DESIGN PROCESS CAPTURE AND SUPPORT

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SUMMARY

The paper presents a model of mechanical engineering design to be used to develop a computer-based design support tool to aid the improvement of the design process. The requirements for this type of tool have been formulated using the characteristics of design derived from both prescriptive and descriptive design literature, and an analysis of a design process in industry. The system is process-based as it is considered essential to use the process rather than the product as the core in order to support the entire design activity. This has been realised by the introduction of a design matrix. The paper will focus on the main issues of capturing design data and supporting addressed by the system, and on the design matrix. Details can be found in [1].

1. INTRODUCTION

In the field of mechanical engineering, both products and the processes of their creation have undergone major changes. Product have become too complex for an individual and so requires cross discipline cooperation. Shorter product life-cycles have forced shorter and more efficient development cycles. Tighter requirements and stronger competition have lead to an increased demand for product quality, and therefore a more effective design process. In order to remain competitive, new approaches are needed for product development. A focus on the design activity rather than on its deliverables, is vitally important for effective and efficient projects in light of the changes identified above.

The research project described in this paper was based on the need to improve the mechanical engineering design process, i.e. to increase its effectiveness and efficiency. An effective process is defined as one that results in a product satisfying the actual need. An efficient process is defined as one that is both effective and in which the applied sources do not exceed the planned sources.

Various means to improve the design process exist. These are: (I) prescriptive models of the design process, e.g.[2]; (ii) handbooks and catalogues containing knowledge needed for design; (iii) methods to support specific design activities, e.g. [3]; and, (iv) computer-based tools. An investigation of these means [1,4] resulted in two main conclusions. First, they have not had the expected impact on the effectiveness and efficiency of the process as a whole. The reasons for this include: inadequate exploitation of existing prescriptive models; poor access to knowledge and methods; and the limited range of application and product-focus of computer-based tools. The latter prevents a proper support of the important early stages of the design process in which the product is still being defined, The second conclusion was that focusing on the design activities (*the* *process*), rather than on the deliverables (*the product*) , and focusing on *support* of the entire process rather than *automation* of a specific activity, would be the most promising approach to improve mechanical engineering design such that it is able to cope with the identified changes.

Section 2 describes the approach taken to develop a system, PROSUS, aimed at improving engineering design by providing a process-based approach. Section 3 elaborates on the main issues addressed by PROSUS, namely capturing design data and advising designers on means to support their process. This is followed by a description of the system in section 4, focusing on the design matrix which forms the core of the system. Section 5 summarises the results of a first evaluation of the system. The current implementation is shortly described in Section 6. The paper finishes with conclusions.

2. APPROACH

The development of PROSUS involved five stages: (1) determination of the characteristics of design; (2) specification of the type of support; (3) development of a set of requirements and functions for the system; (4) development of the system and of the design matrix in particular, (5) evaluation of the applicability and usefulness of the matrix.

Characteristics of design

Several descriptive and prescriptive sources were consulted to find characteristics of design that could be of importance for the development and use of the proposed system. *Descriptive* studies of design offer characteristics of design based on observation. Due to the lack of literature on detailed studies in an industrial context, a design process in industry was observed to find additional characteristics. *Prescriptive* literature suggests ways to improve the design process, such as process models or methodologies, and offers a more complete view of the process than descriptive studies. Both sources were consulted to combine the characteristics of effective and efficient processes suggested by prescriptive sources, with the reality of design practice found in descriptive sources.

Type of support

Based on the analysis of existing computer systems, the system was envisaged: to involve the designer as an important reasoning component in solving the design problem; to be subordinate to the designer; to permit the designer to apply different approaches; and to allow for multiple users and tasks. Furthermore, the system should support the designer throughout the entire process by advising on relevant knowledge, methods, tools and strategies, and it should provide a structure for documenting project data and knowledge, methods and tools.

System requirements

This view on support was used to classify the identified characteristics into 3 groups [5]. Characteristics *to support* or stimulate are those that were observed (in descriptive studies) or are expected (in prescriptive literature) to have a positive impact on the design process. Characteristics *to prevent* or discourage are those that have or are considered to have a negative impact. Characteristics that have *to be taken into account* are those that might have a negative impact but cannot, or only partially, be prevented. This classification provided a first indication of the system requirements. These were then translated into more specific requirements by indicating how a computer system could contribute, i.e. *how* the system could support, prevent or take these characteristics into account. The requirements focus on the interaction between system and user. They take into account the design process as it actually takes place and how it could be improved, and the possibilities of computer technology.

System functions

Based on the final set of requirements the following main functions of the envisaged system were formulated:

- to make designers aware of the steps in the design process by providing issues to solve
- to support teamwork and communication,
- to structure the documentation of design data created throughout the process (design history) to ease retrieval in current and future projects,
- to structure the vast amount of knowledge, methods and tools used in design
- to enable context-sensitive advice on knowledge, methods, tools and design history.

These functions involve two different system roles: a passive role related to capturing design data and an active role related to supporting the creation of this data (see section 3 for a discussion).

System development

It was found that a system offering a process-based view to the designer was the most useful to support both roles. This led to a proposal for PROSUS a *computer-based support system developed around a process-based model of design,* that combines the potentials of a methodical approach, the advantages of computer processing and the knowledge and abilities of designers (see section 4). The underlying hypothesis that; 'the combination of focusing on the design process and computer support serves the effectiveness and efficiency of the process' is supported by several studies, among which [6, 7, 8 and 9].

The building block of the system is the Design Matrix, representing the design process. The matrix supports the design team in documenting the product and the process, and provides the context for the system to integrate and suggest means for the various activities.

Evaluation

The evaluation focused on the applicability and usefulness of the design matrix concept as the core of the system. The evaluation involved experienced designers and was based on a comparison of the design processes of two types of designers: those working with a paper version of the design matrices and those working without design matrices. The findings are discussed in section 5.

3. CAPTURE AND SUPPORT: A PROCESS-BASED SOLUTION

The two main issues to be addressed by a system aimed at improving the design process by providing support throughout the design process are: *capturing* the data resulting from design activities, and *supporting* he creation of these data. The main issues are not representing design data and developing reasoning mechanisms to automate specific design activities, as is the case in so much design research. Only part of the available design data can be captured (see next paragraphs). It is therefore important to make sure that we can represent and reason with what we can capture, i.e. what we can ask the designer to make explicit within an industrial context. The solution proposed in this paper to capture data and supporting designers is a process-based approach. This section outlines the rationale behind this choice.

Design data includes artefact and process data

The summary of last year's Product Structuring Workshop [10] described a product structure as '*a collection of data resulting from design activities which is used by several activities in the company*'. This collection of design data, however, is more than '*the* *elements of a product and the relations between the elements'.* Some of the contributors addressed this by extending the product elements and relations structure to include functions, organs and processes, but this still does not cover all data created during the design process.

Design data includes:

- artefact data such as sketches, drawings, text, calculations, graphs, user manuals, production plans;
- process data: rationale behind artefact data such as arguments and decisions, and data created to find a concept in the first place;
- process administration data: planning data and factual data (who did what, when and how).

Design data is created throughout a design project, i.e. it is evolving. Data therefore include the various alternatives that were considered at different levels of abstraction and for different parts, as well as the reasons for their acceptance or rejection. This rationale should not be disregarded at the end of the project, as it is extremely important both in the design project in which it was created as well as in future (re)design projects to improve the effectiveness and efficiency of the design process and essential for genuine concurrent engineering. If the task at hand involves original design, there will be a large amount of new design data. For redesign or variant design, extensive use can be made of design histories, recreating or modifying the relevant parts only.

It would be useful to capture all design data

It is immediately obvious that a large amount of data is involved. The wish is to capture as much of this data as possible. Data covering the artefact's history supports reuse by increasing the understanding of the design process. It also supports the system's ability to reason about the data and give the designer more advanced/intelligent advice.

Only a small fraction of the design data is being captured

Most of the data that is being captured and publicly available is artefact data related to the final product, such as technical drawings, production plans and installation manuals. Some of the artefact's history may be found in minutes of meetings or review reports. Most process data, however, is not captured at all or only recorded in designers' notebooks and therefore not publicly available.

Not all design data can be captured

Developments in multimedia provide ample opportunity to capture most types of the data, whether text, graphics, video or audio. This is convincingly shown in [11]. The fact that most design data is not captured is not a technological problem but a practical problem. Designing is a deliberate activity, i.e. every component or feature has a purpose or is a consequence of another component or feature (which may be a purpose in itself). The purpose may concern function, strength, manufacturability, aesthetics or just personal satisfaction or belief. While analysing a single component, e.g. the cap of a pen, it becomes immediately clear that it is not possible to capture all these purposes (and those of the various alternatives considered and rejected in the course of the process): why are the dimensions as they are? why is it tapered, why does it have a rim, why does it have a step on the top, why the indentation, why this thickness, and so on.

An indication of the amount of data that could be made explicit, and thus potentially captured, can be obtained from design experiments involving individuals [1] who where asked to think aloud while designing. The video recordings showed, for example, that designers might assess their solutions as much as a 100 times per hour. Only a fraction of this was recorded by the designer. Although the designers spoke almost all of the time, it is likely that even more went on in their minds, as their utterances did not completely explain their resulting artefact data.

At least in an industrial context, we will, therefore, never be able to capture all rationale involved in the evolution of an artefact. Even if data could be made explicit, this would be far too time-consuming and thus defeat the aim to increase effectiveness and efficiency of the design process.

More design data can be captured

Although not all design data can be captured, major improvements can be made on the current situation in which only a very limited amount of design data is captured. To capture more requires support in capturing and encouragement. Asking designer to think aloud and recording this, would make more of the rationale explicit. Although this technique is unsuitable for use in a design office, video recordings can be useful in capturing the design data created in meetings [ref].

In many cases video or audio recordings are not suitable. In general, advantage could be taken of the periods of reflection in which designers, for example, summarise the evaluation of the ideas in a sketch or drawing. A system could encourage the designer to regularly reflect and summarise. Although this requires additional effort, the designer will benefit as it supports deliberation and reuse of data. Research findings showed the importance of timely evaluation throughout the design process [7].

Indexing data requires user input

The purpose of capturing data is to reuse it.. To enable retrieval of relevant data the captured data has to be indexed. The question that arises is how detailed the level of indexing should be in order for the system to be useful.

The level of detail needed for a system to reason about the data is potentially high. This would require substantial additional effort of a designer or it would require a system to have sufficient knowledge about the artefact and the process to interpret the captured data. If the data has been created by specialised software, such as drawing packages, interpretation may be easier. Unfortunately, design processes cannot be covered in their entirety by a string of linked software programmes. Designer remains involved in many of the steps and thus create of much of the design data. In addition, most software do not provide or enable the capture of the range of design data defined earlier, in particular rationale and alternatives. In addition, the interpretation power of a system is likely to be limited for the following reasons: an evolving, that is, a previously not existing artefact is being captured; not all captured data can be interpreted easily, in particular sketches, video and audio recordings; our knowledge and understanding of design is limited.

This implies that the user has to be involved in indexing. As indexing requires additional effort, the level of detail provided will on average be low. However, if the aim is to suggest relevant data to a user, a low level of indexing detail can be sufficient as this paper will show.

Capturing and indexing should be real-time

To reduce the amount of additional effort required from the designers, and increase the chance of capturing more design data, design data should be captured and indexed in real-time, i.e. during the design process. This has the additional important advantage of the data in the system being up-to-date which is required for supporting genuine concurrent engineering.

Capturing and indexing should be process-based

An artefact model is necessary to capture the artefact, but such a model is insufficient for supporting the entire design process, and thus for capturing the data created in this process. The most promising approach is process-based rather than artefact-based for the following reasons. Design data is not limited to artefact data (although it is strongly related to the artefact). The artefact is evolving while design data is being created. Design data results from design activities, and therefore has a direct link with the design process as a sequence of design activities. The process can provide the context for the system to 'understand' the data, even if the data is captured without interpretation.

A basic level of capturing and indexing can provide substantial support

A minimum system functionality of capturing data without interpretation (such as scanning sketches or using a word processor) and requiring only a small additional indexing effort of the designer will be insufficient to prepare the data for knowledge based reasoning. Based upon a model of the process, however, this basic functionality is sufficient to support retrieval of relevant design data, and, as the developed system will show, to improve the design process because it supports:

- teamwork and communication, e.g. to update new project members
- reuse of design data in current and future projects by providing an artefact's history
- genuine concurrent engineering.

In addition, the process model can guide the design process itself.

As this is a minimum functionality, the system should allow for a shift in task distribution and for different levels of implementation, for example to adapt to developments in computer science or particular company characteristics.

Support can be improved

In creating design data, the design team makes use of data from various resources: data from handbooks, experts, software programmes that are available and the design data of previous projects. As outlined in the introduction, in practice very few of the available resources are being exploited despite their potential to support the development of the product and, in many cases, to ease or even enable the initial problem statement to be translated into a successful product. Hence it is important to support designers in finding the relevant design resources.

The available resources support specific activities. A model of the process would, therefore, provide a way of linking resources to design activities and integrating the resources. This allows the system to suggest suitable resources depending on the activity in which a designer is involved.

Summary of system requirements

A system that aims at improving the effectiveness and efficiency of the design process should have a user-friendly and real-time way of capturing design data, and an effective and efficient way of indexing design data and design resources, so that retrieval of relevant data and sources is quick and easy. Only then the system is applicable by a design team throughout a design process, i.e. during the evolution of the product. A workbench, providing a process-based view on the data and the resources in the system is considered the most promising and robust approach to design support.

4. PROSUS, A PROCESS-BASED SUPPORT SYSTEM

The identified requirements and functions (see section 3) led to proposal for a support system, named PROSUS, developed around a model of the design process. The development of PROSUS focused on the interaction between user and system. PROSUS consists of modules on three levels (see fig. 1): a primary level, a control level and a support level. The matrices are the working areas of the design team.

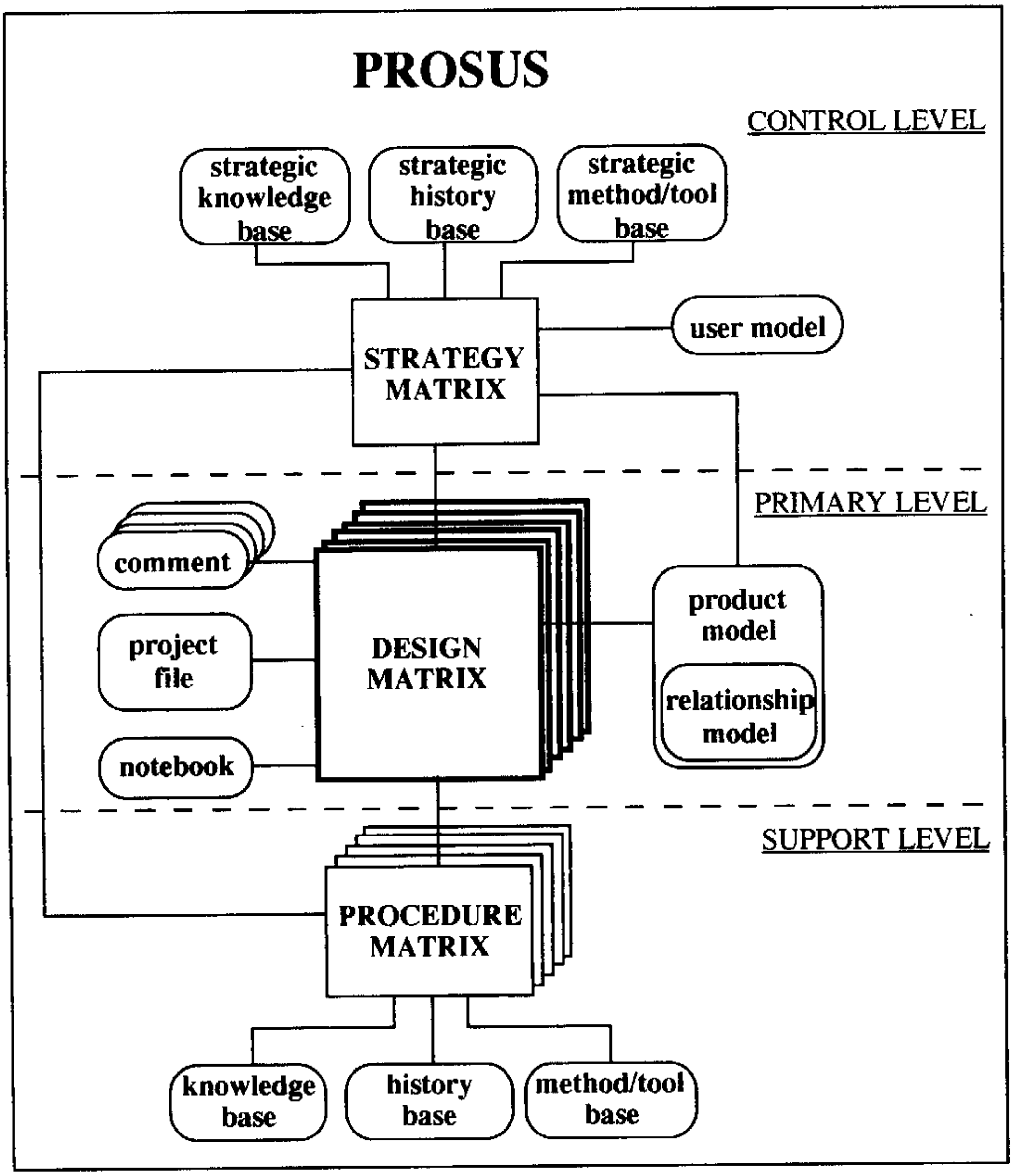

Fig. 1 PROSUS, a process-based support system

The design matrix

The basic building block of PROSUS is the design matrix, which represents the design process as a structured set of issues and activities (fig. 2). This process model does not describe how designers *do* design, nor does it prescribe how they *should* design. It suggests how designers *could* design, by providing a framework for supporting their activities. The design matrix is based on a combination and extension of two models: Methodical Design, a problem-oriented approach to design [12], and the argumentative approach to design proposed by Rittel [13, 14]

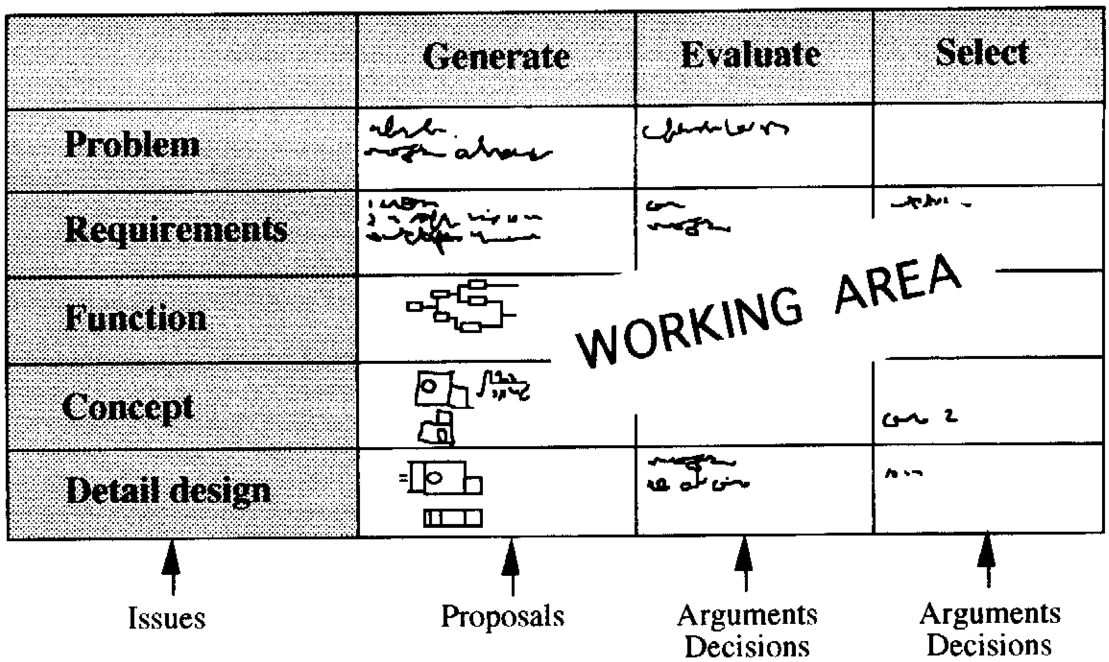

Fig. 2 A design matrix (simplified).

The first column provides the *issues* that are relevant in a design process., They are related to the process stages distinguished in Methodical Design. Issues are solved by the activities Generate, Evaluate and Select, related to Rittel's approach. Generate results in *proposals* for the issues concerned. Both Evaluate and Select result in *arguments* and *decisions*. They provide the design rationale supporting or opposing a proposal. Evaluate is defined as assessing whether a proposal is promising at all, i.e. could be pursued further, based on a comparison with requirements and other criteria. Select is defined as determining which of the solutions that passed the evaluation is most promising, i.e. should be pursued further.

Designers use the matrix to design by entering design data. Data can be entered in any order; no sequence of addressing cells is prescribed, nor do all cells have to be filled in. The cell identification provides the index for future retrieval. It provides the system with a context for 'knowing' the contents of the design data, without having to have knowledge to interpret the data and without requiring additional indexing effort from the designer.

The amount of data that is potentially created is large. The cells are intended to encourage designers to make more design data explicit. One matrix would not sufficiently, as the amount of data in each cell would still too much to be of use in retrieving relevant data. It can be argued that issues reoccur in the design process for each assembly or component. Therefore, an additional matrix is introduced every time a new assembly or component is being created. These matrices differ slightly from each other, because some of the issues involved in creating an assembly (such as the assembling process) are not relevant for creating a component or selecting a standard component, and vice versa. Once completed, the design history consists of a set of matrices each containing a description of the design process of a particular product, assembly or component, providing the rationale that was applied during its creation. In contrast to other design history tools, the description is structured around the rationale applied and may not be chronological: the matrix structures the results of the process independently of the sequence in which they were generated.

The fact that a matrix is process-based, extends its use beyond that of a structured, but fairly passive notebook. As described earlier, the system can use the matrix to provide support by suggesting relevant sources of data to solve the issues. Guidelines, methods and tools relate to particular steps in the design process. The cells in the matrices represent these steps and can thus be used by the system to suggest relevant sources, including data from other design projects that were captured in the same way. Support can also be provided by the system making use of the various default links that exist between the cells.

It will be clear that design administration data can be captured without much additional effort of the design team. The system can log who was doing which task (given by the cell of a particular matrix) when and how (which methods or tools were being used).

The implementation of the matrix does require a versatile easy-to-use user interface to encourage data capture, but does not have to rely upon the availability of advanced software solutions such as sketch interpretation and natural language recognition nor upon the use of formal design languages by the designers to be useful. Once advanced solutions become available these can be integrated and potentially increase the amount of support that can be given to the design team.

The other elements of PROSUS

The product model shown in figure 1 is derived from the design matrix. It contains the results of the issues addressed and therefore describes the product, its elements and their relations in terms such as their functions, requirements, and geometry.

Comments are remarks, questions or information transferred from one project member to another, and related to the contents of one or more cells in the design matrix. Comments enable project members who are not authorised to modify the contents of a specific matrix to react on its contents leading to enhanced communication.

Many documents are produced and used in a design project such as correspondence, trip reports, management summaries and minutes. They rarely relate to a specific product element, i.e. design matrix. These documents are stored in the project file.

Desigerns can make use of personal notebooks for temporary storage of data they do not want to become public (yet).

The design matrix does not provide issues related to author, time and means: "Who solves the issue(s), when and how". This is dealt with in special procedure matrices. A procedure matrix links one or more cells of a design matrix with the knowledge base, history base, method and tool base. The history base stores the design matrices, project file and product model of each of the projects that have been executed in the company. The data related to the final product can be found in the product model. The design matrices contain the rationale behind the results in the product model, including each alternative considered. The project file contains general data.

A design matrix deals with the different steps in the design process. A procedure matrix deals with the ways to execute a step. A strategy matrix deals with the sequence of steps. This matrix aids the designer in finding the current most promising strategy. This interactive process is based on: (1) process status (derived from the design matrices); (2) available resources and means (extracted from the procedure matrices); (3) the product status (stored in the product modei); (4) strategic means (in terms of knowledge, methods and history); and, optionally, (5) a model to tailor strategy proposals to approaches often applied by a specific user. The structure of the matrices and their links suggest a default strategy which is based on problem-oriented strategies found in prescriptive literature. First indications are that this type of strategy has a positive effect on the product if applied in a flexible way [7].

5. EVALUATION

The design matrix, being the core of PROSUS has been evaluated in an experiment involving eight experienced designers. The main issues were applicability and usefulness. The designers were asked to think aloud while solving a design problem. Four of the designers received a set of paper matrices to work with after a short introduction to the matrix approach. The other four designers received blank sheets of paper and were expected to work as normal. The evaluation was based on a comparison of the design processes of the two types of designers by analysing the video recordings and the data the designers created.

The findings were considered promising: many typify successful design processes. The designers using design matrices generated more concepts, documented more of their design process including arguments and decisions, assessed their solutions more often and throughout the design process, and were able to apply various approaches.

With regard to the overall aim to improve the effectiveness and efficiency of the design process, the data did not give support. No differences in product quality could be measured, and the design processes of the designers using the matrices lasted longer than the processes of the other designers. Several possible explanations for these two findings were identified that point towards the experimental set-up of the evaluation. Computer implementation and more elaborate experiments are needed to confirm or reject these explanations. The overall results of this evaluation, however, were considered sufficient to justify further development and implementation.

6. IMPLEMENTATION

Parts of the model can be realised using existing computer technology. The combination of these parts into a full implementation, requires a major effort. A start has been made to integrate the core ideas of PROSUS in the Integrated Design Framework under development in the Cambridge University Engineering Design Centre.

The Design Matrix concept is used as the workbench for the user, providing a process-based view on the data in the system. The Cambridge Product Data Model presented at last year's workshop [10] provides the central storage space. Some computer tools, developed in-house and commercially available, have already been linked to the product model. A first prototype of the Integrated Design Framework is now in place, providing basic links and features. An evaluation of this prototype is to commence shortly, using the data created in an in-house design project. This data was captured using the design matrix concept. This evaluation will be followed by an evaluation involving the use of IDF during a design process.

7. CONCLUSIONS

The paper proposes a system to support mechanical engineering design throughout the design process. The system aims at improving design by putting the emphasis on the design process rather than on the artefact. This is realised by introducing the Design Matrix which provides a process-based view of the system. The design matrix encourages design data to be captured, reduces the effort involved in indexing, and provides the context for the system to suggest relevant guidelines, methods and tools to the designer. Initial evaluation of the matrix was positive. Further evaluations involving an implemented version is expected to contribute to solving several of the still outstanding issues.

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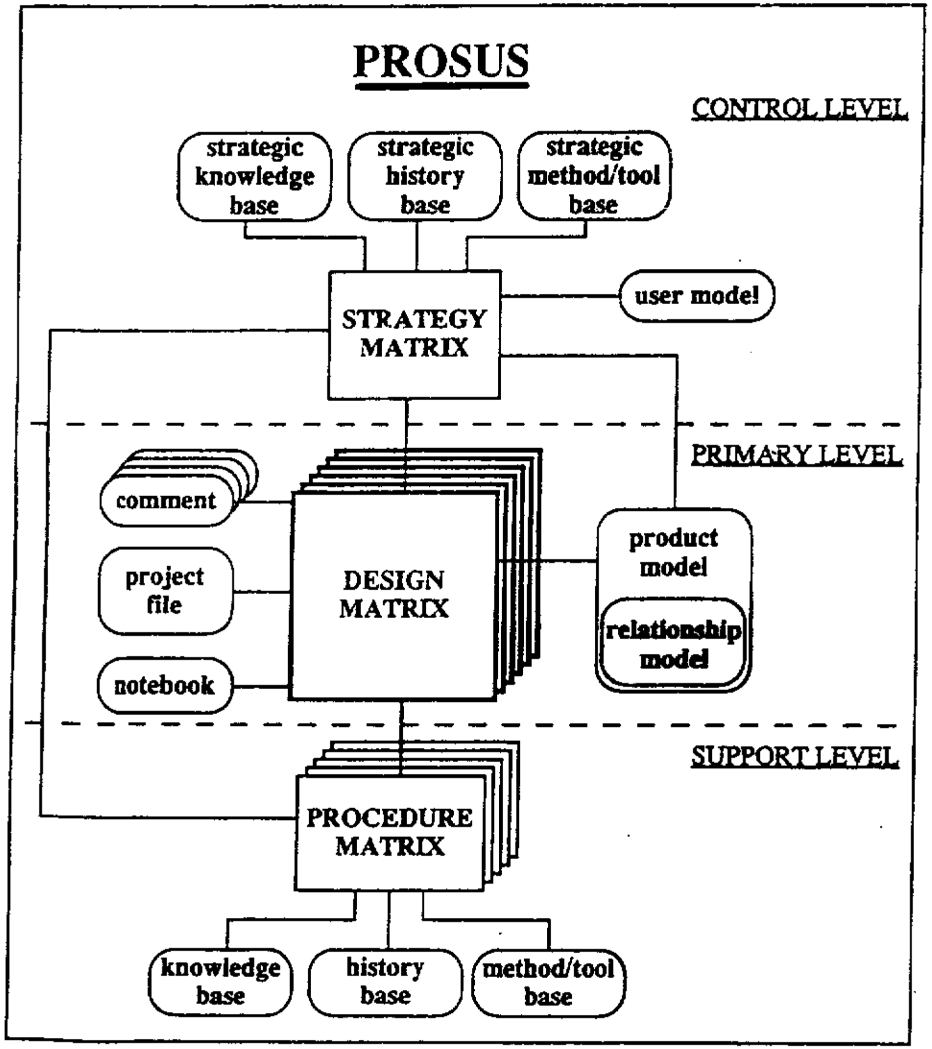
IMPROVING THE DESIGN PROCESS

Main issues:

Capturing design data
Supporting the creation of design data

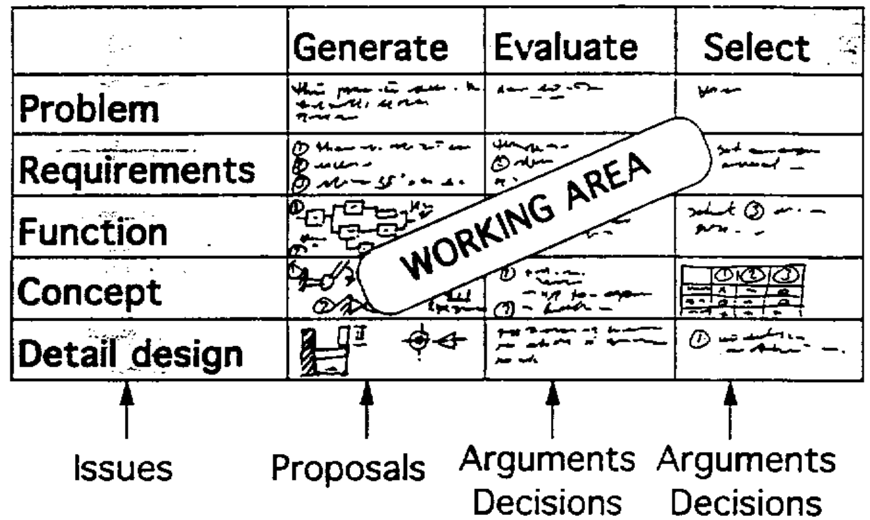
Most promising solution:

a process-based approach



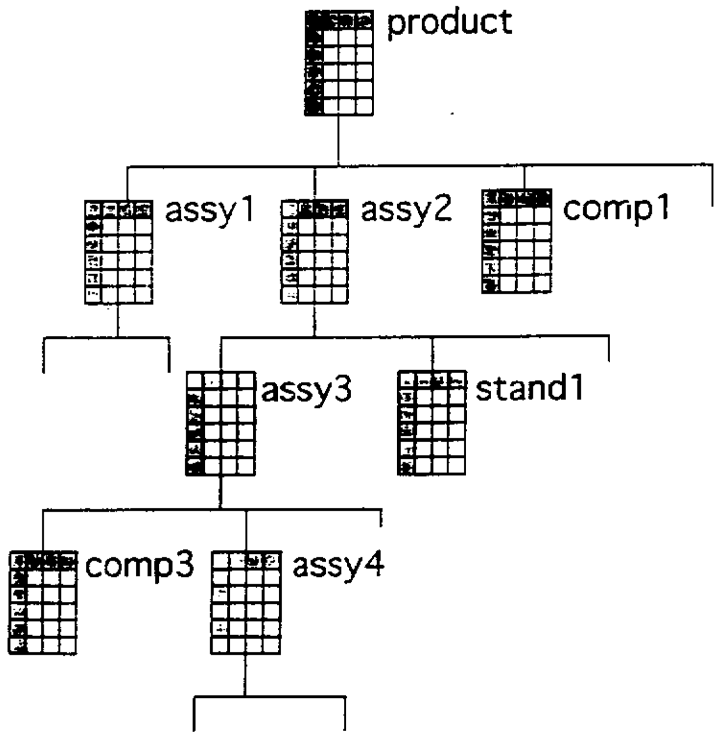
PROSUS WORKBENCH

DESIGN MATRIX: represents the design process as a structured set of issues and activities



Functions:
- supports a methodical process
- structures documentation and retrieval
- supports teamwork and communication
- provides context-sensitive advice

MATRICES AGAINST ARTEFACT



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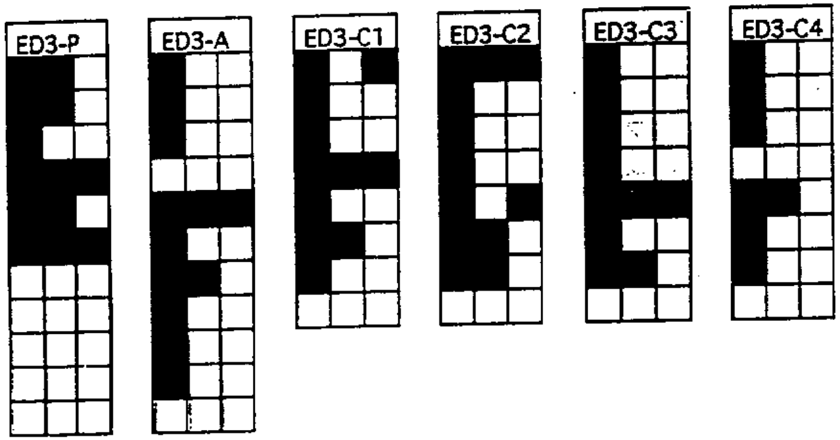
EVALUATION RESULTS

Designers using design matrices:

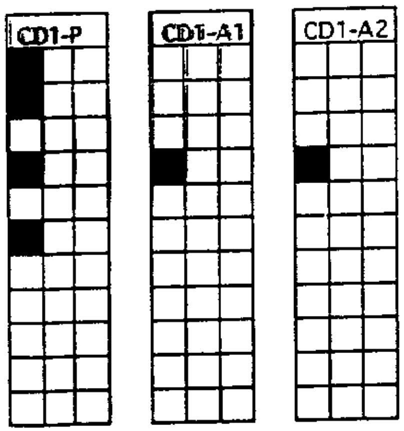
- used a variety of approaches;
- generated more concepts;
- addressed more issues;
- spent more time on problem analysis;
- documented more arguments and decisions;
- evaluated more often;
- evaluated throughout the design process.

CELLS ADDRESSED IN WRITING

with matrices

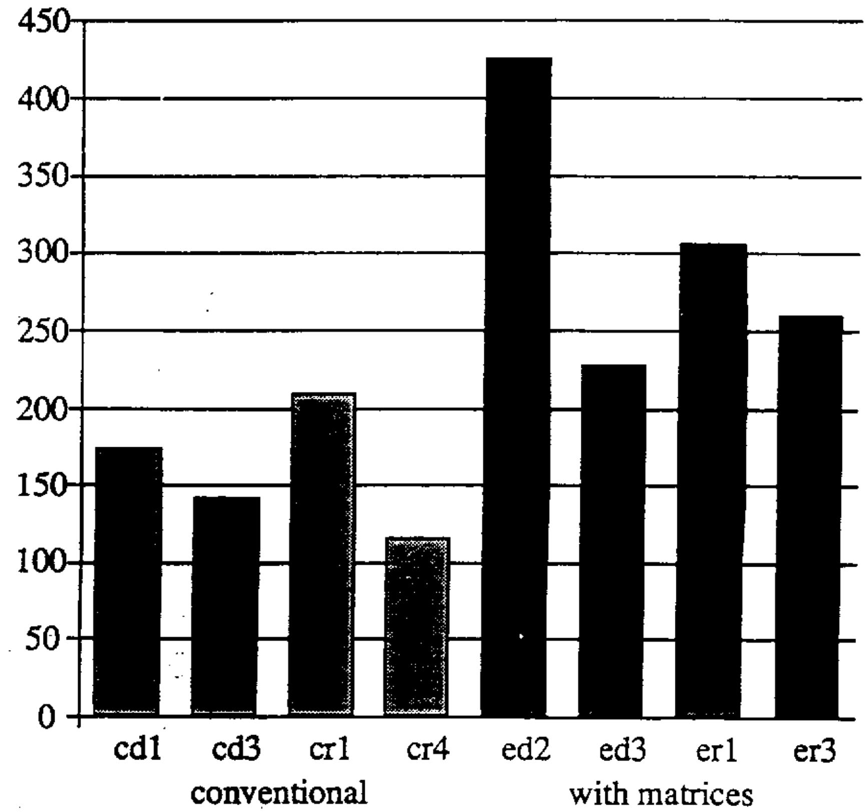


conventional



CAMBRIDGE EdC

NUMBER OF EVALUATIONS



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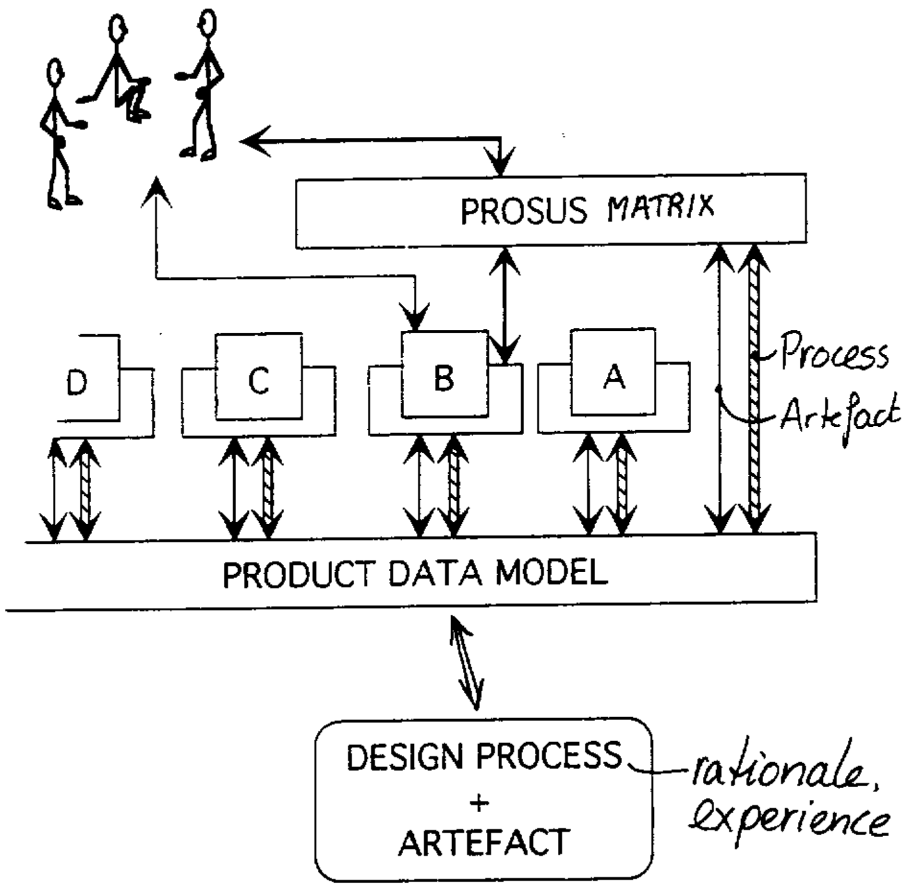
INTEGRATED DESIGN FRAMEWORK



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PROGRESS

- Matrix tested and used
- PDM tested and linked to EDC tools
- Prototype IDF/PROSUS
- Evaluation