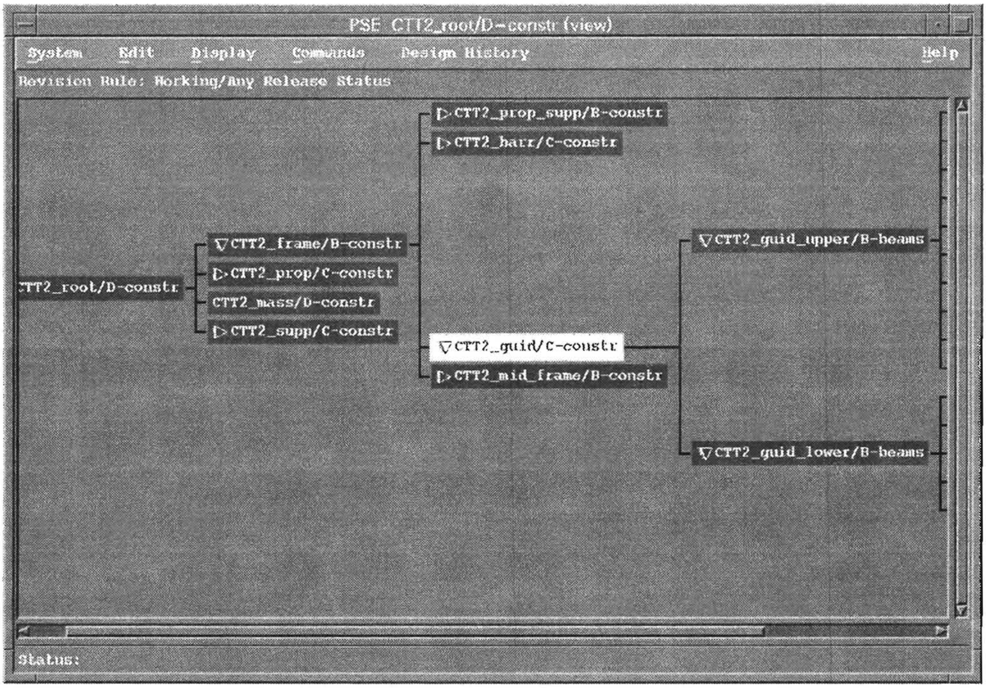


Figure 4.21: Selection of components from final product structure.

For example, suppose we want to retrieve the decision making that underlies the selection of the Guiding Beams. The crash mass slides along these beams. (See Figure 3.20 in Chapter 3 for more details.) Figure 4.21 shows the selection of the corresponding Item Revision in the product structure. The Find Discussion function is used to query the database for the Discussions that are related to the selected Item Revision.

Figure 4.22 shows the search results. Immediately we have found the most important Discussions that occurred during the design of the guiding beams. Originally, a concept was chosen to guide the crash mass. (This is the Discussion on top of the list.) Then, the decision was made to use a friction bearing to guide the crash mass. (The fourth Discussion.) Before they selected the type of guiding beams for the frame, (second from the top in the list) the designers reviewed and changed the original concept. (The third Discussion from the top.) Lower in the list, we can find more general decisions regarding the frame and the general concept of the crash test-rig.

More tests, during which we retrieved the Discussions that are related to specific product data, showed that this works very effectively and easily.

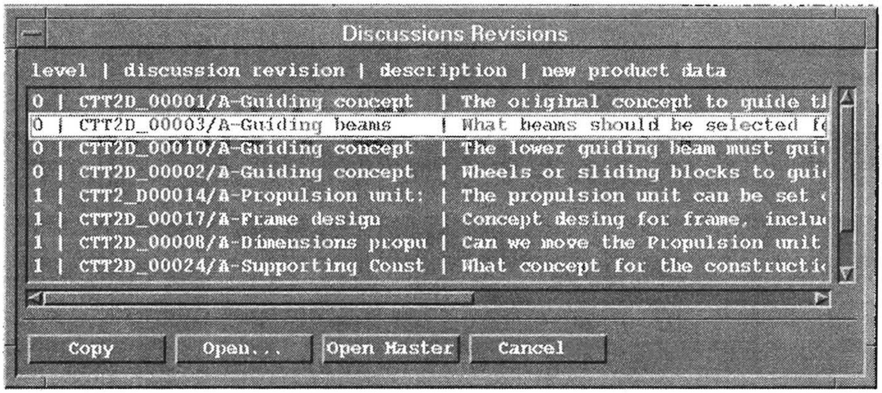


Figure 4.22: Discussions that are related to the selected component.

Specification 2B - Searching for potential solutions

The development of a product is an evolutionary process. During a design process, a product evolves in steps. Each step involves the generation of solutions and their evaluation. An effective way to search the design history for the previously proposed solutions to a specific problem, is to identify the product data that is a requirement or constraint to the problem at hand, and retrieve the decisions that are based on this data. In many cases, the Discussions will be aimed at the translation of the requirements and constraints into a practical solution.

For example, suppose we would like to find more concepts to guide the crash mass. A good starting point is the original set of requirements, in which no concept at all was defined, but which specifies the required masses and velocities. There are Discussions that underlie the selected Item Revision. (See Figure 4.23.) The first Discussion contains the approval of the original set of requirements at the start of the project. The second Discussion describes new requirements which were added later on. By performing a *Where Used* query on the first Discussion in the list, we find the Discussions that are influenced by the selected Discussion, and consequently are based on the original set of requirements.

Figure 4.24 shows the results of the query. The results turn out to be very accurate. The retrieved Discussions are all on a conceptual level. The Discussion on top of the list contains the selection of the original guiding concept. It describes the alternative solution concepts that the team considered and their supporting and objecting arguments.

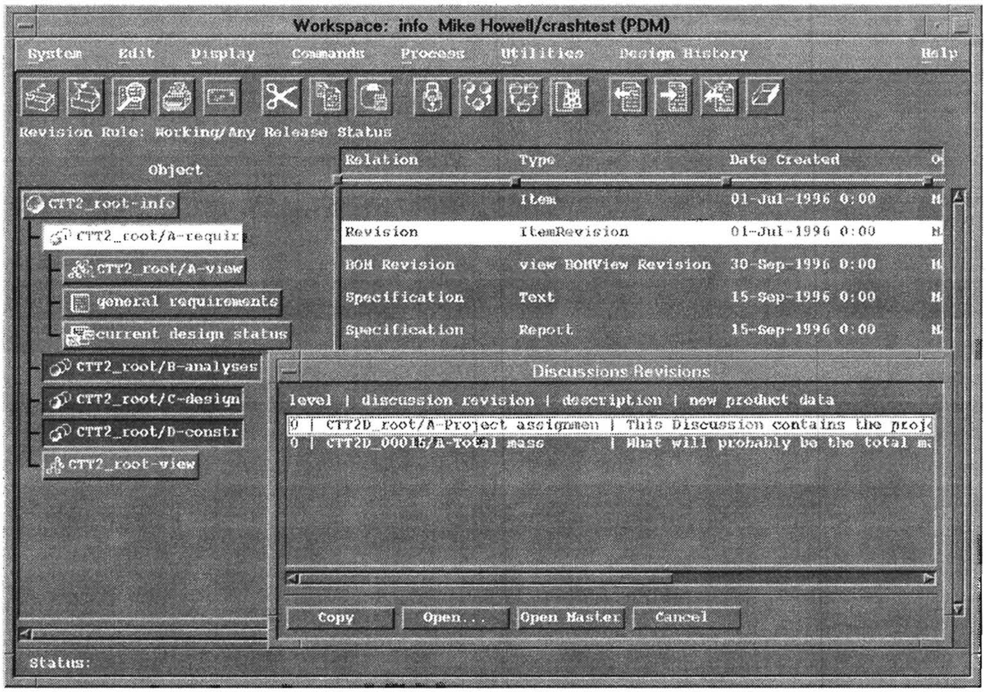


Figure 4.23: Find the Discussions that lead to the original set of requirements. The large window shows the selected Item Revision, which specifies the original requirements. The 'Discussions Revisions' window shows the underlying discussions.

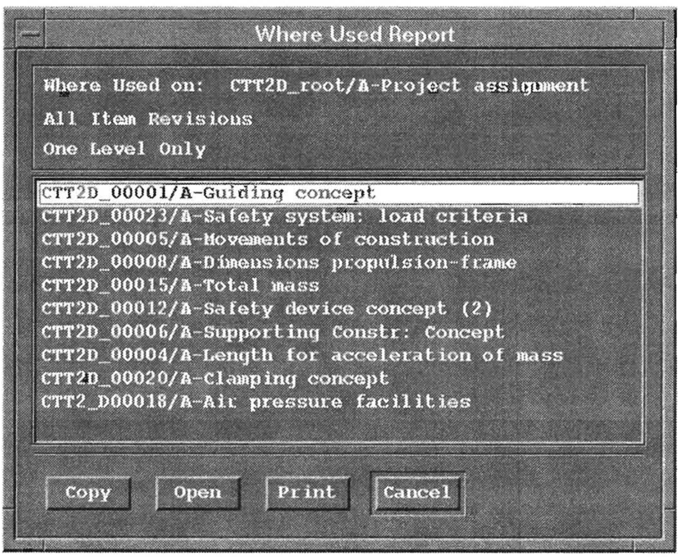


Figure 4.24: Retrieval of the Discussions that are based on the original set of requirements.

Specification 2C - Investigating whether a solution was previously proposed or not

If a user wants to improve a feature of a design, then he can find in the design history whether the same improvement was also proposed earlier or not. For example, the crash mass in the crash test-rig is propelled pneumatically. The propulsion gas is air, which is provided in bottles under high pressure, up to 200 bar. These gas bottles are leased from a gas supplier. Now suppose that someone proposes to fulfil the need for compressed air by means of an in-house compressor. By searching for the Discussions that underlie the propulsion assembly (see Figure 4.25) we find the original Discussion on how the compressed air should be provided. The contents of this Discussion show (see Figure 4.26) that the designers not only thought of buying their own compressor, but that they also considered using the compressor of another department or the one of the local diving club.

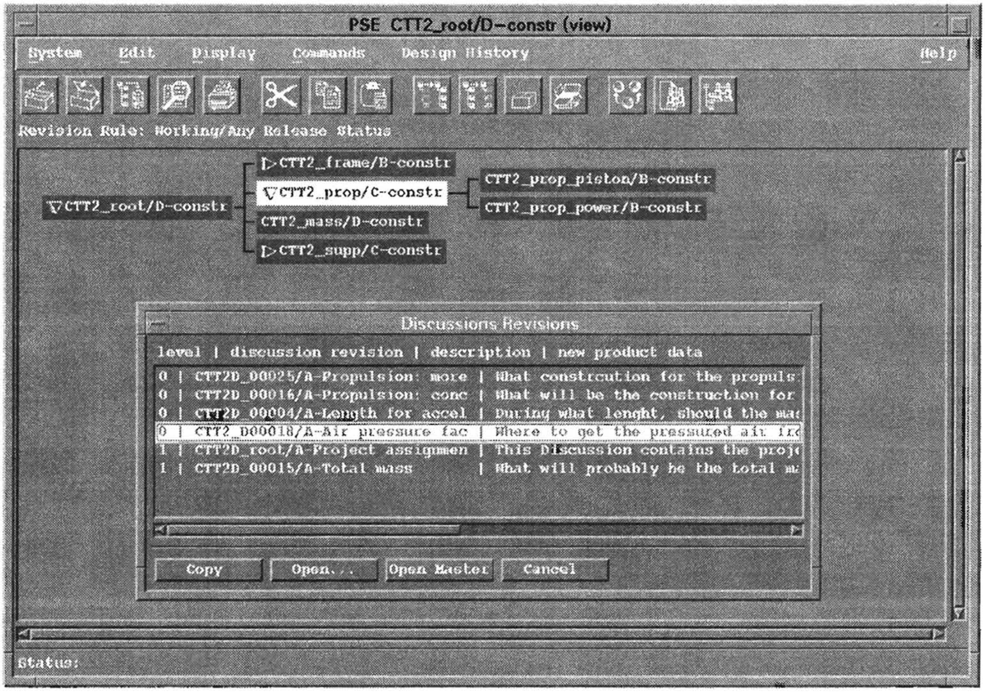


Figure 4.25: Retrieval of the decisions on the final design for the propulsion assembly. The large window shows the selected Item in the product structure. The 'Discussions Revisions' window shows the underlying Discussions.

Specification 2D - Retrieving specific documents which were used during the design process

The Proposals, Arguments and Constraints in the design history contain direct links to the related product data. By retrieving the reasons behind a specific part of the product, it is easy to locate the very file or document that was used during specific stages of the design process.

For example, the Discussion from the previous example (see Figure 4.26) contains references to the correspondence between the design team and suppliers of compressor equipment.

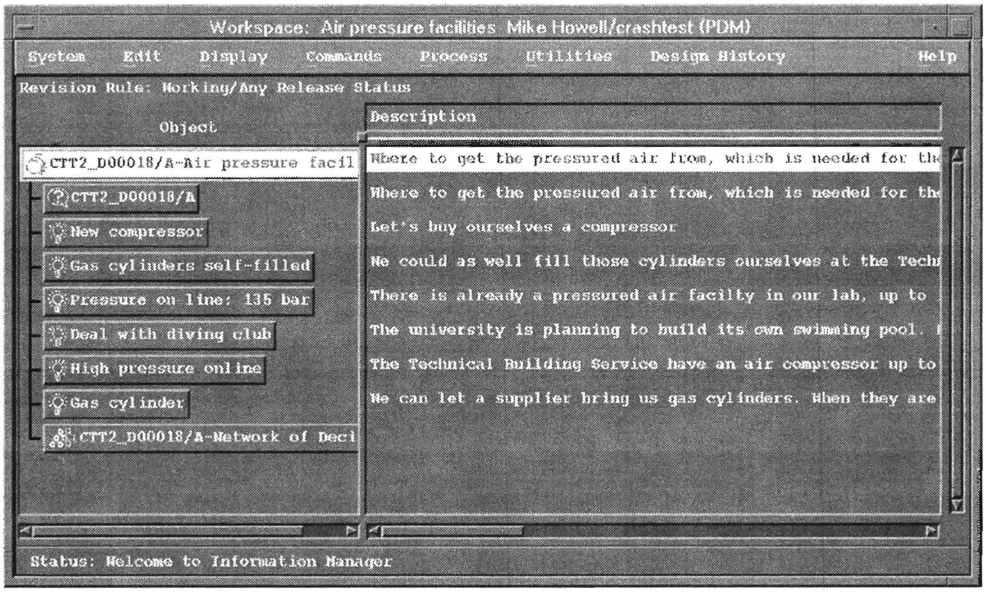


Figure 4.26: Contents of the Discussion on the air pressure facilities for the crash test-rig.

Specification 2E - Studying the lessons learned during the design process

For the retrieval of the most critical decisions in the design process, (see also Table 4.5, p.70,) the following two functions have been implemented:

- Retrieval of the five Discussions which have the longest time interval from Issue to Decision, (see p.89 on the Longest Living Discussions function,) and
- Retrieval of the five Discussions with the largest number of references to Item Revisions by means of the New Product Data relationship, (see p.89 on the Discussions With Most New Product Data function.

The idea behind these queries is that they identify the Discussions that possibly decelerated the design process or that led to large iterations. When considering the observed design process of the test-rig, it can be said that the design of the guiding system and the design of the crash mass were most critical. The designers needed most effort to design these parts, and several times they needed to reconsider earlier made decisions regarding these parts.

Figure 4.27 and 4.28 show respectively the results of the first and the second function, for the design history of the crash test-rig. The results indeed include two Discussions on the guiding system (see Figure 4.28) and one Discussion on the crash mass (see Figure 4.27.)

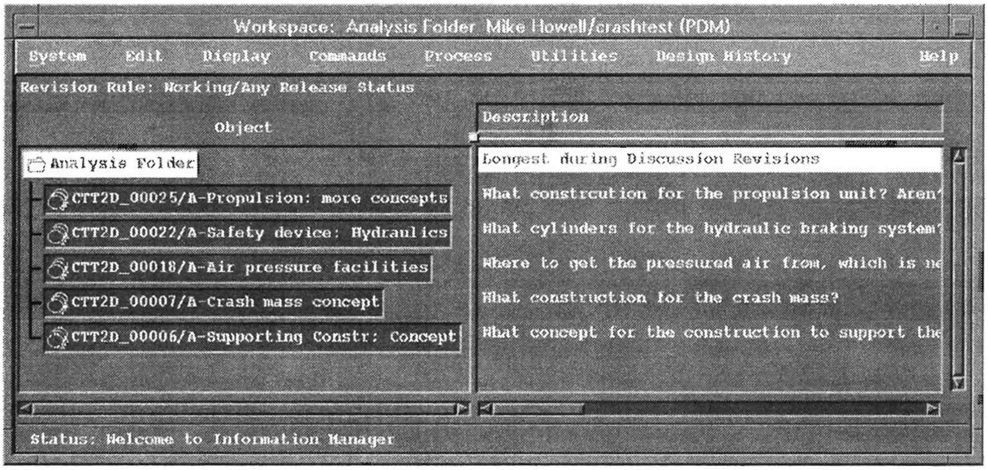


Figure 4.27: Discussions with the longest time to resolution.

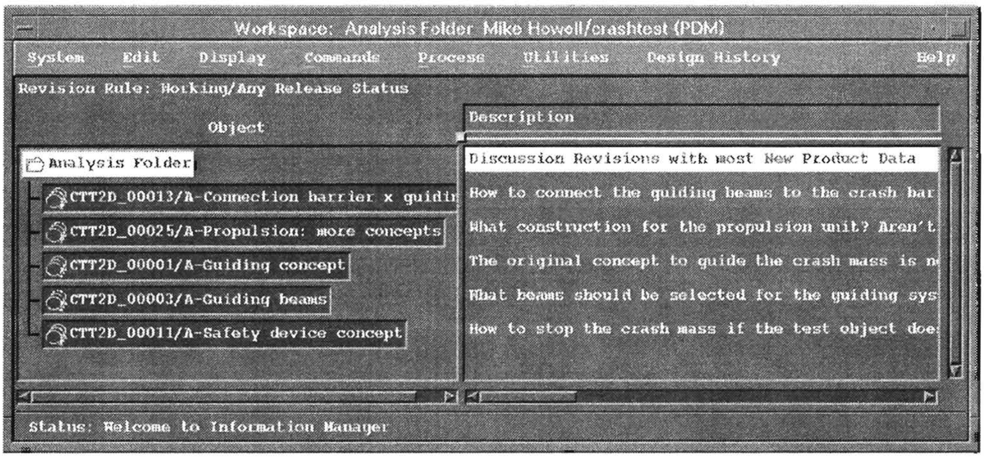


Figure 4.28: Discussions with the largest number of *New Product Data* references.

Specification 2F - Studying bottlenecks in the design process

To find the Discussions that decelerated the design process, (see also Table 4.6, p.70,) the user can search for:

- Retrieval of the five Discussions which have the longest time interval from Issue to Decision, (see p.89 on the Longest Living Discussions function,) and
- Retrieval of the five Discussions which have the largest number of sub-Discussions. (Discussions that were both raised and resolved within the time interval of the parent Discussion.) See also p.89 on the Bottleneck Discussions function.

For the first function, see the previous paragraph. (Specification 2E.) Figure 4.29 shows the results of the second function.

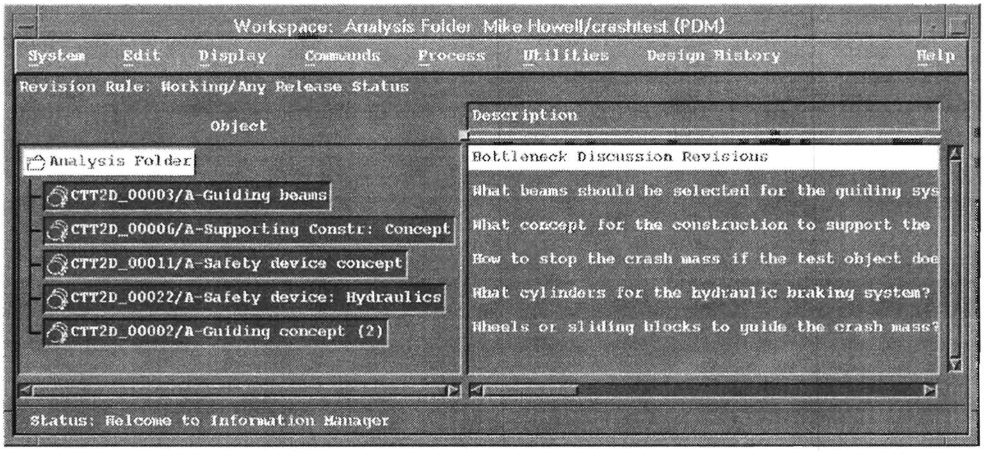


Figure 4.29: Discussions with the largest number of sub-decisions.

It is problematic to assess the results in an objective manner. From the test-rig's design history, it is hard to identify the issues that really slowed down the design process. The search results in Figure 4.27 and Figure 4.29 correspond to the observation that the safety device and the propulsion unit were developed at a slower speed. However, this was not caused by technical problems, but by the fact that the responsible designer gave priority to other activities than the design of these parts.

Specification 2G - Support for changes to the product

If a decision needs to be reviewed, the user can use the Where Used function to retrieve all Discussions that are based on (i.e. *served by*) the current Discussion. This paragraph discusses two examples.

Figure 4.30 shows the results for the Discussion on the air pressure facilities for the propulsion unit. (See also the assessment of Specification 2C.) There is only one Discussion that might be affected when the decision on the compressed air is changed. This result is correct. The way, in which the propulsion unit is provided with compressed air, can be considered fairly independent from the rest of the construction.

Figure 4.31 shows another example. If the original guiding concept would reviewed, then this would affect a whole network of other Discussions. It requires that all later guiding concepts will be reviewed as well, including the concept for the crash mass.

Specification 2H - Consistent decision making

Recent decisions can be easily retrieved by means of the Find Discussions on Attribute function. Figure 4.14 shows the dialogue. For example, the user can retrieve all Discussions that were made during the last month by a specific user. This function is an easy and quick way to locate the Discussions that meet any arbitrary set of criteria.

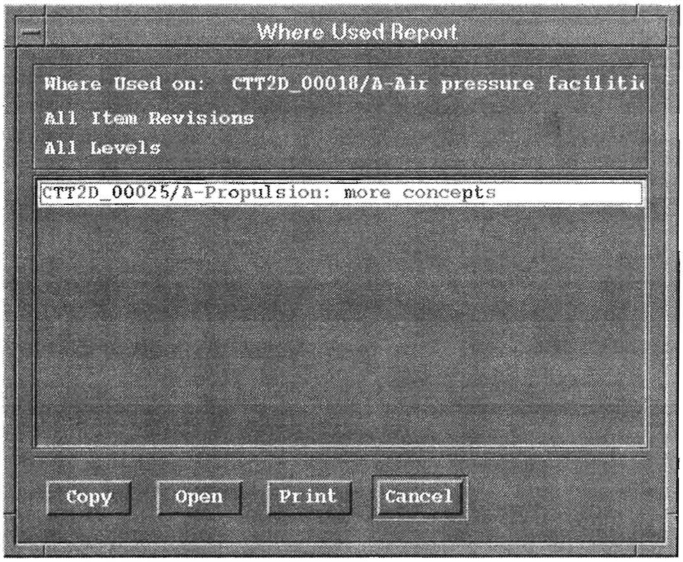


Figure 4.30: Discussions which are served by the selection of gas cylinders as the primary source of energy

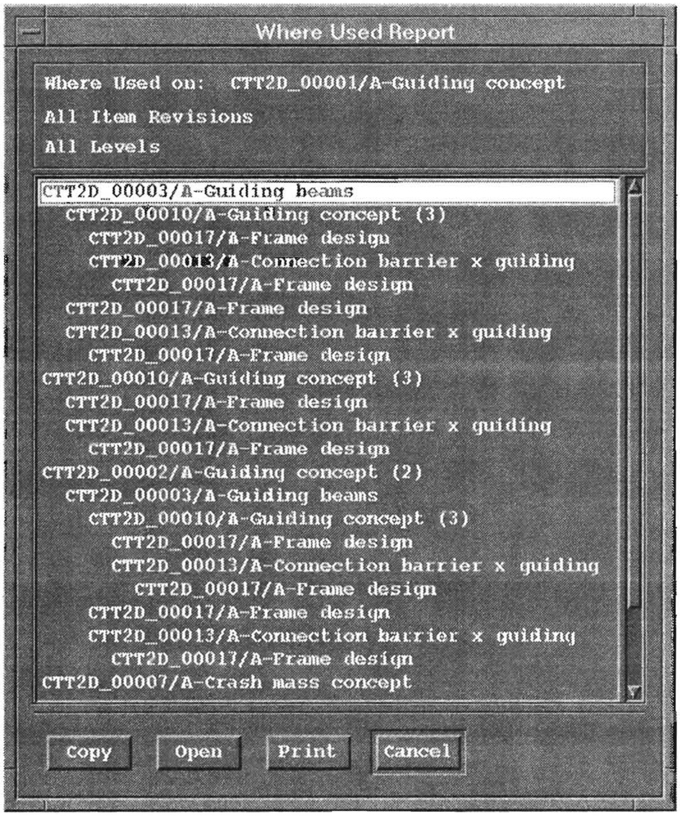


Figure 4.31: Discussions which are based on the selection of the concept to guard the crash mass.

Specification 2I - Support in conflict resolution
The use of a design history system to support the communication among designers in a design project can't be evaluated here.

Specification 2J - Control of project progress
The control of project progress requires advanced functions to search for Discussions, for example a function to map the progress of decision making to the progress during previous projects. Functions that support such queries haven't been implemented in the current prototype.

4.7 Conclusions

The design history can only be captured and retrieved effectively if design histories are considered as a part of the data that is required to support current and future business processes. Therefore, Product Data Management is a platform that is appropriate for the implementation of a design history system. By definition, product data management covers the management of design histories. However, state of the art PDM systems are focused on product data and provide no means to store the underlying reasoning and decision making. Moreover, state of the art PDM systems focus on providing the user with the most *actual* information, instead of showing the evolution of the product during its design process.

The implemented prototype design history system integrates the capture and retrieval of design histories with the management product data. Its powerful search and retrieval functions enable the user to get an accurate view on the processes that underlie the final product. Decisions can be easily found back from the actual product information. The decisions contain links to related documents in the product data base. The result is more than the sum of a PDM system and a design history system. Nevertheless, the capture and storage of design decisions imposes no burden or constraints on the actual product model or business process model that is used to manage product data.

Although the concept, that the design history system is built on, is very strong, the user interface of the prototype design history system can be substantially improved. The current implementation presents design history information in forms, i.e. static window layouts with fields that are filled with attribute information from the database. To view the design history information, for example to view the contents of a set of Proposals and their Arguments, the user must open and view more windows at the same time. This makes the user interface sometimes confusing. A more sophisticated interface should present design history information in a more graphical manner.

Still, the implemented prototype design history system is a good demonstrator of the essential concepts of design history. Moreover, the current set of retrieval functions is just the beginning. If the retrieval of design histories is tested in a real design environment, then this will probably lead to more and better ways to support the design process with design history information.

5 *Retrieval of design history information*

5.1 *Introduction*

From the research on the capturing of design histories (see Chapter 3,) it was concluded that design history capture is feasible in practice. Moreover, the designed and implemented prototype design history information system (see Chapter 4,) demonstrates that design history functions can be well integrated with state of the art methods and tools for product data management in engineering design. However, a tool that solely captures and stores information, doesn't improve the re-use of product knowledge and information. To do so, the design history system must support designers in the *retrieval* and *re-use* of knowledge and information. The information that is stored in the system must match the knowledge and information that are needed during (re)design processes. Moreover, designers must be able to search and find the required information in the system. This information must be represented in such a way that it can be easily learned and understood

The present chapter explores the way in which information will be retrieved from a design history system and the contributions of the system to an improved design process. An insight in the way a design history system contributes to an enhanced re-use of design knowledge and information was gained by means of a literature survey and two case studies.

A literature survey on the information requirements of engineering designers shows the information types that are needed during design, and the extent to which current documentation practices fulfil these needs. Based on these findings we can derive the potential added value of a design history system. A literature survey on the (re)use of information from design history and design rationale systems shows what benefits have been actually achieved in practice with design history and design rationale approaches.

Two case studies were conducted to explore in more detail the information needs of engineering designers and the extent to which the design history system that is proposed in this thesis fulfils these needs. Case 1 describes the redesign a test-rig vehicle component crash experiments. The redesign process was supported by the earlier captured design history from the original product design. (This original design served as a test case for design history capture, see Section 3.3.2.) To learn more about the information that the redesigner needed from the original design and the extent to which the design history had supported the retrieval of this information, we interviewed the redesigner after the design process. Case 2 describes the observation of a design team who worked on the prototype design for a new inkjet printer.

During three months, designers were observed to learn what information they needed and how a design history system might have provided the required information.

The next section discusses the literature survey on the retrieval and re-use of design information. It discusses the information requirements of engineering designers and the extent to which current information sources fulfil this need. Moreover, it discusses the benefits that are claimed for design history and design rationale systems and the proof that can be found for these claims. Section 5.2 is closed with a discussion of the implications of these insights for our design history system. Section 5.3 discusses the two case studies that were conducted. It presents the experimental set-up of the experiments and discusses the results. The chapter is closed with the conclusions on the retrieval of information from a design history system and recommendations for further research.

5.2 The information requirements of engineering designers

The following sections explore the research by other researchers on the information handling behaviour of engineering designers. The first section explores the general -non-design-history-related- research. It discusses a model of the information processing designer, the types of information that are needed during design, the sources from which a designer obtains his information, and the extent to which these sources in current engineering design practice fulfil the information needs. Section 5.2.2 discusses the research on the use of design history and design rationale systems. It discusses the advantages of such approaches and it explores the empirical proof for these claims. Section 5.2. is closed with a discussion of the implications on the use of the design history system in this thesis.

5.2.1 General research

Information processing by designers
Figure 5.1 shows a model of the information processing behaviour of the engineering designer as proposed by Stauffer and Ullman (Stauffer 1991). The designer performs design activities in a design environment. This environment consists of an external (outside the mind) and an internal (within the mind) environment. Within these environments, a designer performs problem solving activities by which the 'Design State' is changed step-by-step. The Design State contains all information that has been created at a certain time point. It is stored both in the internal environment and in the external environment. Each problem solving activity uses parts of the information in the design state, processes it and adds new information to it. For example, to select the material for a certain part, a designer must select the relevant information, then he must set up an appropriate load model to calculate stresses and displacements, and then use these results and other requirements to compare the usability of several alternative materials. To process all this information, it must be loaded in the designer's 'Short Term Memory.' The designer uses notes, drawings and sketches during his task because

the storage capability of his short term memory is only limited: A designer can only work with up to seven different chunks of information at the same time.

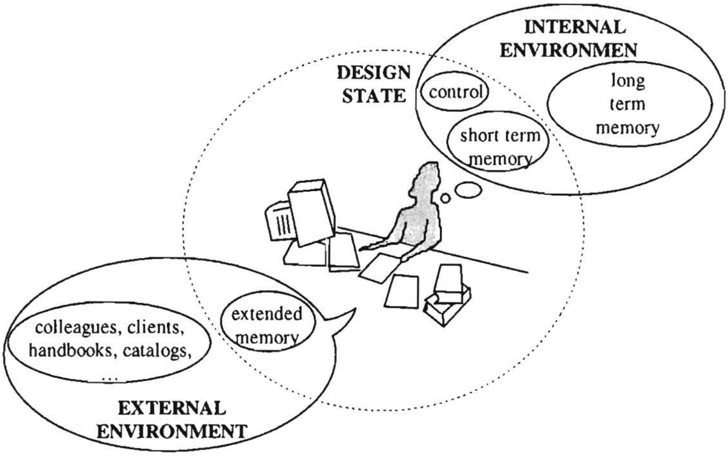


Figure 5.1: Model of the engineering designer as an information prcoessing system. Adapted from (Stauffer 1991).

New information that is not present in the current design state, and that can't be derived from it, must be retrieved from either the designer's 'Long Term Memory' or external sources like handbooks, reports and colleagues. The long term memory is a source that is easily accessible, has short retrieval times, and has an unlimited storage capacity.

The search for, and the retrieval of required information that isn't present in the designer's long term memory or in his direct environment, is often hard. The next section will show that it is mostly scattered over various sources. Especially if a designer doesn't exactly know what he is looking for, it is hard to locate the right piece of useful information. If a designer needs information that is outside the immediate design environment requires, then the designer must stop his current design activities, and use his memory and his cognitive capabilities to look for this information. Consequently, only in the cases where design work stops because substantial information is missing, a designer will start searching for it.

Often, design is not performed by a single person, but by a design team or group of collaborating designers. In such a situation, the exchange and transfer of information becomes extremely important. Various designers must have access to the same 'Design State', or must be able to keep their personal design spaces consistent. The designer becomes a node in a network of providers and receivers of information (Court 1995). However, an effective exchange of information will not be enough for effective teamwork. Often, the designers need to 'stick their heads together' to tackle the most critical problems. Whereas individual activities consist for a large part of 'procedural work', i.e. performing design tasks which are structured and straightforward, teamwork is dominated by 'knowledge work,' i.e. the diverse and ad hoc tackling of 'wicked' problems (Shum 1998). The resolution of such problems is done by negotiation and argumentation. In contrast with individual work, searching for information is hardly ever a group activity. Only if the problem can't be solved because of lack of information, subsequent search activities will be started in preparation of the next team session.

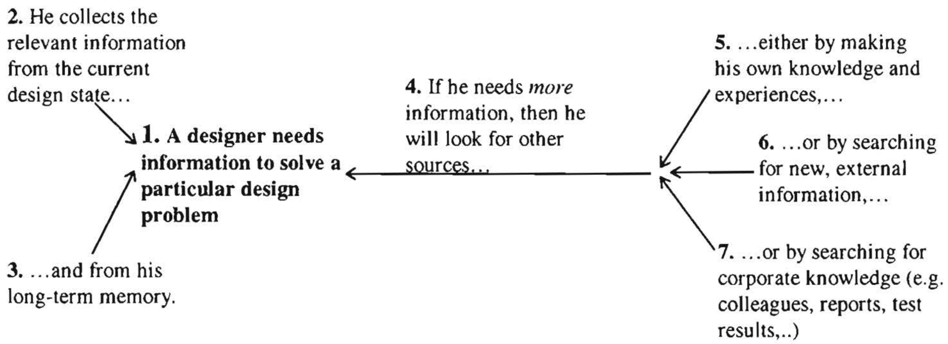


Figure 5.2: Model of the information-retrieving designer.

Based on this discussion, some of the processes can be identified that are involved in searching, retrieving and using information in the design process. Figure 5.2 shows this process. On the left side of Figure 5.2 there is a design problem, or issue, that must be resolved. Resolving this problem requires the collection of data, information, experience and knowledge. Based on it, the designer can find a good solution. The required information comes primarily from the current design state and the long term memory. If this results in a situation in which the problem can't be solved with high confidence, then a designer needs more information. This information may come from various sources. A source can be in- or outside the organisation. Moreover, a designer can generate the required information himself, for example by doing experiments.

What source a designer will select to start searching, depends on the expected quality and result of the search. The quality of an information source depends on the five "A's" (Court 1995):

- Availability of the source,
- Accessibility of the source,
- Applicability of the offered information,
- Authenticity of the offered information, and
- Amount of information found.

The need for information

Figure 5.3 shows an extensive but still incomplete list of the types of information that are needed during design. What information a designer does actually need, in what amount and at what level of detail he needs it, is influenced by factors like (Court 1995):

- The character of the design assignment,
- The organisation of the design project,

- The type of learner the designer is,
- How the product fits into a sequence of predecessors, and
- What information is demanded by downstream phases in the product life cycle.

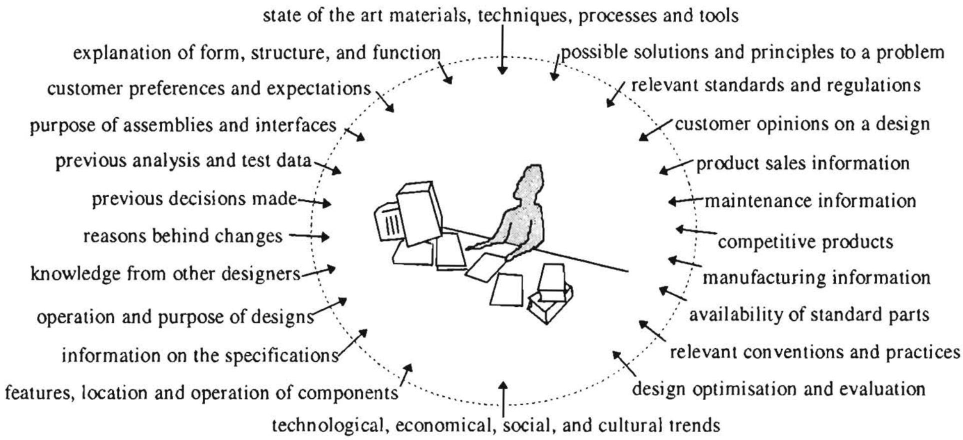


Figure 5.3: An incomplete listing of some of the information types that are involved in design

A survey of 200 experienced designers in the UK (Court 1993) shows that redesign is an essential part of every day design work. 20 % of all design work is spent exclusively on variant and adaptive design. Only 32% is spent exclusively on original design. The remaining 48% is a mix of original, variant, and adaptive design. Information on previous designs is therefore very important. The survey showed that designers spend 18% of their time on searching for information.

The information needs of engineering designers can be researched in more detail by investigating the *requests* for information during design activities. Information requests can be identified by observing designers that pose *questions* or make *conjectures* on the current or a previous design (Kuffner 1991). A question is a request for information on an aspect of the design that is uncertain to the designer. For example, a designer may pose himself the question 'Is this steel?' A question may be directed either to the designer's own memory, his notes and drawings, or external information sources like handbooks and colleagues. A conjecture is a conclusion about the design that the designer infers from incomplete information. A conjecture results in information that the designer believes, supposes or assumes, but which he doesn't know for certain. For example, a designer may make the conjecture 'I think this is steel.'

Kuffner and Ullman (Kuffner 1991) studied the information requests during design by observing three designers who performed redesign tasks. During the experiment, all questions and conjectures that were directed to the original and the adapted design were recorded and analysed. In total, more than 120 questions and 240 conjectures were identified from the three design sessions.

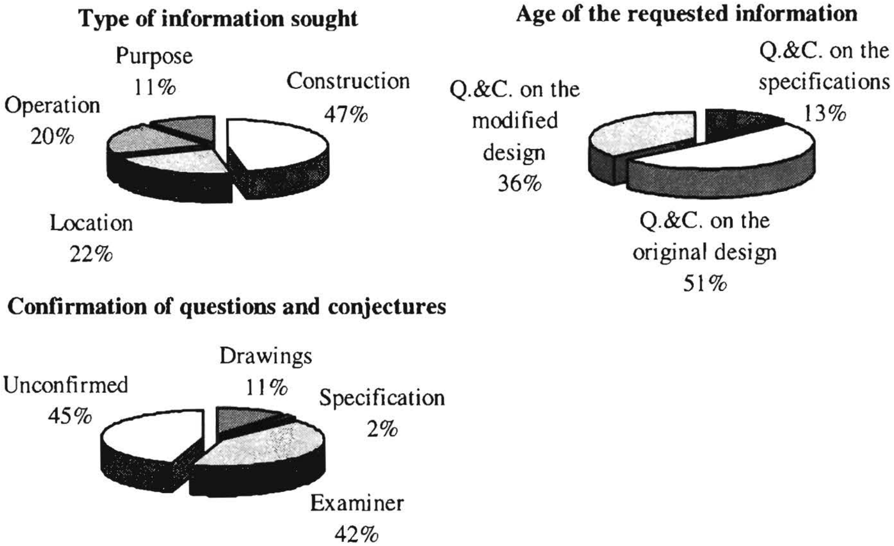


Figure 5.4: Age, type and confirmation of questions and conjectures. Adapted from (Kuffner 1991).

Figure 5.4 shows the results. All questions and conjectures have been categorised according to their age, the type of requested information, and whether the needed information was provided or not.

The majority of the requested information appears to concern the original design. Most questions and conjectures are on the construction and location of components. Less frequent are questions and conjectures on the operation and purpose of the product and its parts. Only a minority of the questions and conjectures can be answered by the documentation on hand.

Most questions and conjectures are answered by an examiner. This examiner was a person who was familiar with the original design and who was available as an information resource during the experiments. The majority of questions that must be answered by the examiner are on the product's purpose and operation. (This isn't shown in Figure 5.4.) This indicates that mechanical engineering designers are interested in more design information than is contained in standard design documentation, which generally consists of blueprints and specifications.

A similar experiment was performed by Baya, e.a. (Baya 1992). Two designers were studied, while performing the redesign of a continuously variable shock absorber. During their redesign task, the observant studied the questions that the designers asked regarding the original design.

The experiment resulted in a total of 240 identified questions. Figure 5.5 shows some of the results. For classifying the questions, a different framework was used than for the study by Kuffner and Ullman (compare Figure 5.4), but the trends, relevant for design history usage, are the same. The largest part of the desired information directly concerns the definition of the original design, (e.g. its construction, its performance, or the location of components or their interrelations.) A smaller part of the questions concerned the underlying reasoning and on how the shock absorber worked. Most information requests concern information from the final, detailed design. However, 43% of all questions concern the earlier design stages. This supports the claim that information from the earlier design stages is important for redesign.

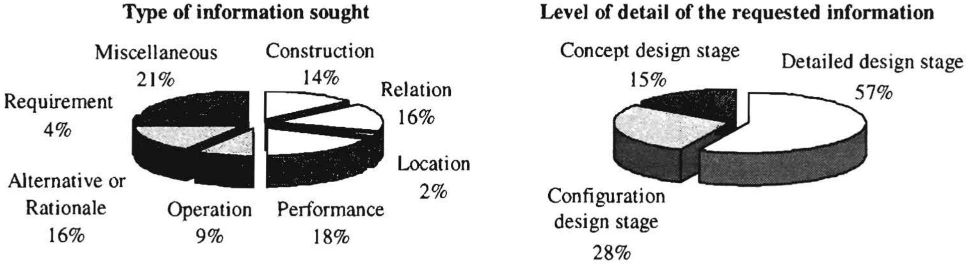


Figure 5.5: Level of detail and type of questions. Adapted from (Baya 1992).

A third research that focused on the information requests of engineering designers during redesign and is presented by Khaldikar e.a. (Khaldikar 1996) produced similar results. During the experiment, the observed redesigners could retrieve information from the original design from a database system.

Here, it was found that an equal amount of data was needed from the detailed and the conceptual stages. The most frequently asked information types were construction information and information on design details. 48% of all queries concerned these types of information. Information types which are provided by a design history system, like alternatives, rationale and decisions, were asked for in 25% of all cases. The less dominant questions were on operation and requirements.

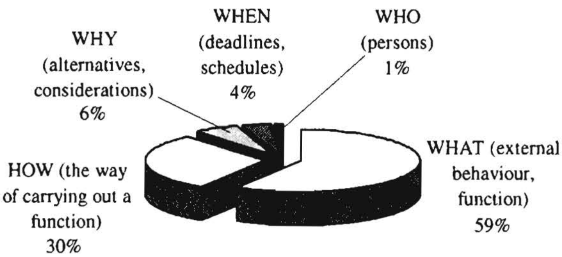


Figure 5.6: Type of questions asked during (software) design team meetings. Adapted from (Herbsleb 1993).

The type of design activity influences the need for information. During design team meetings, different information is required. Herbsleb e.a. (Herbsleb 1993) observed and classified the questioning behaviour of designers during team meetings. Various real (Japanese) meetings and the minutes from 38 meetings on software requirements definition and preliminary software design were observed. Figure 5.6 shows a classification of questions according to their type. 'What' and 'How' questions are highly dominant. 'Why' questions are rarely asked in a meeting. This indicates that either 'Why' questions are less important, or that they are only asked outside meetings. Another explanation might be that the answers to 'Why' questions are inferred by asking 'What' and 'How' questions.

Information sources

An information source is a place where information is stored. A source can be a physical place where information is stored, for example a paper-based archive with reports, a computer-based information base, or a personal contact. A source is located on the inside or outside the organisation. Designers must retrieve their information from a variety of sources that are available to them. Figure 5.7 gives an overview of common sources in an engineering design environment.

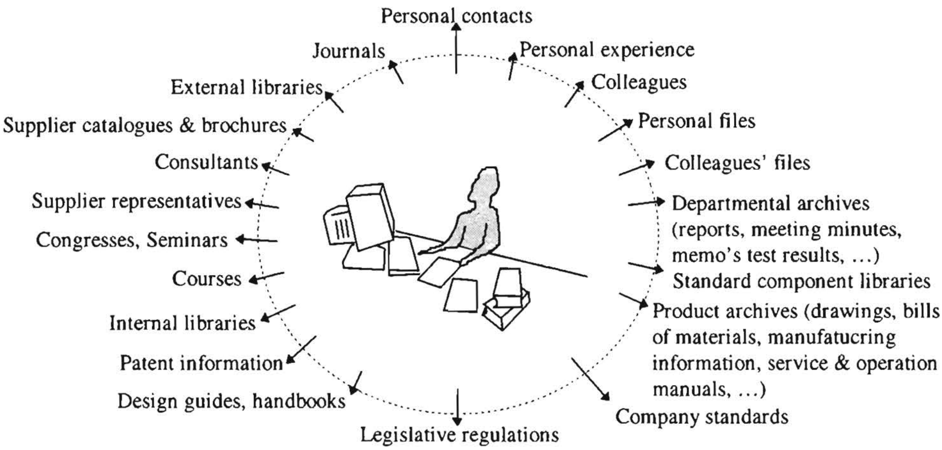


Figure 5.7: Sources for engineering design information

Although an engineering designer has a variety of sources at his disposal, the available sources are inadequate for an effective re-use of design information from *previous projects*. A survey of 200 engineering designers in the UK (Court 1993, Court 1994) showed that decisions and their underlying rationale are only recorded in personal archives, or that they aren't documented at all. Personal archives are for example diaries, logbooks, and meeting minutes. These sources are available for personal reference only. They aren't fit for sharing across a group of designers.

The reports that are written during a development project often contain important backgrounds and concepts behind the design, like specifications, specific problems and expectations and plans for downstream design activities (Blessing 1994). However, their access is difficult if the report isn't present in the designer's local environment and if the designer isn't aware of its contents.

The documentation that currently remains from design projects, mainly consists of released product information, describing the final product. Often, this information is properly archived and indexed for later retrieval (Court 1993). However, the main purpose of most documentation in engineering design is the communication with downstream design processes and for legal purposes. It doesn't give any information on the stages, the design went through, or backgrounds behind decisions.

This observation is supported by an examination of the information accessing behaviour of engineering designers. An analysis of 20 designers (Court 1997) showed that the information sources which designers access most frequently, are colleagues, internal reports, existing drawings, supplier catalogues and personal contacts with suppliers. Their personal memory is a very important source of information. It doesn't only serve as a source for the re-use of data and knowledge. It also helps to find the location in which certain information is stored.

Detailed background information and personal experience which is documented in notebooks, memo's and meeting minutes are hardly ever accessed, probably because they are difficult to access and browse. Information technology offers new opportunities to capture and share more background information, for example by documenting e-mails in a discussion database, and publishing and sharing project data on the World Wide Web (Feland 1997). However, the re-use of this information by such tools over the borders of a project, e.g. in a subsequent project, hasn't been explored yet.

5.2.2 Design history research

Experience with the re-use of design history and design rationale information in subsequent development projects are scarce. Here the benefits of such an approach claimed by other researchers are discussed. This section discusses the retrieval capabilities design history systems and their effects on design processes. Moreover, this section will explore the experimental proof for these merely theoretical claims.

The claimed benefits of the (re-)use of design histories

The final goal of using a design history system is to help in improving the design process, i.e. a product of higher quality, at reduced cost can be developed within a shorter time to market. It has been hypothesised that design history or design rationale systems contribute to this by enabling improved communication, improved organisational learning (Gruber 1991) and improved reasoning (Lee 1991). Figure 5.8 shows the claimed benefits for design history and design rationale notations and their interrelations.

An advantage of design history and design rationale systems that is often claimed, is that it improves design reasoning. If a design rationale notation, such as IBIS or QOC (see Chapter 3,) is used to explicitly express and structure design problems *during* team- or individual work, then this will improve the quality and effect of the problem solving process and the design process as a whole. The design rationale notation supports the breaking down of complex problems into a clear structure. The method visualises the current state of the design (Lee 1991). It shows the issues that are currently being resolved, the alternatives and proposals that are currently available and the interrelations between current and previous issues and decisions. This makes it easy to keep track of issues and decisions, to critically reflect on the current problem state and to maintain consistency in solutions and criteria (Shum 1994).

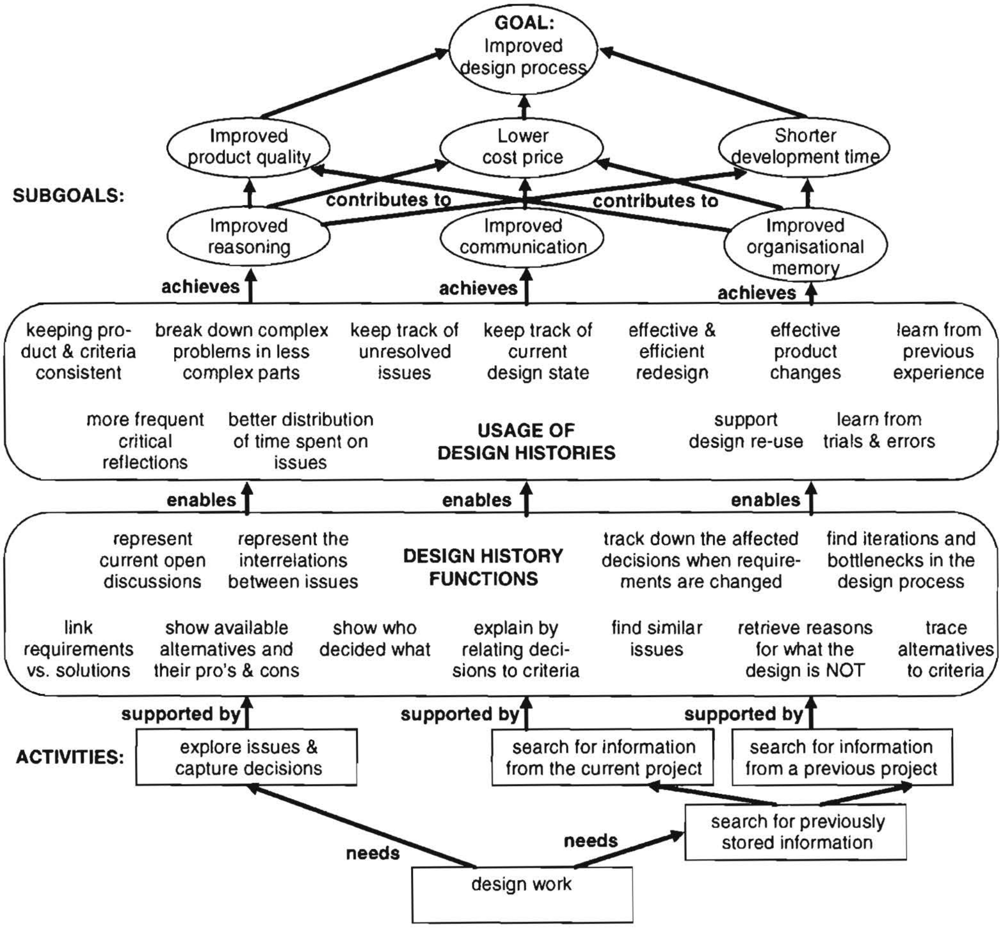


Figure 5.8: Benefits of a design history system and its contribution to improved design processes.

Another claimed benefit of the use of design rationale and design history systems is that they improve communication. This is achieved by sharing recently captured decision information among groups of designers. The decision records provide designers with actual information regarding the design problem that are currently being resolved, the progress of the problem solving efforts and the underlying argumentation. The records can be used to track down the right people and to improve understanding between different stakeholders in the decision making (Shum 1996, Shum 1998). Both in the current and in subsequent design projects.

Improved reasoning and communication aren't the only benefits of a design history system. A third benefit is the improvement of the organisational memory. A design history is a very detailed source of information that contains both the reasoning *and* the design process that underlies the final product. If all designers in an organisation are provided with this information source, then this improves the re-use of knowledge and information. It accelerates organisational learning and it prevents designers from 're-inventing the wheel.' A design history system improves the organisational memory because it enables designers to:

- Find similar problems, their alternative solutions and the argumentation for accepting and rejecting alternatives,
- Search for previously proposed solutions on specified criteria,
- Make efficient re-use of previously generated design documents like drawings, calculations, models and so on,
- Retrieve the decisions behind the product,
- Retrieve the reasons for the product being *not* something else (Moran 1996),
- To learn from previous experience and learn from previously experienced trials and errors,
- Assess the impact of changes in requirements, and
- Tracking down the affected decisions when a product is being modified.

Proof of claimed advantages

The primary aim of the design history system that is proposed in this thesis is to improve organisational memory. An improved communication is considered as a sub-goal of this. The improvement of design reasoning by means of a design history notation is considered to be of minor importance for our design history system. Whether a design history or design rationale system improves design reasoning or not, is still under discussion. Other researchers have reported both advantages and negative effects of the use of a design rationale notation to improve design reasoning. Therefore, it was decided (see Section 3.2.2) to develop a purely descriptive approach for capturing the design history, that isn't used as a method to improve design reasoning.

This section discusses the proof that has been reported by other researchers on the contribution of design history and design rationale approaches to an improved organisational memory. However, very little has been reported in literature on the re-use of design histories and design rationales in other projects. Only a few advantages that have been experienced under practical or laboratory conditions are reported by other researchers.

The IBIS and the QOC design rationale notations were used by design teams over a longer period of time. During these experiments, information that was previously captured was sometimes re-used at a later stage. The following benefits of the re-use of this information are reported in (Yakemovic 1990) and (Shum 1994):

- Summaries on earlier discussions can be circulated to the members for preparation,
- Re-viewing design rationale records helps finding unresolved issues that had been neglected for a longer period of time,
- Design rationale records are a valuable resource when it is necessary to revise previous decisions either to alter them or to recollect the considerations that contributed to them, and

- Design rationale records help to identify other related issues when a specific issue needs to be revised.

It must be remarked that in these cases the persons who re-used the design rationale records were also the persons who originally captured them. Moreover, the observed design cases concerned software design, not the development of a physical object.

Blessing (Blessing 1994) performed a series of experiments under laboratory conditions from which a redesign task, that was supported by design history information, could be compared with one, that was supported by traditional forms of documentation. The designers that had, in addition to the drawings from an earlier design, also the (textual) descriptions of issues, alternatives and argumentation at their disposal, judged that the decision rationales gave clues to issues and solutions that they would have otherwise overlooked.

An relevant observation from these experiments was that designers, in order to re-use information from an earlier design, spent far more time on studying drawings and sketches than on textual information. Apparently, graphically represented information stimulates designers more to have a look at it, than textual information does. An explanation is that information is obtained or deducted faster by looking at a drawing or a sketch than by reading a text. Moreover, by looking at a drawing or a sketch, an experienced designer will quickly see what kind of information he can expect. The relevance of a piece of text is far more difficult to judge from a quick glance.

5.2.3. Implications for design history systems

A designer will only start searching for information if he is really forced to do so. Search activities interrupt design work. If this interruption can be avoided by making conjectures and assumptions about the missing information, then a designer will do so. Whether a designer will start to search additional information or not, depends both on the content of the desired information and the ease of its retrieval. Research on this subject shows that a designer makes an estimation of the effort that it will take him to search for certain information and the chance of finding it, before he actually starts a search (Blessing 1994).

The research on the information requirements of engineering designers shows the importance of information re-use from a previous design. Not just the original requirements and the final design are needed, but also the intermediate steps through which the product went during its development. The designer needs information on the operation of the product, its functions, the way requirements are established, and the interrelations between its components. This goes far beyond geometrical, manufacturing and maintenance information.

From an evaluation of the sources that are currently available to designers, it can be concluded that the sources aren't fit for an effective re-use of design information from previous design projects. The majority of background information is stored only in the minds of designers and in their personal archives. This explains the current importance of knowledge transfer via personal contacts. Another important source are reports. However, their re-use is problematic, due to the fact that it's hard to retrieve the right chunk of information from a large collection of these paper based documents. This calls for an appropriate structure for storage and retrieval of information from previous projects.

The design history system that is proposed in this thesis aims at the improvement of the organisation's design memory. The information that can be retrieved from a design history system has the potency to improve design re-use, learning from previous experiences and making modifications to existing designs. Current documentation in product development divisions fails to support such tasks well. It requires an integrated approach in which both product data from all design phases, and background information on alternatives and evaluations are available to designers.

Currently, there is insufficient evidence to prove that design history or design rationale approaches enable an improved knowledge re-use in engineering design, nor is there any evidence that denies this claim. The retrieval and re-use of information that has been previously captured in a design history notation is an area that requires more and deeper investigation.

5.3 Experiments

5.3.1 Experimental set-up

To gain more insight in the re-use of design history information, the approach to design history as proposed in this thesis was tested. To test and evaluate the approach, there are four possible approaches:

- A review of earlier capturing cases (See Chapter 3) and distillation of the relevant observations on the usability of information,
- A more fundamental research approach, aimed at the establishment of a theoretical foundation for the need and usability of a design history system, without actually using such a system,
- Experiments with a prototype design history system, filled it with information from a previous case and letting, and used by subjects during redesign tasks for which the information in the system is essential, and
- Field tests in which a design history system is used on a larger scale (by more people) and during a longer period for both the capture and retrieval of design histories. These test are used for extensive observations on the use and usefulness of the system.

For the first approach, there are three candidates. These are the three cases, which were described in Chapter 3. However, concerning the usability of the captured information, the capturing experiments already showed that it was difficult to make observations on the re-use of this information. This was caused by the limitations of the captured design histories with respect to broadness, length and the level of detail of the provided product information. However, for 'Case 1' in Chapter 3, the development of a crash test facility, a situation occurred which was a unique opportunity to learn more on the re-use of the captured information. After the project finish, a subsequent project was started to redesign the facility. This was performed by a new designer, who was not familiar with the original design process. By providing this design with the (paper-based) design history from the original design, the retrieval and re-use of this information could be observed. This is described as 'Case 1' of the present chapter.

For the second approach, which is to gain deeper insight in the way design history information will be used without having an operational system available, another case study was performed. We observed a design team in industry during three months and their specific needs for information, and design history information in particular, were investigated. This is described as 'Case 2' in the present chapter.

The third approach, testing a prototype system which is filled with a design history, was not performed. Section 4.6 described a functional test of the prototype system, which was filled with information for this purpose. However, an evaluation of the system that goes beyond an evaluation of its functionality is out of the scope of this thesis.

The fourth approach, actual field testing of the system would be a next step. This is recommended for future research.

Section 5.3.2 discusses the experimental method and the results on the use of a design history for the redesign of the crash test facility. Section 5.3.3 discusses the results of a three-month observation which was aimed at determining the information needs of engineering designers in a practical situation and the potential advantages of a design history system.

5.3.2 Case 1: The development of a crash test-rig - revisited

Setting

For the research on vehicle crash-worthiness, the Section Automotive Engineering and product Design at the Eindhoven University of Technology, decided to build a test-rig for small scale crash experiments on vehicle components. Five students, a technician from the university workshop and a lecturer on vehicle crash-worthiness developed a detailed design within six months. They based their design on the conceptual design that was developed earlier. The test-rig's design history was recorded from the moment the students started working on the design, until they finalised their detailed design. The capturing of this design history has been extensively reported in Section 3.3.2. Figure 3.17 (see Chapter 3) shows the detailed design. The design history that resulted from this design process describes the 66 major issues that the designers tackled. It must be noted that the captured design history was only available on *paper*. The prototype computer-based design history system hadn't been implemented yet.

The detailed crash test-rig design wasn't used to build the actual test rig. Towards the end of the design process, it became clear that the financial and technical risks involved in the production of a full scale test facility were rather high. To play safe, it was decided that first an intermediate size test-rig would be build. This redesign wouldn't be fit for all the experiments for which the full scale design would have been used. However, the risk for errors or flaws in the design which might be found during its production and testing was much lower than for the original full scale design.

The crash test rig was redesigned by a young, but relatively experienced designer, a graduate student in mechanical engineering from a polytechnic school. In advance of his study, the designer had been working for several years as a technical drafter. The redesign lasted four and a half months, including the generation of drawings and other required documentation. In the twelve months that followed after this period, the supporting construction and the measurement system were further developed and the actual test rig was build. Figure 5.9 shows the actual construction.

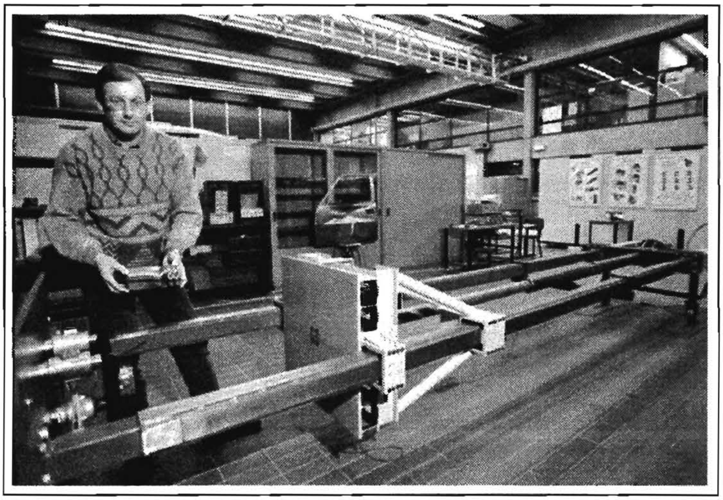


Figure 5.9: Realised product: The crash test rig. (Photo: Bart van Overbeeke (Cursor 1998).)

The redesigner wasn't familiar with the original design, nor its design process. He had to acquire this knowledge on the original design from various sources. The most important source was the technician from the university workshop, who had been involved in the original design. This technician coached the redesigner and reviewed his work. Other sources for information were the technical drawings and the detailed reports that remained from the previous project. Moreover, the designer had a copy of the design history of the original design. The design history was a file which contained the 66 decisions that were made during the design process, including references like sketches and calculations. This information was printed on paper and included a list of all documented issues and a categorisation of issues according to the sub-modules of the test rig.

The designer was interviewed shortly after he finished the redesign. This was done to investigate the information needs of the designer and the extent to which the design history provided the needed information. Based on this interview, interesting conclusions can be drawn on the usability of design history information in this specific case. The following section discusses the topics that the interview covered and the applied interviewing technique. The results of the interview are split up in two separate sections. First, the information that was needed for the redesign task will be discussed. Then, the extent to which this design history fulfilled the need is discussed. Section 5.3.2 is concluded with a discussion of the results.

Interview

The aim of the interview was to explore the potential and the practical usability of the recorded design history to support the redesign of the crash test rig. Therefore, the interview was meant to provide an answer on the following questions:

1) In what steps was the product redesigned? What were the major issues that were tackled during these steps?
2) What information *on the previous design and unknown to the redesigner* was needed for each step?
3) From what sources did the designer obtain the required information? To what extent did the available sources (i.e. the drawings, the reports, the technician and the design history) fulfil the need? Was there information which could not be obtained, but which would have had consequences on the design, if it were available?
4) Did the redesigner use the design history file? What information did the redesigner seek in the design history? What was the quality of the information that the designer was able to find? Could he have found the same information elsewhere?
5) What information from the original design, that the designer re-used, but that he didn't retrieve from the design history, can also be found in the design history? What information can't?
6) What information has been documented from the redesign? Where is this information stored? Is there sufficient information documented to support future redesigns and modifications? If the redesign's history was also captured, then could it be useful in the future?

The interview was semi-structured. The interviewer prepared a set of open questions that were closely related to the questions above. After listening to the initial answer of the designer, the interviewer asked questions that were more focused on the actual events during the design process and the technical issues behind the redesign. Every claim that the designer made and which was more general, had to be explained by means of examples. For example, when the designer said he had used one report in particular, the interviewer asked him what information he used from it and for what design activities he needed this information.

The interview lasted 70 minutes and was audio-recorded. The results are based on this audio-recording and the notes that were made during the interview.

Information needs and sources

Figure 5.10 summarises the information needs and available sources for the redesign. It shows, along a time scale, the stages that the design went through, the information that was needed for each stage, and the sources from which the designer obtained his information.

Figure 5.10 indicates that a variety of information is needed from the original design to enable an effective redesign process. To perform the redesign, the designer didn't just rely on the final drawings that resulted from the previous design process, but he needed also deeper insights and backgrounds in the functions, concepts and calculations that underlied these drawings. For example, to understand the required range of masses and velocities for experiments, the designer needed more information on the kind of experiments that should be performed on the test rig, what would be measured and for what purpose. Moreover, the designer needed to know how the major dimensions of the test rig were derived from the requirements for the original design. To do so, he needed insight in the calculations that were originally performed to deduct the right combination of masses, forces and acceleration lengths.

The most important sources, from which the designer obtained his information, were the reports on the original design and the memory of the laboratory workshop technician. The reports were useful because they were rather detailed. The reports didn't just describe the major features of the design and their backgrounds. They also contained the detailed calculations on which certain dimensions of the design were based. The technician had regular discussions with the redesigner. The technician not only monitored the validity of the redesigner's decisions, he also advised on the future steps that had to be taken.

The design history contains the same information that the designer obtained from the technician, drawings and reports. Moreover, design history contains more backgrounds and alternatives on the original design than the reports do. These interview shows that these backgrounds are very important to re-use certain conceptual design solutions in the appropriate manner in the redesign.

An important observation was, that the redesign process was different from the original design process. The original design process was executed in a 'breadth-first and top-down' manner. During this process, the final product was developed in small steps and for each step, the possible solutions were carefully explored. In contradiction to this approach, the redesign process was executed in an 'in depth and bottom-up' approach. The first design stages were mainly focused on studying the original design and the identification of the functions, concepts and parts that could be re-used in the redesign. Based on this information, a detailed design was proposed which was then worked out in detail. The first stages of the redesign process needed information from *all* stages of the original design. The latter stages of the redesign

Aug

1. Orientation & Preliminary design

(Determination of crash mass, barrier mass and propulsion pressure and diameter; set of requirements and wishes, determination of major components and concept.)

Design activities: Reading reports on the previous design, Collecting original requirements, Calculating combinations of masses, velocities and absorbed energies
Needed information: (i) What is the current design like, how is it dimensioned & calculated, what interdependecies in the design, why developed in a particular way. **(ii)** What is the original concept for propulsion system and its major dimensions, how is everything calculated, how does it work. **(iii)** Requirements / Aims of the construction: The what and the why of the experiments.
Used sources: (i) Report on the design of propulsion and frame,**(ii)** Report on the design of the crash mass,**(iii)** Report on the original concept, **(iv)** Drawings of the design, **(v)** Discussions with the laboratory assistant, on various themes and backgrounds, **(vi)** Interview with the lecturer on crashworthiness, on what should be measured under what circumstances, **(vii)** A simulation calculation of masses, velocities, accelerations and forces.

Sep

2.1 Design propulsion unit

(Detailed design of cylinder and piston for propulsion, including dimensions, geometry, material and assembly structure.)

Design activities: Calculation of velocities and forces, making a design for piston and cylinder, calculation of stresses, selection of materials
Needed information: (i) How were these calculations were performed previously, **(ii)** what are the precise load criteria for several parts, **(iii)** how is the construction in the previous design.
Used sources: (i) Report on the frame and the proulsion unit **(ii)** Discussions with the technician.

Oct

2.2 Design frame and crash mass

(Detailed design of both the crash mass and the frame, including dimensions, material and assembly structure.)

Design activities: Calculation of forces, Calculation of stresses, selection of materials and component dimensions.
Needed information: (i) How were these calculations performed previously, **(ii)** what are the precise load criteria for several parts, **(iii)** how is the construction in the previous design.
Used sources: (i) Report on the frame and the proulsion unit **(ii)** Discussions with the technician.

2.3 Certification of propulsion unit

(Detailed design of high-pressure parts of the propulsion system and certification of the construction.)

Nov

Design activities: Literature research on design rules for constructions under high pressure, dimensioning of components according to these rules, and certification by the 'Steam Institution'.
Needed information: (i) What is the original concept like, and **(ii)** design rules for dimensioning and safety by the Steam Institution.
Used sources: (i) Report on the frame and the propulsion unit **(ii)** Handbook for high pressure constructions **(iii)** Contact person at certifying institution.

3 Detailed design

(Full product documentation package, containing all drawings and manufacturing information.)

Design activities: Drawing the construction in CAD, doing some checks on dimensions, making some detailed changes and calculation of nuts and bolts, and welding points.

Dec

Needed information: (i) Current design infromation **(ii)** Best practices for production.
Used sources: (i) All current design information **(ii)** Discussions with the technician.

3 Documentation

(Report, describing the final design and the underlying calculations.)

Design activities: Writing the report.
Needed information: Current design information.
Used sources: All current design information.

Figure 5.10: Design phases, needed information and available sources for the redesign of the test-rig.

process were merely based on the information from the first stages of the redesign process. Information from the original design played a minor role in these latter stages.

The redesigner was content about this approach. If he had to do the same project again, he would follow the same course of action. It resulted in a straightforward design process, during which no really difficult problems occurred.

Design history usage

The redesigner only used the design history if the other information sources didn't provide the needed information, or if the information that they provided was unsatisfactory. During the interview the redesigner was asked whether the availability of the design history record had been useful or not. Het judged that, while the other sources of information were available as well, the presence of the design history had been useful, but not extremely important for the quality of the result, or the time needed to complete the design.

It must be noted here that the design history was file, with all discussions and their referenced documents like sketches, calculations and simulation results, printed on paper and sorted in the chronological order of the issues. To retrieve information from the design history, the user had to identify the relevant issues from a list. Then he could find these issues in the 300 pages of the document. This didn't invite a user to browse and query the design history. Especially not, if the answer to a question might be given by a set of closely related Discussions. The redesigner had only received a small explanation of the design history's content and structure and didn't receive any training. We expect that this has a negative influence on the (re-)use of design history information.

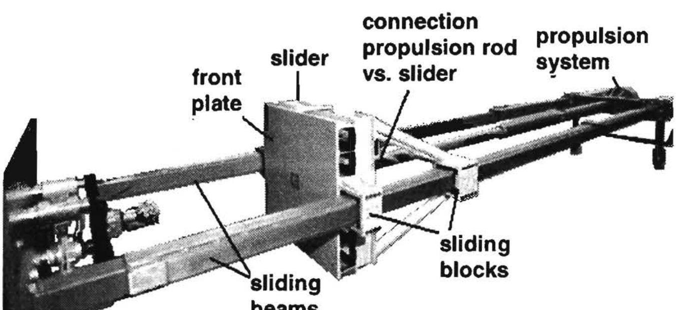


Figure 5.11: Parts on the redesigned product for which the design history was consulted.

During the interview, we discussed four occasions, during which he consulted the design history (see also Figure 5.11,) more elaborately:

1) The basic concept for the slider;
2) The design and the calculation of the plate that is mounted on the front of the slider;
3) The design of the construction around the sliding blocks of the crash mass, and

4) The connection between propulsion system and slider.

The following paragraphs discuss for each occasion the information that was needed, the information that was found in the design history, how satisfactory this information was and whether this information could also have been found elsewhere or not.

In the original design, three beams supported the slider. For the redesign, two beams were used to fix five of the six degrees of freedom of the slider, instead of three like in the original design. For this issue, the designer needed more information on the discussions that lead to the original motion concept. The design history provided the following information. In the beginning, the designers chose a concept that used only two beams with a square-shaped cross-section. However, due to the high loads on the structure, only I-shaped beams would provide enough bending stiffness. Therefore, the team finally decided to use three I-beams to guide the slider.

This information was very useful to the redesigner. Due to the lower forces on the smaller scale test-rig, a concept having only two beams with square-shaped cross-sections could be used. The design history was the most detailed source of information on this subject.

When the designer worked on the redesign of the slider, he wanted to know how the front plate was designed originally. He wanted to know how the thickness of the plate was calculated and what were the load criteria for this calculation. The design history revealed the various concepts that were considered, their simulation with a finite element model and some of the results. Based on this information he decided that, due to the different load conditions, he would not use any of the original concepts, but that he would develop a new concept.

Another design activity for which the redesigner used the design history concerned the way, the sliding blocks, i.e. the surfaces on which the slider slides, are mounted on the slider. The redesigner couldn't find detailed information on this subject in the reports. The design history revealed that the original designers had developed several concepts, and that some concepts had even been modelled in a finite element system. Moreover, the design history revealed that an actual decision had never been made because all developed concepts were too heavy and therefore unacceptable. Based on this information, the redesigner decided to develop his own solution.

A similar situation occurred for the interconnection between the slider and the bar that 'pushes' the slider when the slider is propelled. The slider is only propelled over a certain distance. When the slider reaches the end of this distance, the pushing bar is released and stopped, and the slider moves on. The redesigner wanted to know how this issue was solved in the original design. He found that the original designers had raised the issue, had developed several alternatives, but that the issue was left open. Meanwhile, the technician had developed his own ideas on how this issue might be resolved. With his help, an elegant solution was finally found.

In these four occasions, the design history had been a source that provided more information than any other information sources. In two of the four cases it gave the designer information that he could directly use in his own design.

Discussion

This case shows in depth, what information one particular redesigner needed from an original design. The redesigner didn't only need the final product drawings and the specifications for manufatcure and usage. He also needed background information, like the purpose and operation of (sub)systems of the product. Moreover, he needed to know how the final dimensions, materials and components of the product were related to other dimensions and materials. This information was extremely important for the re-use of the various concepts and ideas, on which the original design was founded.

If the information that the redesigner needed is compared with the information that can be found in the design history, then it can be concluded that the design history *could* have provided the redesigner with all information on the original design that he needed. However, the redesigner preferred to obtain his information from the 'living memory' of the technician and the rather detailed reports. Only when these sources didn't provide the required information, he used the design history as an alternative source. We expect that if the retrieval and re-use of design history information would have been supported by a computer-based design history system, and if the designer had been more familiar with the concept of design history, he would have consulted the design history records more often.

5.3.3 Case 2: A prototype design for an inkjet printer

Goal

The aim of this experiment is to make an inventory of the information needs of designers and the sources that they access in a case in industry. The results are compared to the information that a design history system could have provided, if it would have been available. Based on this comparison, conclusions can be drawn on the way, a design history system would have been used and the effects of this usage on the design process. The case has been reported in depth by Keijzer (Keijzer 1998).

Experimental method

During a period of four months, we observed a team of twenty-two designers in industry. The observant kept a record of the major issues that were raised during this period and who solved them at what time. Towards the end of the observation period, the observant had interviews with seventeen designers of the group. For each interview, the observant selected an issue on which the particular designer had been recently working, and for which he or she had searched for information. The observant discussed the following questions with the subject on this particular issue:

1) What data and information were needed for the resolution of the issue? What information wasn't present when he started working on the issue? What extra information was needed during the process of resolution?
2) Where did the designer search for information? What information did he find?
3) Was the information, which was found, satisfactory?
4) Could a design history system have provided this information? What search criteria would have been used to retrieve the information form the system? Could the information from the design history system have contributed to a better design result or an accelerated design process?
5) What has been documented from the current issue? If a future designer has to deal with a similar or related issue, then how can he take advantage of the knowledge that was gained in the current issue? If the current issue was documented in a design history system, then would the re-use of knowledge and information be enhanced?

To show the interviewed designers what kind of information can be retrieved from a design history system, the observant recorded ten related issues that occurred in the first half of the observation period. This collection of design decisions and their underlying reasoning were printed on paper and shown to the designers during the interview.

The results don't give information on *all* the information that the group of designers searched for during the four months of observation. However, the seventeen interviews cover the major issues that the designers resolved during this period and for which more information was needed than what was present in the current project documentation and the designer's minds. Therefore, the results can be considered as a minimum indication of the information need for this particular case.

The average duration of an interview was one hour.

Setting

The observation was performed at the research and development department of Océ Technologies in Venlo, The Netherlands. There is no direct relation between this experiment and the experiments on design history capture (see Chapter 3), although all the three case studies were done inside the same company. This experiment involved designers that were unfamiliar with our research on design history.

The project that we observed was aimed at the development of a new inkjet-based printing technology for printers and copiers. A preceding project started several years before the current project. It had resulted in a new conceptual design that achieved the required printing quality under laboratory conditions. In the current project, the printing technology had to be further developed. More production, manufacturing and functional aspects would be taken into account. Within two years, the project had to result in a new technology platform. This would be a new printing and ink technology that was fit for apllication in a new product range, including the required tools, procedures, processes and the involved chain of suppliers.

The experiment focused on the twenty-two project engineers that worked on the construction of the new printing head assembly and its manufacturing processes. The project team consisted of engineers with various backgrounds, e.g. mechanical engineering, electronic engineering, embedded software technology, physics, material technology and mechatronics. The production and assembly of most parts of the final design would be carried out by suppliers. Therefore, the engineers paid much attention to aspects related to early supplier involvement.

Information requirements and sources

Each interview that was held after the period of observation, focused on the resolution of a particular issue. This subsection present the information that was needed during the resolution of these very issues.

The desired information has been categorised in four categories:

1) Information that describes the current state of the product and the project;
2) Information that describes the decisions, reasons and backgrounds 'behind' the product;
3) Information that leads to new knowledge, and
4) Information that is needed to find the right parties who can solve the issue.

The upper two categories concern information that is, in documented form or in the memory of designers, already present in the project or within the company. For issues that need facts on the current design, the required information is classified in the first category. For example, to design a prototype with slightly different dimensions than the previous prototype, a designer needed the drawings and material list of the previous prototype. For issues that require a deeper insight or understanding in the current design state, the needed information is categorised in the second category. For example, when a new prototype at first didn't perform well, the designers had to fall back on previously gained insight in the causes of typical malfunction behaviours.

The latter two categories are used to classify issues that need new knowledge or information which isn't present in the company yet. For issues that require new, fundamental knowledge on certain matters the needed information is classified in the third category. For example, to find a suitable cleaning method for the production of a component, a designer gathered books and articles on detergents and their application areas. For issues, for which an expert outside the company is searched who can solve the problem, the needed information is categorised in the fourth category. For example, to produce a certain component according to given specifications, a designer searched for the supplier who had the appropriate technology, instead of 'inventing' a suitable process by his own.

Figure 5.12 shows the results of the classification of the information that was needed to resolve the seventeen issues. The sum of the percentages is more than 100% because a single issue may fall into more than one category.

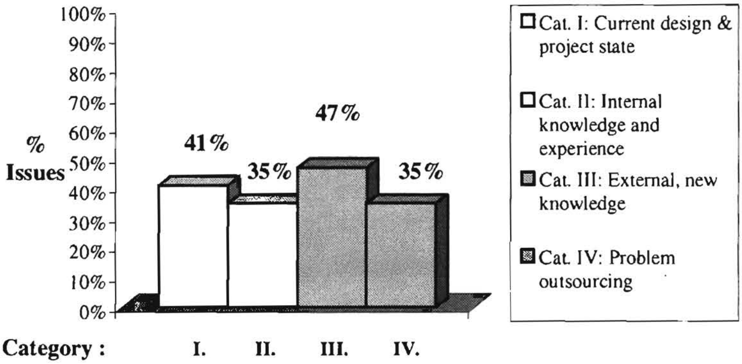


Figure 5.12: Classification of needed information.

Figure 5.12 shows that there is a high need for new, external knowledge and information in this stage in the development project, (see the grey bars in Figure 5.12.) This is caused by the fact that the printing technology that the designers developed, was entirely new to the company. However, the percentage of issues that require information that is already present in the company, is just as high. (See the white bars in Figure 5.12.) Especially the information in Category II is the type of information that can be retrieved from a design history system. Traditional sources of information don't provide this information very well.

To search and retrieve information, the designers used various sources. A design history system that contains the history of the previous years of development work, wasn't available. Therefore, the designers had to retrieve this information from various other sources. Figure 5.13 shows the used information sources for each category.

Figure 5.13 shows that personal contacts with colleagues and the personal archives ('desk and file drawer') of colleagues are the most important sources for internal information. For each information request in Category I and II, information was retrieved from these sources. Moreover, to find the right external contacts who can solve a particular issue (Category IV), designers used in all cases their personal contacts and privately stored data as well.

This observation agrees with the general observation that a large part of previously generated knowledge and information is distributed and exchanged via personal contacts. If the organisation becomes so large or complex that it becomes difficult for a designer to identify and contact any other member of the organisation who might have important knowledge or information, the designer won't be able to acquire the desired information. A design history system can provide a comprehensive structure in which more product knowledge and information can be recorded and shared than what is currently available for re-use.

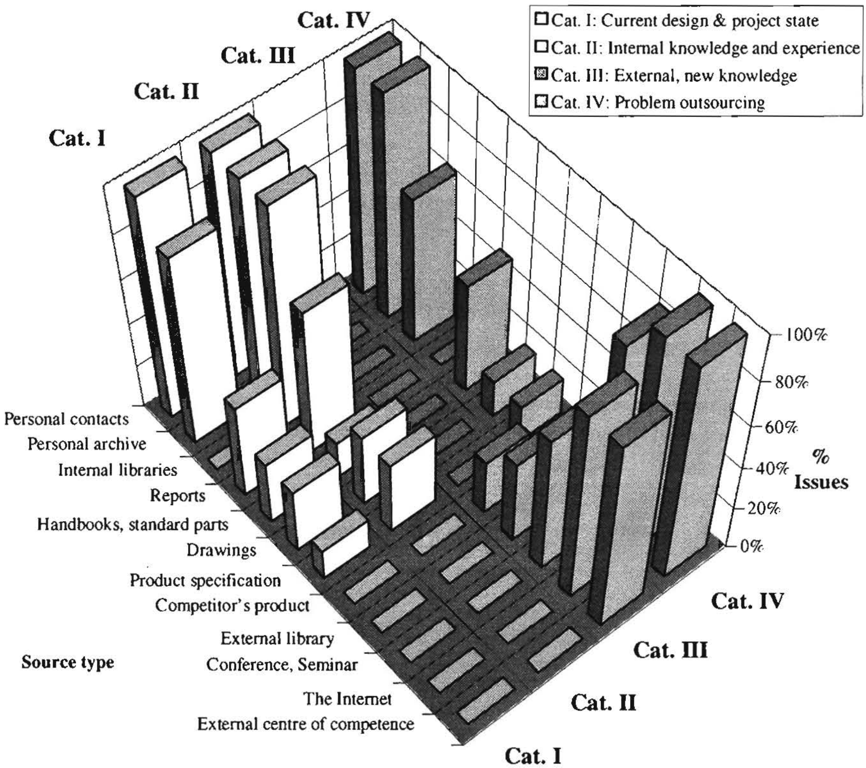


Figure 5.13: Various sources from which the designers obtained information, split up in four types of information.

Figure 5.14 shows the extent to which the designers were satisfied with the information they finally retrieved from the available sources. The designers were asked if they had found the information that they needed. No designer answered a 'No.' In every case, at least some useful information was found.

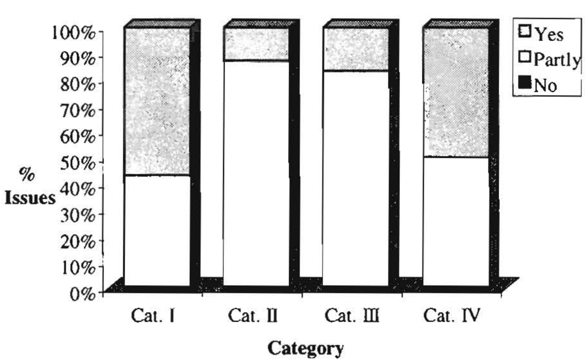


Figure 5.14: Did the designers find the needed information from the available sources?

Figure 5.14 shows that the information that is categorised in category II and III is more difficult to find than the information in the other categories. A reason for this is that a designer who searches for the knowledge that underlies previous design efforts, or certain experiences, can't tell in the finest detail what he is actually looking for. In other words, he can only vaguely describe the information that he is looking for, nor does he know if this information really exists. A design history system is aimed at improving the retrieval of project information. It enables more effective searching and a shorter searching time.

Need for design history information

The results show that there is a substantial role for design history information, if accessible. Half of the issues on which the designers were interviewed needed information or knowledge which was already present within the organisation. Whether a designer can actually find the information that he needs, depends highly on the personal contacts that a designer has, or can establish, and the private collection of information of these contacts. A design history system makes more of the reasoning that underlies previous design efforts by other design teams directly accessible, and enables a quick identification of the persons that have even more useful knowledge and information.

To judge whether the designers would have actually used a design history system or not, if it would have been available, a further breakdown of the issues was made. Figure 5.15 represents the results.

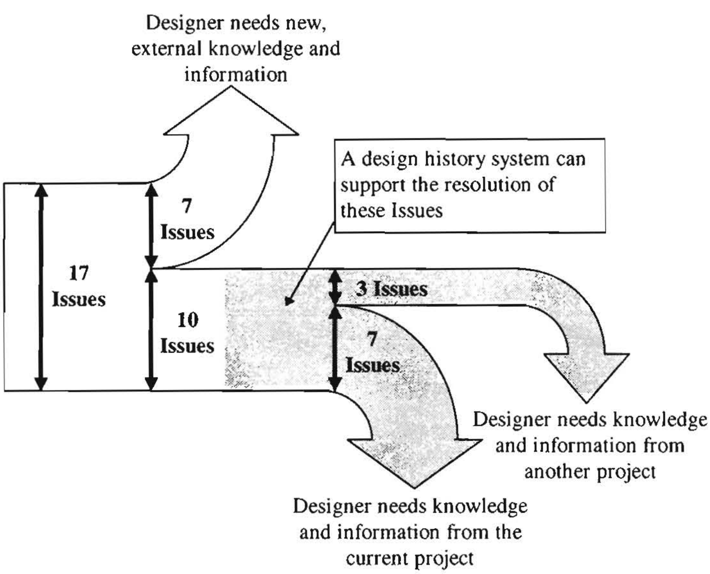


Figure 5.15: Breakdown of issues in groups for which a design history system is used in a particular way.

For seven of the seventeen investigated issues, the designers needed exclusively information that wasn't present within the organisation yet. It had to be acquired from external sources.

The other ten remaining issues required corporate knowledge and information. For these issues, the designers would have probably used the design history system. For seven of these ten issues, the designer required knowledge and information that was created previously within the same project. For three issues, the designer required knowledge and information was created in other projects with no direct relation to the current project. For example, to find the right solution to bond two materials, a designer wanted to learn more of the experiences that other designers in another project had with a particular type of glue.

During the observed design project, the designers didn't record its design history. Figure 5.16 shows in which locations the designers did document information regarding the resolution and the underlying argumentation of the seventeen explored issues. (As far as they actually documented it, Figure 5.16 gives no information on the level of detail in which decisions were documented.) The difference between a report and a memo is that a report has an official status. It is indexed and stored in a central archive. A memo isn't. It is sent to a dedicated audience and it isn't centrally archived.

Figure 5.16 shows that most information is stored in places that aren't centrally accessible over a longer period of time after the completion of the project. Only reports and drawings (the white bars in Figure 5.16) are indexed and stored in a central archive. For almost every issue, something can be found back in a report. However, this is information is probably not in the same level of detail as the issues that are represented in a design history. Moreover, it is often hard to retrieve a particular piece of information from an archive with thousands of these paper based reports. This explains why reports show a much lower score as a source for the *retrieval* of information, than as a place to *store* information. (Compare Figure 5.3 with Figure 5.16.)

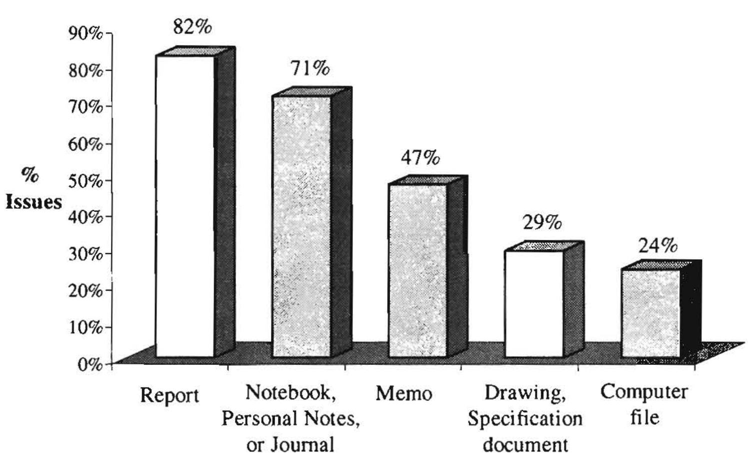


Figure 5.16: Where did the designers document their decisions?

It can be concluded that the knowledge and information that were gained by the designers during the observation period, haven't been secured for an effective re-use in the future. If similar issues will be raised in the future, it will in many cases be problematic to take advantage of the insights and experiences gained at present. The re-use of knowledge highly depends on the personal networks of the people in the organisation because no design history system was used to capture more in-process information.

Discussion

From this case study we can draw interesting conclusions regarding the retrieval of information from a design history system and the effects on the design process in practice. The exploration of the information that was needed during the observation period shows that a design history system doesn't provide an answer on *all* requests for information. It 'pumps' previously gained knowledge and information to later development stages or to other projects. New knowledge or information, that wasn't previously gained in the organisation, can't be retrieved from the design history system. However, a design history system *can* help to identify the information that must be gained from external sources, because it makes explicit what knowledge and information is actually available within the organisation and what information is still missing.

Moreover, the results show that, if a design history system, containing previous design decisions and their rationales, would have been available, it would have had an added value. The information that is stored in a design history system could in only be found via personal contacts and (in some cases) in reports. Moreover, many experiences that the designers gained during our period of observation, couldn't be documented in a way that it enables retrieval and re-use by future designers.

5.4 Conclusion

The time that it takes to launch a product, its cost price and its actual success on the market depends on numerous factors. Therefore, actual contribution of a design history system to the improvement of a design process in terms of time, money and quality are hard, or maybe even impossible, to measure.

To draw conclusions on the benefits of the design history system that is proposed in this thesis, the best approach is to *compare* state of the art methods for the archiving and retrieval of design information and documentation, with an improved situation in which a design history system has a place. In this chapter, the information needs of engineering designers were compared with the information that is provided by the design history system. The sources that are currently available to designers for the retrieval of both internal and external information were compared with the retrieval of information from a design history system. Moreover, the actual needs for information and its retrieval from various sources were observed from two real design processes and were compared with the way, a design history system could have supported these processes.

Most design project in engineering design are dominated by *redesign* activities. They are aimed at making modifications to a design or designing new variants of an existing product or product module. Only a minority of design activities are aimed at the development of totally new concepts that aren't based on any existing design. The information of previous products and their design processes is therefore extremely important for efficient and effective design processes. Investigations by other researchers of the information needs of engineering designers show that designers not only need a detailed description of the final product, i.e. *what* the product was like. Just as important are the operation of the product, the purpose of its features and the logical steps that underlie the product's final materialisation, i.e. the *how*, the *why* and the *who* of a product.

The sources that are currently available to designers, like a drawing archive and reports, don't support an effective re-use of design knowledge and information. Nowadays. the documentation remains from a design process is mostly the minimum that is required for downstream product life cycle phases, like manufacturing, service and recycling. Current documentation techniques aren't aimed a supporting future (re)design work. Due to this, the transfer of knowledge and information mainly takes place via personal contacts. A design history system provides the means to alter this situation.

Two case studies were performed to investigate the information needs of the designer, the fulfilment of these needs by the currently available sources and the potential improvement of design information re-use by means of a design history system. Both cases showed that designers need deeper information on a design than what can be found in drawings and (if available) reports. Contacts with someone who is familiar with the products and prototypes that preceded the current design are essential for a design to take advantage of previously gained knowledge and experience. If these contacts can't be established, due to the size and complexity of the organisation or simply because someone has left the company, then a design history system becomes an important back-up. The case studies showed that the information that is needed matches with the information that is stored in a design history system.

6 Conclusions and recommendations

6.1 Conclusions

To accelerate design processes and increase product quality by means of the re-use of design knowledge and information, we developed an operational design history information system. By means of this system, product development organisations can capture and retrieve the steps in which they develop their products and the rationale of the underlying design decisions.

Organising product development information around the *decision making* that occurs during design is a new approach, which is not comparable to any other known approaches for information and knowledge management, such as organisational measures, groupware, product data management and approaches using artificial intelligence. A design history enables a product development organisation to capture design knowledge and information which currently remains tacit. Still, it allows the capture of this knowledge and information in a purely descriptive and non-disturbing manner.

An examination of the literature on the subject of design history, design rationale and design intent showed that many issues need to be further explored before it can be concluded whether a design history approach is feasible or not. Although various representations and concepts have been proposed in literature, only little is known yet about the more practical aspects of these systems. Regarding the capturing of design histories, a minor number of experiences have been reported in literature. Many potential approaches haven't been explored at all yet. Moreover, even less is known about the retrieval and re-use of design history information and their effects on design processes and organisational learning.

Three cases studies, during which the design history from a real design processes was captured, were used to specify and evaluate a design history capturing approach. The experiments showed that the reasoning which underlies a design can be effectively captured by recording design decisions. The representation used to describe the decision making process by means of Issue-, Proposal-, Argument- and Decision elements, has proven to be a very useful format. The captured discussions give a complete and accurate description of the major alternatives and their supporting and objecting arguments.

The decision making can be most efficiently captured by recording *group decisions* only. In all three cases, on average two decisions a week had to be captured from each design team to represent the design history in the required level of detail. The case studies showed that the major decisions and critical design conflicts are discussed in team meetings. However, due to the informal character of the observed teams, more information on the alternatives and aspects that were not discussed in team meetings were gathered and added to the design history records. During the case studies, an observant did all the capturing activities. In practice, the most efficient approach is that designers take part in the capturing of group decisions as well.

To support the developed concept for capturing, storing and retrieving design histories, a prototype design history information system was built. It was implemented by customisation and adaptation of a commercially available Product Data Management (PDM) system. Nowadays, state of the art PDM systems offer only functions for managing *product data* that has reached a certain status level. They provide no means to store the underlying *reasoning and decision making*. However, design histories can only be captured and retrieved effectively if design histories are considered as part of the formal deliverables of a development project. The extension of a PDM system with design history functions enables organisations to handle design history information this way.

The prototype design history system was filled with an earlier captured design history and then evaluated with respect to the requirements that were defined at the beginning of this thesis. The evaluation shows that the design history system offers the required functions for capture, storage, searching and retrieval to support an effective re-use of design knowledge and information. The system integrates the capture and retrieval of design histories with the management of product data. Its powerful search and retrieval functions enable the user to get an accurate view of the processes that underlie the final product. Decisions can be easily retrieved from the actual product information that the product developers used during the design process. The decisions contain links to related documents in the product data base. Nevertheless, the capture and storage of design decisions imposes no burden or constraints on the actual product model or business process model that is used to manage product data.

To gain more insight in the capabilities of our design history system to improve the re-use of design knowledge and information, the information needs of designers were compared with the information sources that are currently available to designers in practice, and with the information that is provided by the design history system. This was done in two case studies.

The results are encouraging. Both cases showed that a detailed description of a finished product is insufficient to effectively re-use the concepts, functions, solutions or geometrical information from a previous product design. Just as important as the *what* of the product are its operation, the purpose of its features and the logical steps that underlie the product's final form, i.e. the *how*, the *why* and the *who* of a product. The underlying rationales behind previous design decisions that are captured in a design history system will be particularly useful to provide this information for future users. Moreover, both cases showed that the documentation, like drawings and reports, that was available to the designers during the observed cases, didn't provide them with all the information that they needed.

During one case, we observed the redesign of a product from which the design history had been captured earlier. We compared the information that was needed during the redesign, with the information that was present in the design history. The comparison showed that the needed information matched with the information in the design history.

6.2 Recommendations

A more effective management of knowledge and experiences is currently being considered as one of the key factors for accelerated design processes and a sustainable innovation of products. The design history information system that is proposed in this thesis can be an enabler to such an approach. At this moment, it is still hard to say what will be the actual contribution of the re-use of design history information to design processes in terms of time, quality and money. However, the experiments and the prototype information system presented in this thesis demonstrate that the capture, storage and retrieval of design histories are feasible in today's practice. The research on the concept of design history must therefore continue and should be aimed at making it mature for application in practice as soon as possible. The following courses of action are recommended for these future research activities.

The approach to design history that is presented in this thesis is applicable in a wide range of different design processes. Indeed, a design history captures information that can be observed in every type of design process, and the need to capture and retrieve the reasoning that underlies a design is present in almost every design process as well. However, it is recommended to introduce the capture and re-use of design histories first in one of the following application areas because, in these types of design processes, the need to re-use design knowledge and information is very strong:

- Product development environments in which there is a clear distinction between 'Pre-Development' design projects, during which new technologies and concepts are developed, and 'Commercial Development' projects in which the deliverables of the pre-development projects are incorporated in one or more actual products that are launched on the market. The design histories of pre-developed technologies and concepts will enable a more effective transfer of knowledge and information from the pre-development to the commercial development stage.
- Design processes in an Engineering to Order environment. The rapid development of custom-made products requires the availability of predefined product architectures and standard building blocks as a starting point. The design histories of these architectures and building blocks will well support their re-use and correct application.
- Design processes that involve extensive Collaborative Engineering. Capturing design histories from the co-operation among designers that are working from remote locations supports asynchronous communication and decision making. Moreover, it enables the designers to track down other designers who have been responsible for certain design decisions.

To develop the concept of design history further, additional experiments in practical settings in industry are recommended. The case studies that were presented in this thesis were very effective to gain realistic and reliable experiences. An area that requires further investigation is the retrieval and re-use of information from design histories. To learn more on the advantages that can be achieved by means of the information that is available in a design history, the following two types of experiments are recommended:

- Perform experiments with the prototype design history system that is filled with the design history from the crash test rig, or another case, and let subjects perform retrieval and redesign tasks on it. Gain feedback from the subjects on the use and observe the effects on their design activities.
- Perform field tests in which a design history system is used by more people and during an extended longer period of time. Observe extensively the use and usefulness of the system.

To enable more realistic experiments on the retrieval and re-use of design history information, further enhancements to the user interface of the current prototype information system are recommended. The current prototype version offers the basic functions to search, retrieve and browse through the design history. However, the ease of navigation and reading that a user experiences while browsing design histories, can be substantially improved. Discussions and their interrelations must be represented in a way that is more easy to read. The functions for navigation and searching should be presented in such a way to an inexperienced user, that they enable operation by intuition.

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Acknowledgements

This thesis and the work it presents could not have been created without the efforts of many others. First of all, I wish to thank the students who contributed to the project during their final year: Arnold Beunis, Marco van Doveren, Michiel Houben, Erik Houbolt, Coenraad Keijzer, Alex van der Linden, Patrice Maas and Dorus van Rooij. I enjoyed our co-operation very much.

I acknowledge my promotors prof.dr.ir. R.F.C. Kriens and prof. L.J. Leifer PhD, and the commission members prof.dr.ir. J.C. Wortmann and prof.dr.ir. H.J.J. Kals for their support and advice during the preparation of this thesis. I especially thank prof. Kriens for his incentive enthusiasm. Furthermore, I want to thank the Stan Ackermans Institute for supporting the project.

An important part of the research was conducted at the research and development department of Océ Technologies, in Venlo, The Netherlands. I am very grateful for being given this opportunity and I want to thank all the managers and engineering designers who have contributed to the research. I am particularly grateful to Inge Driessen, Pieter van Groos, Toon Hermans, Lucie Huiskens, Debbie Mous and Erik Stulemeijer.

I wish to express my appreciation to the people of Unigraphics Solutions B.V., who made it possible to build the prototype design history system. In particular, I wish to thank Regis vanden Bussche and Wim Vos for their great support.

My colleagues at the section Automotive Engineering and Product Design of the Eindhoven University of Technology, and in particular my fellow 'AIO's' Ard, Bas, Daan, Dirk, Sander and Theo are acknowledged for their help and the pleasant working atmosphere.

Finally, I want to thank my parents, my friends and, last but not least, Chantal. Thank you all for giving me the time to finalise this work.

Eindhoven, July 1999.

Curriculum Vitae

Silvan Wiegeraad was born on July 23, 1971 in Sittard, The Netherlands. He grew up in Oisterwijk and attended the Maurick College in Vught in 1983 from which he graduated in 1989. In 1989, he started his study Mechanical Engineering at the Eindhoven University of Technology. As his study proceeded, he specialised in the field of automotive engineering. In 1994, he received his MSc. degree in Mechanical Engineering after a final project at Mercedes-Benz AG in Sindelfingen, Germany. He performed experiments with fibre reinforced plastics to evaluate their feasibility for application in car structures. At the end of 1994, he started working as a doctoral researcher (*'Assistent in Opleiding'*) at the Faculty of Mechanical Engineering, Section Automotive Engineering and Product Design, on the development of the design history information system. Towards the end of 1998, he finalised his research. The research results are reported in this thesis. Since February 1999 he has been working as a Product Data Management (PDM) Consultant at the Philips Centre for Manufacturing Technology (Philips CFT).

STELLINGEN

behorende bij het proefschrift

Development of a Design History Information System
Capturing and Re-Using the Knowledge Behind the Product

door

Silvan Wiegeraad

Eindhoven, 30 september 1999

I.

Het aandeel van persoonlijke voorkeuren, politieke motieven en willekeur in de besluitvorming in een ontwerpproces, wordt vaak overschat. (Dit proefschrift.)

II.

Voor toepassing in de praktijk dient een Design History systeem geen losstaand systeem te zijn, maar dient het geïntegreerd te worden met een ander ontwerpgereedschap, zoals een PDM-, CAD- of CAE- systeem. (Dit proefschrift.)

III.

De grootste uitdaging voor een succesvol Design History systeem is niet het verzamelen en beschikbaar stellen van de gewenste informatie, maar om ontwerpers daadwerkelijk *gebruik* te laten maken van de beschikbare kennis. (Dit proefschrift.)

IV.

Bij het ontwikkelen van hulpmiddelen voor het ontwerpproces moet men oppassen voor het 'Droste' effect. Dit treedt op wanneer een hulpmiddel voor het ontwerpproces wordt toegepast op zijn eigen ontwikkeling. Deze werkwijze lijkt verleidelijk, echter de objectiviteit, die een wetenschapper dient te betrachten, komt hiermee in het geding.

V.

Zoals de invoering van kantoorautomatisering niet heeft geleid tot een afname van het papierverbruik, zo zal het gebruik van computernetwerken voor intensieve samenwerking vanaf gescheiden locaties, niet leiden tot een afname van het zakelijk reisverkeer.

VI.

De verschillen tussen een individu uit de ene cultuur en een individu uit een andere cultuur zijn vaak niet groter dan de verschillen tussen twee individuen uit dezelfde cultuur.

VII.

De groei van mobiele telefonie zoals die momenteel op grote schaal plaatvindt, is een klassiek voorbeeld van het omarmen van technische mogelijkheden zonder stil te staan bij de vergaande maatschappelijke gevolgen.

VIII.

Om de toestroom van techniekstudenten weer te laten toenemen, en daarmee te voorzien in het noodzakelijke aanbod van technici op de arbeidsmarkt, is het van groot belang dat techniek in de mode komt.

IX.

De vercommercialisering van het zenderaanbod op de Nederlandse televisie heeft drie positieve effecten: Meer televisiestations, waardoor meer werkgelegenheid in de amusementswereld; Hogere reclame-uitgaven, waardoor meer werkgelegenheid in de reclamewereld; En een minder aantrekkelijk programma-aanbod waardoor kijkers kiezen voor alternatieve vormen van tijdsbesteding.

X.

De groei op ons hoofd is gelukkig niet gekoppeld aan de groei in ons hoofd.

The re-use of knowledge and experience in the development of complex mechanical products, such as cars, planes, and photocopiers, is problematic. The increased complexity of the organisation hinders the exchange of experiences directly between people. Moreover, the documentation that currently remains from design processes is unfit for an effective re-use of knowledge and information.

To prevent product developers from 'reinventing the wheel', this research is aimed at the development of a Design History information system. By means of this system, design teams can capture their design decisions and the underlying rationales, and make this information available for re-use. The re-use of this information supports complex product modifications and the development of the next product generation.

This thesis presents the development and verification of a method for design history capture, the design and implementation of a prototype design history information system using Product Data Management (PDM) technology, and an investigation of the retrieval and re-use of information from design histories.