Engineering Design
Theory and practice

A symposium in honour of Ken Wallace

edc cambridge

Professor John Clarkson, MA, PhD, MIEE, CEeng
Mari Huhtala, MA

Engineering Design Centre, Department of Engineering, University of Cambridge,
Trumpington Street, Cambridge, CB2 1PZ, UK

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Foreword

There have been profound changes in engineering design teaching and research since Ken Wallace came to Cambridge in 1978. These changes have been part of a worldwide movement and they have had a huge effect on what we do. A quarter of a century ago, there were still people here who doubted whether design was a proper subject for university study. Now the inclusion of design in university teaching and research is unquestioned. Ken's enthusiasm, energy and diplomacy persuaded the doubters. He brought design teaching into the mainstream of our curriculum, established design research on a sound footing, and, above all, taught colleagues and generations of students how important design is and what rewards and satisfaction it can bring. The Cambridge Engineering Design Centre became the means of achieving that transformation. From the outset, Ken took the lead and he became the EDC's first Director. At the same time, he played an increasingly influential role internationally, travelling widely and promoting the EDC's work and research programme. Now it is recognised as one of the world's leading university centres for design engineering.

This book marks Ken's contribution, over a quarter of a century, to the EDC, to Cambridge University and to the international design community. It is a token of the esteem and affection in which we hold him. Distinguished colleagues and friends have taken the time to prepare chapters. The result is a valuable collection of papers, covering a wide range of different topics, which will remain a permanent record of the directions and priorities of design research in 2005. I congratulate the EDC's present Director, John Clarkson, whose concept the book is, and who invited the contributors and edited the volume under a necessarily tight time constraint. One of Ken's first tasks when he came to Cambridge was to translate into English the famous German design textbook Konstruktionslehre by Pahl and Beitz. It is especially fitting that Gerhard Pahl was able to accept John's invitation and has written one of the chapters of this book.

Ken was Rolls-Royce's Apprentice of the Year in 1968. Nearly 40 years later, he received one of Rolls-Royce's Awards for Creativity. I am proud to have been one of his colleagues throughout much of this long period and it is a great pleasure to introduce this festschrift to mark Professor Wallace's 60th birthday.

David E Newland
Emeritus Professor of Engineering
University of Cambridge
March 2005

Preface

A festschrift for Professor Ken Wallace – how can that be? It seems like only yesterday that I rejoined the Cambridge University Engineering Department as a Lecturer in Engineering Design. The date was 1 April 1995 - All Fool's Day! I was assigned to work under the tutelage of a certain Ken Wallace, co-founder and Director of the fledgling Engineering Design Centre (EDC) and an inaugural winner of the Pilkington Teaching Prize.

Ken proved to be an expert teacher, helping me with the new challenges of lecturing and encouraging me to participate in the research of the EDC. I found the latter a vibrant group with a clear vision for their research, much of which still defines our work today. Ken's expert guidance continued as I took over as Director of the EDC in January 1997 and he remained, as Chairman, active in managing his research within the prestigious University Technology Partnership, a joint venture between Rolls-Royce, BAE Systems and the Universities of Southampton and Sheffield.

As Ken approached his 60th birthday, it seemed appropriate to mark the event with a festschrift – a celebration. However, what began as a simple idea soon blossomed into a major conspiracy. Christa and Mari have expertly spun a web of deceit involving most of the world's leading design academics and Ken's family – the EDC office has been abuzz with secret conversations, plotting and general skulduggery. The plan was to gather together Ken's colleagues from the international research community with his past and present researchers in order to celebrate his contribution to design research. This book represents one of two outputs from this process, the other being a symposium that was held in Trinity Hall, Cambridge, on 11 April 2005.

I am indebted to those of you who were able to provide chapters for this book, and for presenting them at the symposium, and to Mari for doing an excellent job in preparing the manuscript. I would also like to thank all those who attended the symposium, where numbers far exceeded our expectations, and to thank Christa for organising the event so expertly. Without your time and contributions we would not have had so much fun.

This book contains a mix of chapters addressing design theory, design education, design practice and critically, the interplay between these topics. Together they represent a significant contribution to current design thinking – I hope you will enjoy reading them.

Working with Ken has been a privilege and always a pleasure. He is a master craftsman, skilled in his art and generous in his help and encouragement. Ten years on I may have served my apprenticeship, but I still have much to learn from the Master.

John Clarkson
Professor of Engineering Design
University of Cambridge
March 2005

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Chapter 1
Engineering knowledge management

Saeema Ahmed, Rob Bracewell and Sanghee Kim
University of Cambridge

On partnerships between design research groups and industry, Ken Wallace has long held the view that a few carefully nurtured long term relationships make for far more effective research than many superficial ones. This philosophy is exemplified in his career-long association with Rolls-Royce, which over the last seven years has culminated in his foundation and co-directorship of the UTP for Design. For all who have had the privilege of researching in this environment of trust and cooperation with the companies that Ken has fostered, it has been a great experience.

Formed on 1 October 1998, the BAE SYSTEMS/Rolls-Royce University Technology Partnership (UTP) for Design is a long-term research partnership linking the two companies and the Universities of Sheffield, Southampton and Cambridge. The UTP is embedded within the Cambridge Engineering Design Centre (EDC), where it contributes significantly to the knowledge management research of the EDC.

BAE SYSTEMS and Rolls-Royce both supply complex products and services in aerospace and other industrial sectors. Essential market differentiators for the companies are performance, safety, reliability, short time to market, high quality and low cost of ownership. Continuous improvement of the product definition process is essential for the companies to maintain world-class performance against these measures.

The companies identified three key design areas that needed to be researched to enable further improvements to be made to the product definition process:

- role of innovation and people issues within the process (Sheffield)
- optimisation of the design taking into account all relevant factors (Southampton)
- management of the total knowledge needed for the design task (Cambridge).

The overall aim of the Sheffield research into human factors and innovation is to understand and improve the people and organisational aspects of the design process. The work adopts a broadly sociotechnical emphasis which lays stress on the interconnectedness of the social (people and organisational) and technical (methods, tools and techniques) issues.

The overall aim of the Southampton research into design search and optimisation is to understand, develop and improve the increasingly sophisticated search and optimisation software tools being used by both companies. These tools span commercial products, plug-ins to commercial codes and fully in-house capabilities.

The overall aim of the Cambridge research in engineering knowledge management (EKM) is to understand how to make more knowledge available to designers and engineers in a readily usable form. This includes both novices who are acquiring expertise in a particular area, as well as experienced staff who need to move into a new area to meet changing business requirements.

The UTP's overall research programme represents a novel approach based around the interaction of technologies, tools, processes and people.

Engineering knowledge management

In the future, there are likely to be fewer opportunities to talk to the experienced designers and technology experts who were involved in previous projects. The specific aims of the EKM research are:

- to understand the capture, storage and retrieval of engineering design knowledge
- to understand decision making in engineering design and the nature of design expertise
- to develop theories that can form the basis of new methods and tools
- to develop and test prototype methods and tools.

The twin research approaches used in the Cambridge UTP are 1) undertaking empirical research in industry and 2) creating and testing robust prototype software. The empirical research contributes towards a better understanding of how a designer approaches design tasks, and of the design knowledge employed. This understanding underpins the research and evaluation of methods, tools and processes to improve the management of knowledge, which are implemented where appropriate in prototype software.

Engineering design is a knowledge-intensive activity. Knowledge exists in the heads of individuals and provides them with the capacity to make decisions and adopt courses of action. What is stored and transmitted externally is information and data. Knowledge is generated and evolves: (1) by observing; (2) by interpreting information; and (3) through reasoning.

An example of implicit knowledge is the strategy adopted by an experienced designer to undertake a particular task in the design process.

Explicit knowledge can be articulated. Once articulated, it can be represented as information, e.g. written down, and thus stored externally and transferred. An example of explicit knowledge is the factual description of a process or product. Implicit knowledge cannot be articulated by the person possessing it, but it is possible for it to be elicited and articulated by others. An example of implicit knowledge is the strategy adopted by an experienced designer to undertake a particular task in the design process. The designer may not be able to articulate the strategy employed: however, researchers can identify these strategies through methods such as protocol analysis. Tacit knowledge cannot, by definition, be articulated, but its role in the design process can be investigated. An example of tacit knowledge is the intuitive feel that an experienced designer has for the correct shape of a component in a product. Table 1.1 describes information and explicit, implicit and tacit knowledge with examples.

	Stored externally	Stored internally in human memory		
	Information	Explicit knowledge	Implicit knowledge	Tacit knowledge
Process	Descriptions of the design process (e.g. information)	Explanations about the process (e.g. rationale)	Understanding about the process (e.g. strategies)	Intuition about the process (e.g. insights)
Product	Descriptions of the product (e.g. information)	Explanations about the product (e.g. rationale)	Understanding about the product (e.g. relationship)	Intuition about the product (e.g. insights)

1.1 Classes of knowledge and information

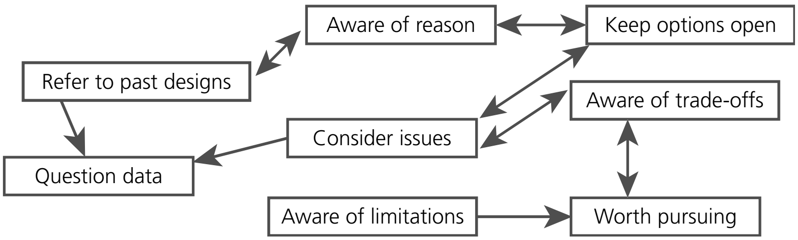
The EKM research has been organised under seven projects for which the objectives, research methods employed and a brief summary of findings and impact have been set out below. The research projects address issues in the development of an overall framework for the capture, storage and retrieval of engineering design knowledge.

Capture

Use of experience in design

This research aimed to understand the role of experience in design. A number of empirical studies were carried out to understand differences between novice and experienced designers. The methods employed included protocol analysis, interviews and discourse analysis.

The research identified that experienced designers carry out a preliminary evaluation of designs in their heads, thereby allowing them to avoid the trial and error process adopted by novices. The experienced designers had developed strategies, which the novice designers were unaware of. Eight strategies were identified and a method named C-QuARK was developed. Another key finding is the observation that novice designers do not know which questions to ask in two-thirds of cases when seeking information. The method has been used as part of a knowledge capture system, training program and workshops for recent graduate recruits in the collaborating companies.



1.2 C-QuARK method

Design rationale capture

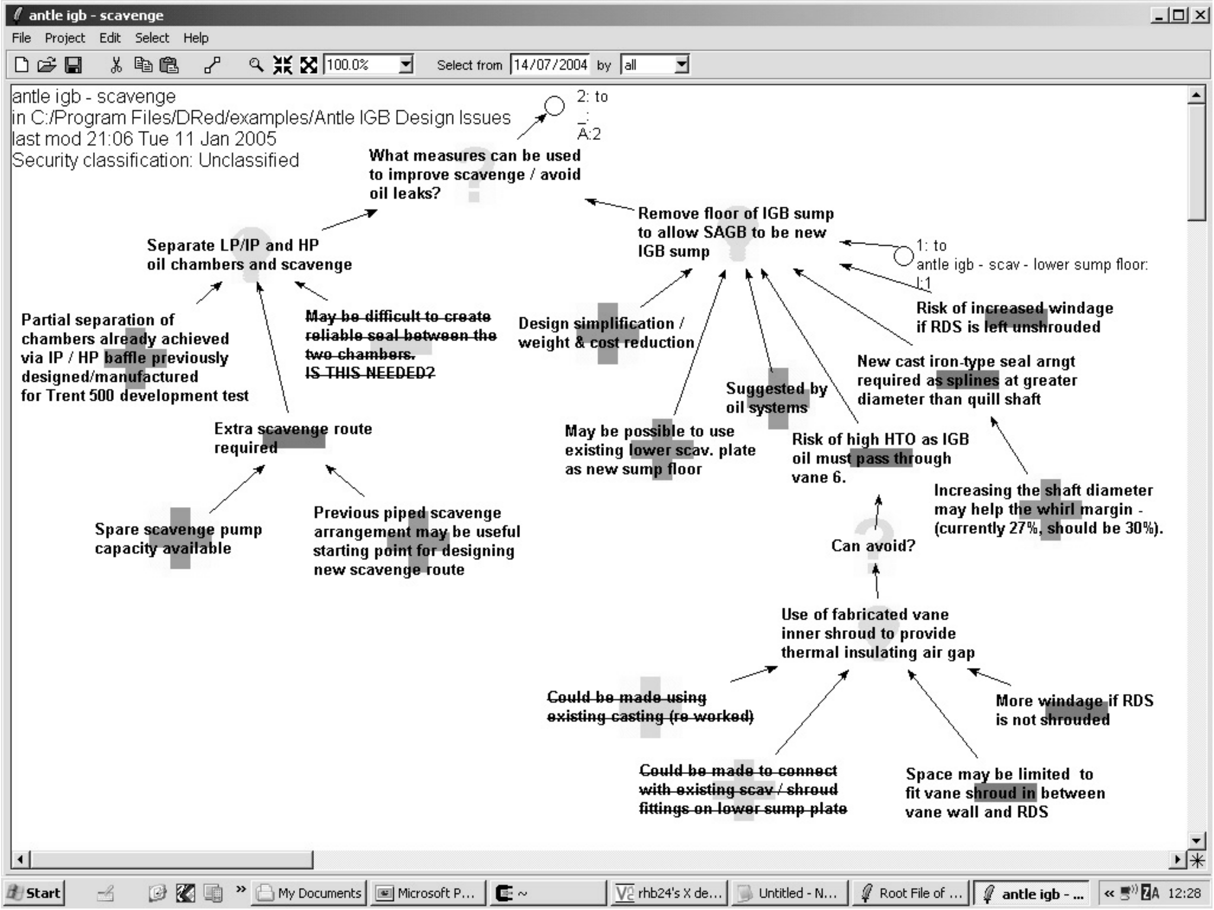
This project aimed to understand the nature of the rationale being deliberated by aerospace designers and to use this understanding to create a practical software tool for its capture, presentation and browsing. The initial approach was one of graphical modelling of the argumentation contained in existing textual design reports. This led to the rapid development of a simple rationale capture tool, named DRed (Design Rationale editor). This tool was delivered to a handful of Rolls-Royce designers, who used it on 'live' design projects. While initially crude, it nevertheless proved to be effective. Its functionality was extended and refined in a rapid succession of releases, in response to invaluable feedback from the designers using it.

Following favourable results of a questionnaire of early users, use of DRed was extended and it is now rapidly being adopted within Rolls-Royce. For example, the use of DRed is now mandatory for all design scheme reviews on Rolls-Royce's JSF F135 project. Feedback from designers at Bristol, Derby and Montreal suggests that DRed improves decision making and communication – as well as reducing the need for lengthy reports. Having been accepted by the company's Design Practices Committee, DRed is now incorporated into their standard product lifecycle management (PLM) tool set.

Capturing and structuring design knowledge

This research project aimed to understand engineering designers' information requests and to find what triggers these requests; what types of knowledge the designers require and how they search for it. The results would help to establish what knowledge needed to be captured. A series of empirical studies were undertaken within Rolls-Royce: methods employed included participant observation, observation, diary studies and interviews.

The findings identified that 33% of information requests showed an examining behaviour, which requires support in locating the relevant information. A quarter of the information searches observed were found to be unsuccessful, *i.e.* the information searched for was not found.



1.3 Example of DRed screenshot

Structure

Indexing structure for design

This project aimed to develop and evaluate an indexing structure for capturing and retrieving knowledge and experience. The indexing structure was identified by carrying out interviews with engineering designers.

The findings of these interviews identified four taxonomies as the basis of this indexing method. The taxonomies have been integrated and implemented in software named CITED (Cambridge Integrated Taxonomy for Engineering Design). This can be used as a visible navigational structure to assist browsing when searching for information and to index and retrieve information.

Information retrieval using design guidelines

The aim of this research was to understand how engineering designers intuitively structure, relate and store information in their heads. Experiments were undertaken to investigate how engineers related guidelines. Cluster analysis was employed to identify recognisable patterns in how the guidelines were structured.

The result was an intuition-based classification method that was implemented in a prototype software search tool. In experimental tests this compared favourably with conventional approaches in its effectiveness of retrieval of relevant design information.

Retrieval

Retrieving and using design knowledge

The aim of this project was to predict the implications for design of the widespread trend to switch from paper to electronic formats. The approach was to perform case study experiments to examine the differences in how designers retrieve information presented in the two formats during the design process. One objective was to discover why some designers prefer paper-based documentation.

A case study was the development of a detailed design of flying control surface. Designers in BAE SYSTEMS were observed whilst carrying out the case study in both paper and an electronic format. Various different stages of information retrieval were identified. Designers were able more quickly to browse through information when it was presented in a paper format.

Retrieving knowledge using semantic technology

This research aims to investigate methods of using semantic technology to add value to the storage of information in a variety of repositories, including electronic documents and DRed graphs, in order to improve its retrieval and subsequent interpretation as knowledge. An investigation into the current retrieval methods of design knowledge has been carried out and identified that design rationale is reasoning-based knowledge so that a simple look-up based retrieval is not suitable.

As an example of semantic-oriented retrievals, a discourse-based annotation method has been developed. The discourse annotations are able to extract semantic relations between two texts and provide more accurate content descriptions than that of keyword-based indexing. In order to reduce the human effort of manually annotating such discourses, natural language processing and machine learning techniques were used for an automatic annotation and showed achieved 80% accuracy when tested with a small number of DRed graphs. A prototype named DRedQA (Question Answering) has been developed, to evaluate the discourse annotations for searching and indexing from users' perspectives.

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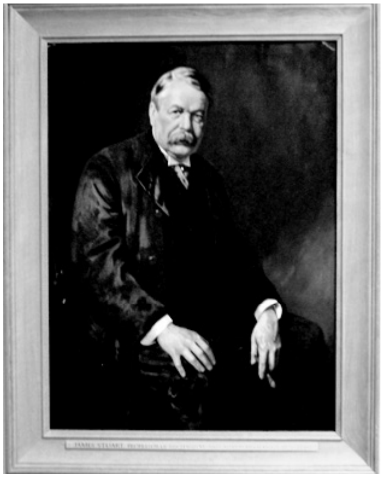
Chapter 2

Materials and design – creating the connections

Michael F Ashby and David Cebon
University of Cambridge

It is a privilege and a pleasure to contribute to this Symposium to honour Ken Wallace. Ken's dedication to teaching and his contributions to the academic standing of the Cambridge Engineering Department have been enormous – its current 5* RAE standing was achieved under his management. But above all, Ken's great achievement is to have created and directed the Cambridge Engineering Design Centre (EDC) and to have built it into a centre of internationally recognised excellence.

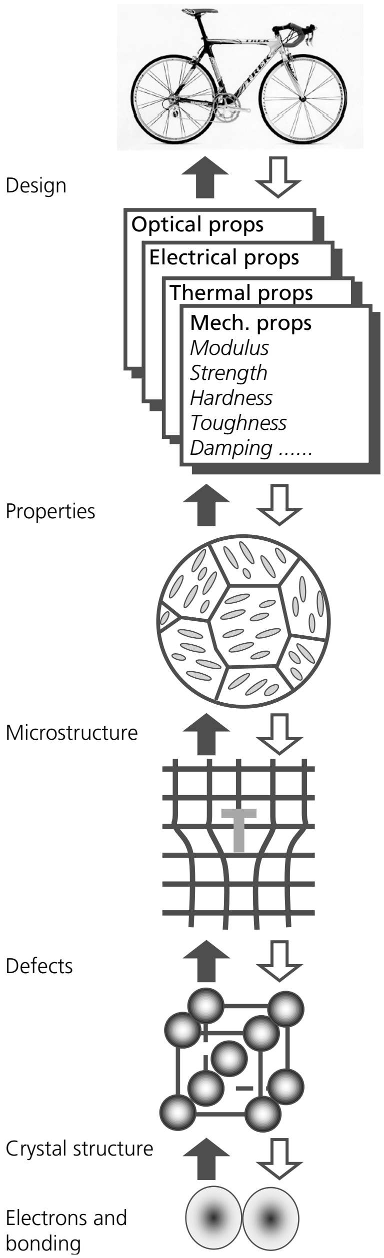
To put this in historical perspective, glance for a moment at Figure 2.1. It is a portrait of James Stuart, Professor of Mechanism and Applied Mechanics, and the first Head of an Engineering Department at Cambridge. He and his near contemporaries certainly engaged in design (think of Telford, Brunel and Parsons) but the concept of design research – or even of design as a discipline in its own right – would not have occurred to them. The idea of design as a discipline in its own right first appears in the history of the department about 1970 with the appointment of Peter Ross and Gordon Glegg. David Newland, who followed in 1976, pressed for a strengthening of design research, with the happy result of the appointment of Ken Wallace. Just in time, you might say – by then the study of design, particularly in Germany, was expanding rapidly, driven in part by the need to cope with the ever greater complexity of mechanical systems, but also because it became clear that understanding the design process presented an intellectual challenge. Today, there are dedicated journals, international conferences and numerous texts on the subject (French, 1985; Ullman, 1992; Ulrich and Eppinger, 1995; Pahl and Beitz, 1996; Cross, 2000).



2.1 James Stuart, Professor of Mechanisms and Mechanics and Head of the Engineering department, Cambridge, 1875–1890

The other subject in the title of this chapter is *materials*. (Materials research in the Cambridge department really started with the appointment of Constance Tipper in 1925, who, working with G.I. Taylor, systematically studied plasticity and fracture in metals.) In James Stuart's day the range of engineering materials was small. The most 'advanced' of materials were steels; add to these: cast iron, brass and bronze, zinc and lead, wood, stone, glass, brick – and you have almost all of them. There were no synthetic polymers; today there are more than 40 000 of them. There were no light alloys; today they number in the thousands. There were no structural composites; now there are hundreds. The materials menu today offers over 150 000 options. So we have a problem that James Stuart and his immediate successors did not have: that of imparting to engineering students a perspective of the world of materials and the means to make rational judgements about them.

In 1987, the authors, with considerable input and encouragement from Ken Wallace, began a project to develop a computerised teaching tool to



2.2 Two alternative approaches to materials education, one science-led the other design-led

assist with materials selection. Out of this project sprang an initial database of material properties, a rudimentary software system and the core of a methodology for materials selection. The methodology built on an approach that had been used for the 1st year teaching since 1975, with the purpose of linking materials teaching more closely to the other courses taught in the department. By 1990, when the EDC was first launched with 10-year funding from the EPSRC, research into materials selection was well established in the department and this naturally became one of the four main research themes of the EDC. One of the contributions to teaching from EDC staff was a course called 'G14 – mechanical design', one quarter of which focussed on materials selection. It used the software – then called the 'Engineering Materials Selector' (EMS) (Cebon and Ashby, 1991a, b) – and it became a test bed for the new approach to teaching materials that we describe in this chapter. (In 1994, the re-named software CMS2 was launched by the newly-formed university spin-out company, Granta Design Ltd.)

The underlying thinking of the new approach was this. Engineers *make* things. They make them out of *materials*. What do they need to know to do this successfully? First, a *perspective* of the world of materials – of the metals, polymers, glasses, ceramics, composites and so forth – from which they are able to choose. Second, they need *methods* for selecting from among these the ones that best meet the requirements of a design. And finally they need *data* for material attributes and – since the quantity of data is large the methods tedious to implement by hand – *tools* to enable their implementation.

The established approach to the materials teaching at that time was science-based (Figure 2.2). The starting point was the smallest unit of structure – the atom – and the nature of the forces that cause atoms to bind together (bottom of figure). From there it progressed to the structure of the solid state, both crystalline and amorphous, and to the defects that structures can contain: point defects, dislocations, grain-boundaries, inclusions, voids and cracks. Most engineering materials are alloys or blends, stimulating a discussion of phase equilibria. But most materials are also processed, and in processing they are far from equilibrium, prompting a discussion of the kinetics of phase transformations and of the ways in which microstructures evolve. This in turn leads to a discussion of transport properties, of strengthening mechanisms, of chemical and of thermal stability. It is a consequence of this approach that the *engineering* properties of materials – the ones students need if they are to *make* something – only start to emerge late in the course. If materials selection for design is discussed at all, it is as an add-on at the top.

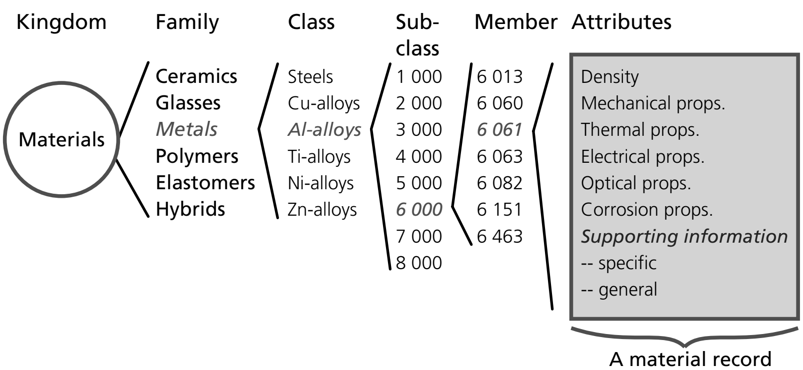
The alternative – a design-led approach – is to invert the order. The starting point now is a design – a lighter bicycle, a safer crash helmet, a more efficient heat exchanger, an eco-friendly disposable cup. We then need a strategy for relating design requirements to materials properties (top of the figure), and tools to implement it. The science is developed as needed to support this.

The selection strategy

A material has *attributes*: its density, strength, cost, resistance to corrosion, and so forth. A design demands a certain profile of these: a low density, a high strength, a modest cost and resistance to sea water, perhaps. The task is to match the material to the design.

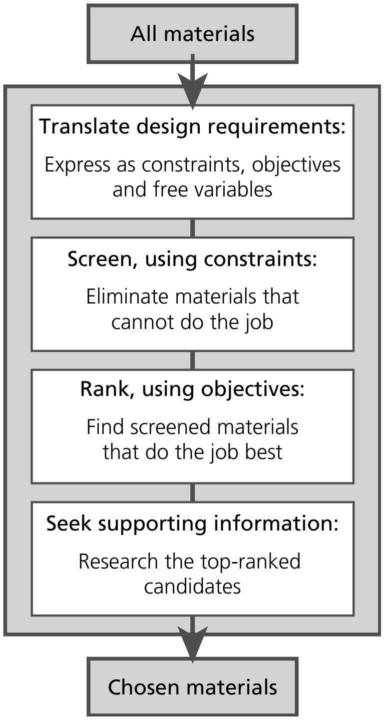
Material attributes

Figure 2.3 illustrates how the kingdom of materials is organised into families, classes, sub-classes and members. Each member is characterised by a set of *attributes*: its properties. As an example, the materials kingdom contains the family 'metals', which in turn contains the class 'aluminium alloys', the sub-class '6 000 series' and finally the particular member 'alloy 6 061'. It, and every other member of the kingdom, is characterised by a set of attributes that include its mechanical, thermal, electrical, optical and chemical properties, its processing characteristics, its cost and availability, and the environmental consequences of its use. We call this its *property profile*. Selection involves seeking the best match between the property-profiles of the materials in the kingdom and that required by the design.



2.3 The taxonomy of the kingdom of materials and their attributes. Computer-based selection software stores data in a hierarchical structure like this.

The strategy for achieving it is sketched in Figure 2.4. The first task is that of *translation*: converting the design requirements into a prescription for selecting a material and process to shape it. This proceeds by identifying the *constraints*



2.4 The strategy. There are four steps: translation, screening, ranking and supporting information. All can be implemented in software, allowing large populations of materials to be investigated.

Function	*What does component do?*
Constraints	*What non-negotiable conditions must be met?*
	What negotiable but desirable conditions...?
Objective	*What is to be maximised or minimised?*
Free variables	*What parameters of the problem is the designer free to change?*

2.5 Function, constraints, objectives and free variables

under which the material must function, and the *objectives* that the design must fulfil. These become the filters: materials that meet the constraints and rank highly in their ability to fulfil the objectives are potential candidates for the design. The final task is to explore the most promising candidates in depth, examining how they are used at present, how they fail, and how best to design with them.

Translation

Any engineering component has one or more *functions*: to support a load, to contain a pressure, to transmit heat, and so forth. This must be achieved subject to *constraints*: that certain dimensions are fixed, that the component must carry the design loads without failure, that it insulates or conducts, that it can function in a certain range of temperature and in a given environment, and many more. In designing the component, the designer has one or more *objectives*: to make it as cheap as possible, perhaps, or as light, or as safe, or perhaps some combination of these. Certain parameters can be adjusted in order to optimise the objective – the designer is free to vary dimensions that are not constrained by design requirements and, most importantly, free to choose the material for the component. We refer to these as *free variables*. Function, and constraints, objectives and free variables (Table 2.5) define the boundary conditions for selecting a material and – in the case of load-bearing components – a shape for its cross-section. The first step in relating design requirements to material properties is a clear statement of function, constraints, objectives and free variables.

Screening: constraints as attribute limits

Unbiased selection requires that all materials are considered to be candidates until shown to be otherwise, using the steps in the boxes below 'translate' in Figure 2.4. The first of these, *screening*, eliminates candidates that cannot do the job at all because one or more of their attributes lies outside the limits set by the constraints. As examples, the requirement that "the component must function in boiling water", or that "the component must be transparent" imposes obvious limits on the attributes of *maximum service temperature* and *optical transparency* that successful candidates must meet. We refer to these as *attribute limits*.

Ranking: objectives expressed as material indices

To rank the materials that survive the screening step this we need optimisation criteria. They are found in the material indices, discussed below, which measure how well a candidate that has passed the screening step can do the job. Performance is sometimes limited by a single property, sometimes by a combination of them. Thus the best materials for buoyancy are those with the lowest density, ρ; those best for thermal insulation the ones with the smallest values of the thermal conductivity, λ, provided, of course, that they also meet all other constraints imposed by the design. Here maximising or minimising a single property maximises performance, but often it is not one, but a group of properties that are relevant. Thus the best materials for a light stiff tie-rod are those with the greatest value of the specific stiffness, E/ρ, where E is Young's modulus. The best materials for a spring are those with the greatest value of σ_f^2/E where σ_f is the failure stress. The property or property-group that maximises performance for a given design is called its *material index*. There are many such indices, see Ashby (2005), each associated with maximising some aspect of performance. They provide criteria of excellence that allow ranking of materials by their ability to perform well in the given application.

To summarise: screening isolates candidates that are capable of doing the job; ranking identifies those among them that can do the job best.

Supporting information

The outcome of the steps so far is a ranked short-list of candidates that meet the constraints and that maximise or minimise the criterion of excellence, whichever is required. You could just choose the top-ranked candidate, but what hidden weaknesses might it have? What is its reputation? Has it a good track record? To proceed further we seek a detailed profile of each: its *supporting information* (Figure 2.4, bottom).

Supporting information differs from the structured property data used for screening. Typically, it is descriptive, graphical or pictorial: case studies of previous uses of the material, details of its corrosion behaviour in particular environments, of its availability and pricing, warnings of its environmental impact. Such information is found in handbooks, suppliers' data sheets, CD-based data sources and high quality Web sites. Supporting information helps narrow the short-list to a final choice, allowing a definitive match to be made between design requirements and material attributes.

Why are all these steps necessary? Without screening and ranking, the candidate-pool is enormous and the volume of supporting information overwhelming. Dipping into it, hoping to stumble on a good material, gets nowhere. But once a small number of potential candidates have been identified by the screening-ranking steps, detailed supporting information can be sought for these few alone, and the task becomes viable.

Implementation: methods and tools

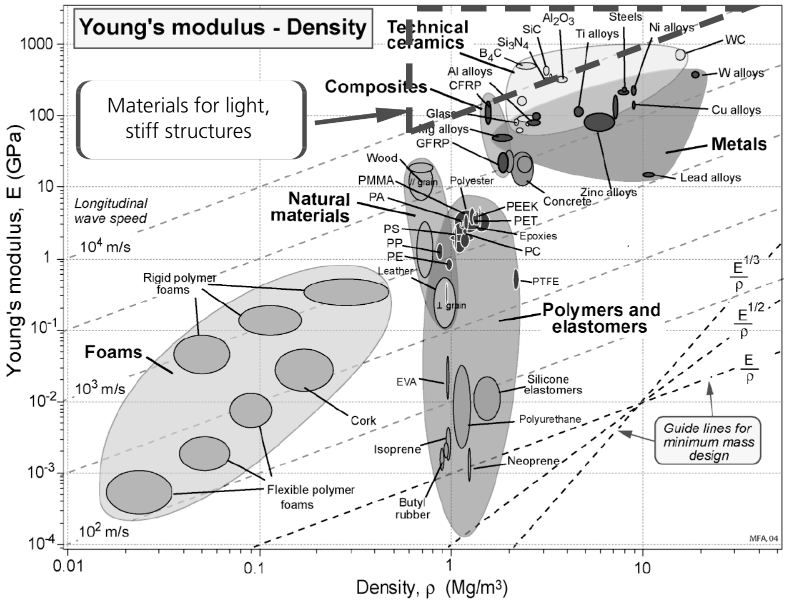
We now have a strategy. How best to implement it? Figures 2.6 and 2.7 illustrate some aspects of a method that we have found to work well. More details can be found in Ashby (2005). The first, Figure 2.6, shows one material property (here the modulus, E) plotted against another (the density, ρ) on logarithmic scales. The range of the axes is chosen to include all materials, from the lightest, flimsiest foams to the stiffest, heaviest metals. It is then found that data for a given family of materials (polymers for example) cluster together on the chart; the *sub-range* associated with one material family is, in all cases, much smaller than the *full* range of that property. Data for one family can be enclosed in a property-envelope, as the figure shows. Within it lie bubbles enclosing classes and sub-classes.

All this is simple enough – just a helpful way of plotting data. But by choosing the axes and scales appropriately, more can be added. The speed of sound in a solid depends on E and ρ; the longitudinal wave speed v, for instance, is

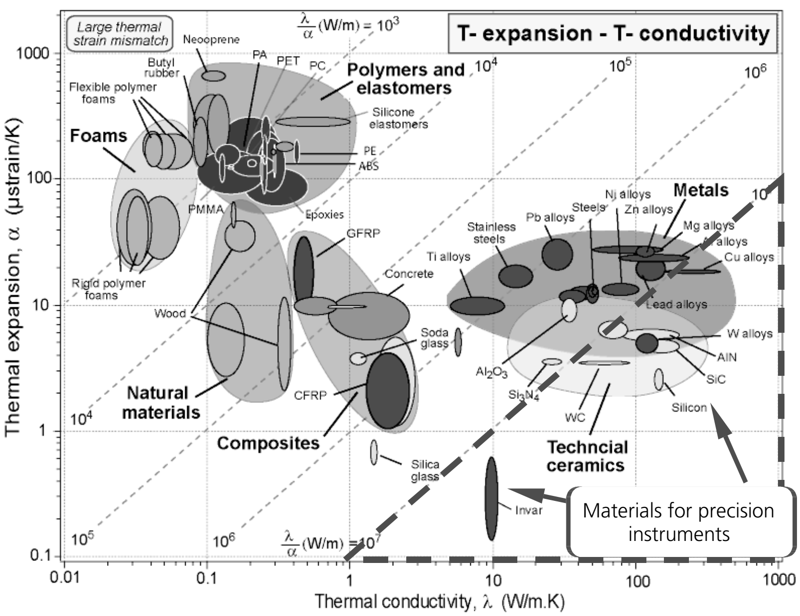
$$v = \left(\frac{E}{\rho}\right)^{1/2}$$

This allows the addition of *contours of constant wave speed* to the chart: they are the family of parallel diagonal lines, linking materials in which longitudinal waves travel with the same speed. Figure 2.7 shows a second example, here two thermal properties – thermal expansion, α, and thermal conductivity, λ. As in Figure 2.6, members of a given family cluster in a small area of the chart: ceramics and metals to the right, with low expansion and high conductivity; polymers and elastomers in the upper left, with ten times the expansion and only 1% of the conductivity of the first two.

Charts like these help students develop a perspective of the world of materials. The charts locate the families in material-property space, revealing the areas that are occupied and (importantly) those that are not. By building the materials attributes into a database and addressing this with appropriate search and graphical software, it is possible for students to make their own charts, plotting any pair of properties they wish. And by structuring the records in the database well, this self-education aspect can be carried further. Figure 2.8 shows part of a material record – that for ABS – contained in the CES EduPack software. (The CMS software was renamed CES3 in 1999, when material and process selection were integrated into a single software system.) (Cambridge Engineering Selector, CES4, 2002). It starts with a description of the material and an image of a familiar object made from it – a good way



2.6 A property chart. Here Young's modulus E is plotted against density on log scale. Charts like these allow a perspective of material properties, and provide a tool for material selection. (Figure created with the CES 4 EduPack software).



2.7 A second property chart. Here thermal expansion plotted against thermal conductivity on log scale. (Figure created with the CES 4 EduPack software).

of conveying information and of encouraging students to observe the materials in products that surround them in everyday life. That is followed by a table of material properties, a list of typical uses, and, in the more advanced version of the software, design guidelines, technical notes and notes concerning its impact on the environment. Finally, each material record is linked to appropriate members of a parallel database of manufacturing processes: those that can shape, join or finish it. Figure 2.9 is part of one of the processes records linked to ABS – it lists information for injection moulding.

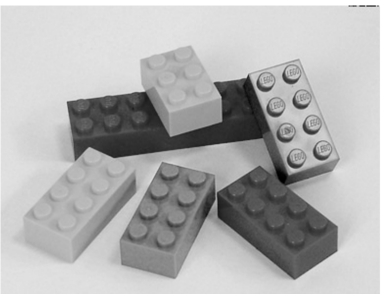
Given such a system, students immediately have a tool. Find materials that are stiff? They are the ones near the top of Figure 2.6. Materials that are light? They are the ones on the left. Light and stiff? The ones above the diagonal, which is a plot of the index E/ρ. Low expansion and high conductivity? The ones below the diagonal of Figure 2.7 (another index, this time λ/α, relevant for the design of precision instruments like hard disk drives). The CES EduPack software in its present form does much more than just create charts and plot indices. It allows the entire strategy of Figure 2.4 to be implemented, allowing sequential steps that apply the constraints, rank the survivors and initiate a search for supporting information via a specially created web portal to materials information, using the top-ranked materials designations as search strings (Material Data Network, 2002).

Adding the science

The perspective provided by the charts gives a rationale for introducing the underlying science. Re-examining the first chart, two questions suggest themselves. First, why are the differences in modulus and density (factors between 10 and 10^5) between the properties of different families so great? And second: what can we do about it – could we make a polymer with a modulus like that of a metal or a metal with the density of a polymer? This can open a discussion of the science, using concepts that an engineering student will readily grasp. Atoms differ little in diameter (factor 2 at most) but greatly in weight (factor 10^2): density largely reflects the atomic weight. Bonds between atoms are like springs: the spring stiffness determines the modulus. A table of typical spring stiffness for the common bond-types (covalent, metallic, ionic, hydrogen etc.) and of atomic packing densities is all that is needed for an order-of-magnitude explanation of the differences between families. The impossibility of tampering with atomic weight or bond strength without invoking fission or fusion suggests that little can be done at the atom-scale to change modulus or density. But suppose you *mix* materials – ceramic fibres in a polymer, or

ABS

The material. ABS (Acrylonitrile-butadiene-styrene) is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colours. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.



Typical uses. Safety helmets; camper tops; automotive instrument panels and other interior components; pipe fittings; home-security devices and housings for small appliances; communications equipment; business machines; plumbing hardware; automobile grilles; wheel covers; mirror housings; refrigerator liners; luggage shells.

General properties	
Density	1.0 - 1.1 Mg/m^3
Price	2.1 - 2.3 \$/kg
Mechanical properties	
Young's modulus	1.1 - 2.9 GPa
Tensile strength	27 - 55 MPa
Fracture toughness	1.2 - 4.2 MPa.m$^{1/2}$
Thermal properties	
T-conductivity	0.17 - 0.2 W/m.K
T-expansion	70 - 75 x 10^{-6}/K
Specific heat	1.5 - 1.6 kJ/kg.K

<u>Links to processes</u>

2.8 Part of a record for ABS

space (making a foam) in a metal? These ideas can be sketched onto the chart, giving an idea of where the 'materials' made in this way would lie.

Other charts give both a perspective of other material properties – toughness, electrical conductivity, dielectric constant, and so forth – and enable their discussion in a way that retains throughout the links with design.

Where is CES EduPack now?

We have alluded to the CES EduPack software. It is a tool, one of many, now developed by Granta Design, that arose from the ideas just discussed. The educational software was Granta's first product, so it is interesting to see who now uses it. Mechanical engineering departments dominate, but there are many others: materials science, aeronautical engineering, product engineering and architecture – some 400 in all. Not all have the same priorities: the needs of students of architecture and civil engineering clearly differ from those of aerospace or product design. One direction of development of the CES software today is in developing tools specialised to the needs of each of these, while at the same time refining the system as a whole. Its adoption by a sector of the French school system, and its use in the US in summer 'Materials camps' for school teachers has encouraged work on a version that might meet the needs of high school teaching more broadly.

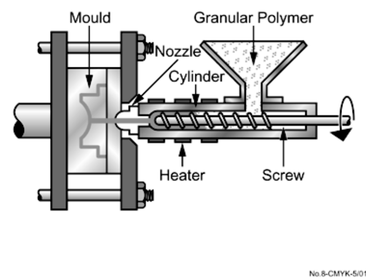
Materials information management in industry

Industry's needs are very different from those of universities. In materials-intensive organisations, such as materials producers and aerospace companies, the objective of the materials 'authority' is to deliver approved in-house data from a central source to engineers across the enterprise. Consequently, the central need for materials software is to manage in-house materials information. This information can be very expensive to gather and maintain and its quality is often mission-critical.

In many organisations, materials information begins its life on a testing machine – either in-house, or increasingly one provided by an external test lab (Figure 2.10). Raw test data, generated and analysed within the laboratories, is consolidated in a single location. This test data is put through various stages of data reduction, model fitting and 'statistical roll-up'. The objective is to generate fully-traceable design 'allowables'. ('Allowables' are statistically-based 'minimum' property values – e.g. the minimum value of strength likely to be found in a sample of the material from a range of sources and batches.) Each data point typically requires testing of tens of test specimens. They can be used

Injection molding

The process. Most small, complex plastic parts you pick up - children's toys, CD cases, telephones - are injection moulded. Injection moulding of thermoplastics is the equivalent of pressure die casting of metals. Molten polymer is injected under high pressure into a cold steel mould. The polymer solidifies under pressure and the moulding is then rejected

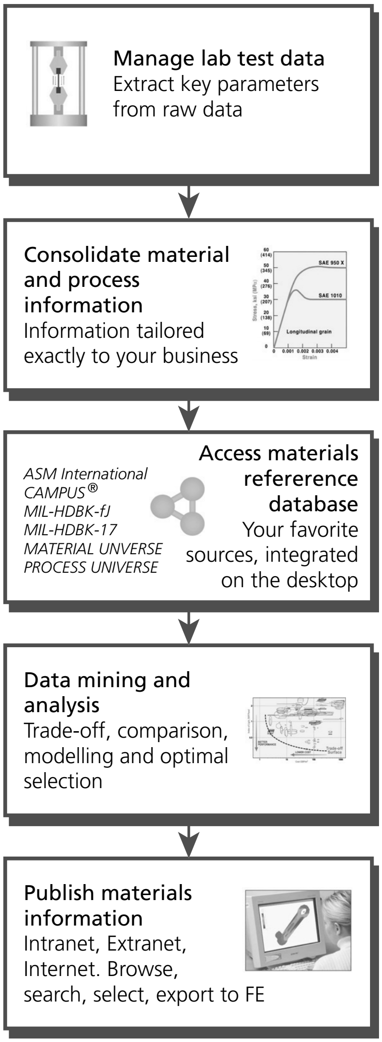


Typical uses. The applications, of great variety, include; housings, containers, covers, knobs, tool handles, plumbing fittings, lenses, etc.

Physical attributes	
Mass range	0.01 - 25 kg
Roughness	0.2 - 1.6 µm
Selection thickness	**0.4 - 6.3 mm**
Tolerance	**0.1 - 1 mm**
Economic attributes	
Economic batch size	10^4 - 10^6
Shapes	
Circular prism	
Non-circular prism	
Solid 3-D	
Hollow 3-D	

Links to material

2.9 Part of a record for injection moulding



2.10 The life of materials information

reliably in (e.g.) FE analysis of a critical component. These property values differ fundamentally from the 'typical' values that are commonly used for materials selection, and stored in the CES EduPack database. This requires specialised scientific data reduction and processing of large volumes of test data, as well as consolidation of records from multiple test conditions (e.g. temperature and strain rate) into single 'functional' descriptions of properties. (For example, characterising a single material for the US Aerospace reference MIL-HDBK-5 (MIL-HDBK-5H-CN1, 2002) typically takes 3 000 tests.) Traceability is key: it is essential to store the raw test data, the material pedigree as well as detailed information about the testing conditions, and to know exactly what processing was performed on the raw data to generate the design values. This processing needs to be performed with a minimum of manual intervention and maximum reliability.

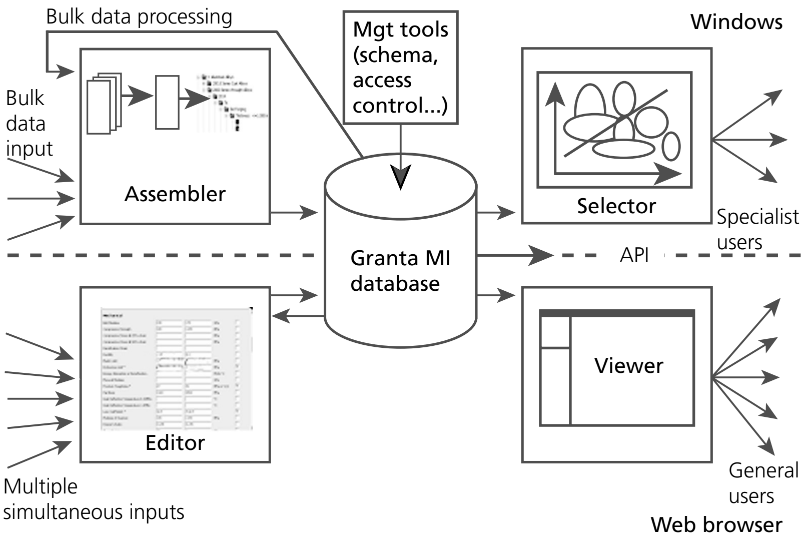
Once in-house design values have been developed, it is often desirable to combine this information with suitable reference information (Figure 2.10). This facilitates comparison of the new material with reference values – e.g. Standards, as well as filling 'holes' in missing data. The resulting data resource can then be opened up to access using a variety of data mining and analysis tools and disseminated to engineers across the enterprise who use the information to design and analyse finished products. In order to do this, the software system must satisfy a number of important requirements. Among these are:

- *Enterprise-wide* deployment. Engineers anywhere around the organisation must be able to add data to the central database and read it from the database simultaneously.
- *Flexibility*. The software must enable complete customisation of the database to allow essentially any data schemas to be represented.
- *Access control*. Rigorous control of read and write access to the data is essential. Some engineers are allowed to enter new test records or perform various kinds of analyses, some can read any data, some can see only approved design data, yet others are not allowed to see classified or export-restricted data. Such access control systems need to be customisable and applicable at the attribute level of the database. This requires powerful administrative tools for handling access control settings.
- *Version control and approval system*. When material data is first generated it is not approved for use in design. After an internal 'sign-off' process, version 1 of data can be approved and released. Of course, in time, the information will be updated, approved and re-released as version 2. This approval and versioning cycle must be handled automatically.

- *Traceability*: It is essential to be able to answer questions such as: "What material data did we use when we designed this component in 1990? How did we derive that information? Did we use best practice at the time? (Or are we negligent in this law suit!)" This requires complete traceability of the data.
- *Referential integrity*: A relational data model is often used to store materials information. In a corporate materials information system, there will be a multitude of links between the data in various tables. A key aspect of maintaining the quality of the data is to manage the integrity of these links. Strict rules need to be enforced to ensure that links are correct and are not inadvertently made, broken or changed.
- *Powerful analysis tools:* It is necessary to provide powerful tools for searching, selection, data analysis, comparison of materials, reporting and export to a wide variety of formats (e.g. for FE analysis codes). Most importantly, the software must be so straightforward to use that engineers are encouraged to centralise their materials data, and not revert to storing personal spreadsheets of material properties.

It is interesting to note that most engineering organisations hardly ever perform *Ab Initio* materials selection of the type discussed above for the educational software. It is very risky to use materials from outside of corporate experience, and there has to be a very strong driving force to make this happen. However, often engineers will perform trade-off studies, comparing a few 'approved' materials for use in a specific application. Materials substitution is also an issue: "can one of our approved materials do this same job more cheaply". The materials selection methodology, originally devised for teaching students about materials selection, has utility here. It can be used equally well for trade-off and substitution studies as for material selection – so the same software system can do both, provided it has suitable source property data.

Granta Design's new 'Granta MI' software suite was built to meet the requirements described above. A schematic of the architecture is shown in Figure 2.11. The software is based on a central web-based database server, which can be accessed both from web browser based applications and from Windows computers. The 'assembler' module is used for automated bulk data processing – lab data input, data consolidation, statistical roll-up etc. 'Editor' is used manually to add and edit individual data items. 'Viewer' is used to view data – to browse, search, select, report and export. It requires little or no training and can be used by engineers and designers throughout the enterprise. 'Selector' is used to perform graphical materials selections and trade-off studies. It is typically used by materials specialists. 'Management tools' is a suite of tools for managing the database – editing its schema, applying access controls, etc. Finally an Application Programming Interface (API) is available so that external software systems (e.g. FE analysis codes) can access the database automatically.



2.11 Architecture of the Granta MI software system

Granta MI is the only tool available to manage the entire material information life cycle. At the time of writing the first version has been released to the Material Data Management Consortium (www.mdmc.net) – a consortium of US Aerospace and Defense organisations that have been involved in its development. It is set for release to the wider aerospace community in Q2 2005, and subsequently to other industry sectors.

Conclusions

The EDC has provided a rich environment in which to work: one that has enabled the connections between the traditional disciplines of engineering science, materials, manufacturing, economics and behavioural science to be developed under the umbrella of design. Two world-first materials design tools – CES EduPack and Granta MI have spun-out of the EDC, making Cambridge University a leading centre of materials information management. Ken Wallace's role as the driving force behind the creation of the EDC is a gigantic achievement.

Acknowledgements

Many colleagues have been generous in discussion, criticism and constructive suggestions that have contributed to CES EduPack and Granta MI over many years. We would particularly like to acknowledge the contributions of Ken Wallace, the staff and students of the Division of Applied Sciences at Harvard University, of staff, post-docs and students at Cambridge, and particularly the members of the EDC and the staff of Granta Design for providing the environment that made this work possible.

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Chapter 3

Some comments on the use of systematic design methods in industry

Herbert Birkhofer
Darmstadt University of Technology

Principally in European countries, systematic design has been elaborated upon since the mid-sixties. The importance of design methods is said to be generally accepted and the use of design methods for creating innovative products is being forced on companies. Amazingly, it was found that systematic design methods – like other design methods – are obviously not wide-spread among industries (Grabowski and Geiger, 1997). Empirical investigations observing designers in industries (Badke-Schaub and Frankenberger, 2004) demonstrate only moderately method-based work as suggested by design methodology. Most often there is a mix of intuitive and experience-based work.

Based on a questionnaire, Gausemeier (1997) claims that holistic methods especially (e.g. QFD) are not applied intensively. Methods which are easier to apply (e.g. creativity methods) are more frequently used. But in truth, the use of these methods is mostly adapted to specific needs and may differ considerably from the published procedure (Birkhofer *et al*., 2002).

The question should be: Why do we still have this situation after nearly 40 years of systematic design research? This chapter attempts to analyse some reasons why systematic design methods are used in practice rather sporadically and often heavily modified. The findings are based on several co-operation projects (Birkhofer, 2004) with about 50 industrial partners over the last 14 years. Some aspects may prove valuable in overcoming barriers to the successful transfer of systematic design methodology in industrial practice.

Design situation in industry

To better understand why design methods are apparently less often implemented in designers' daily work than expected, a detailed look at the working situation in design departments may be informative.

The pressure of daily design work

Design work in most companies can be characterised by various organisational influences, by a multitasking working method, and above all by high time pressure. Customers, as well as management, expect an immediate reaction to new requirements and problems coming up.

In addition, the complexity of products, as well as of design processes, increases. The progress of mechatronics and the trend of companies to become system suppliers contribute to this rise in product complexity. Process complexity increases, as designers have to consider functionality, costs, quality and sustainability of products at the same time. In addition, they have to manage their job within a network of 'shareholders' like marketing, production and purchasing departments and customers as well as suppliers.

Beside the problem of time and heterogeneous design environment there is a severe lack of useful tools, especially for the early phases of design. Designers spend a remarkable amount of time working on the computer. Normally, for embodiment and detailed design they use powerful CAD-systems and simulation tools. In contrast we find only a few software tools for supporting the early phases of product development and designers are forced to awkwardly transfer drafts or sketches to the computer.

Methodical work must meet the design situation

Empirical design analysis (Schneider, 2001) has revealed that designers are frequently forced to make decisions without really knowing their possible consequences. These decisions often depend on the current design situation and are made according to the designers' own experience in using self-acquired and internalised procedures. It seems to be the nature of design work to run a design process quite flexibly according to the actual task, the objectives, and the design environment. Strictly defined design processes (so-called prescriptive processes) based on normative methods are so inflexible and rigid that they meet neither the design situation nor the needs of designers.

Further problems arise when methods are used without recognising their relationship with the current situation designers are actually in. If designers do not properly assess the situation and estimate the benefit of using a method within this situation, they will neither be able to select the suitable method nor to use it successfully. A fully elaborated failure mode and effects analysis (FMEA) might be a totally inappropriate instrument for a quick estimation of a concept's 'pros and cons', but carried out on an embodiment design it may deliver excellent results.

In critical problem-loaded situations even well-trained designers may fail to detect possibilities for the successful use of design methods.

In critical problem-loaded situations even well-trained designers may fail to detect possibilities for the successful use of design methods. Especially under high time pressure, designers often try to proceed as they have in the past in order to avoid mistakes and adhere to the schedule. Hurry on as fast as you can! The only goal must be to get a draft, a sketch on time.

Designers and human behaviour

A key point in understanding designers' work is the awareness that designers are human beings, who do not only act rationally, but are exposed to high emotional pressure within their daily work.

Trust in past experiences

Besides the undisputed benefits of systematic design, we must keep in mind that the majority of excellent products were designed without any explicit use of systematic design methods. And we have to take note that empirical research comparing conventionally and methodically working designers (Günther, 1998) did not provide convincing results demonstrating the advantage of method-based working.

Even designers experienced in using design methods may not recognise their value, because they are not depending on them and succeed without them, using their 'self-acquired toolbox' developed in the past. Müller (1995) sums up this way as the 'standard work style', whereas in critical and unusual situations designers switch to the 'rational working style' and use design methods explicitly.

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The first solution is the best

Many designers like the first solution that comes to mind for a given task because it is usually the most charming one. Having finally generated a solution after all the struggles with a tricky design task seems to be a relief from all the cognitive pain before. Consequently a critical assessment of this first solution is not made and is even consciously neglected. In addition, why should designers present alternative solutions to evoke discussion and criticism? And if the solution later fails or causes severe problems, they may still find a lot of excuses and reasons 'why not'.

The tendency to reduce design risks

Mistakes or shortcomings in a product design will sooner or later become evident and will definitely fall back on the responsible party. For this reason it is understandable that designers tend to prefer tried and true solutions which can be easily adapted to the new task without using sophisticated design methods. However, highly innovative concepts require much more working time and cognitive effort and could cause considerable risks in time, costs and quality.

The dominance of thinking in terms of concrete objects

Using design methods successfully is not only a question of 'how to handle methods'; it also depends on the knowledge of the theory behind the methods. Apparently a lot of designers are lacking fundamental knowledge, like the principles of structuring products, the types of product modelling or the importance of physical effects for product innovation.

The successful use of methods requires a clear concept of product and process models, a linguistic consciousness and the ability to recognise the important and urgent aspects within a component or product (abstraction). For example:

- Drawing up a good requirements list also requires the basic knowledge of how to create good definitions.
- To create a morphological box knowledge is also required about functional concepts, the proper way of functional decomposition and of structuring solutions according to functions.
- Systematic evaluation also needs the knowledge of how to obtain independent criteria and the awareness that the final evaluation result represents no more than a formal addition of individual, elaborated benefits.

Basic requirements to establish methodical work in sustainable design

The following remarks may be seen as an attempt to overcome some difficulties in transferring the systematic design methods mentioned above to industry.

Motivate designers

Forced by the restrictions and requirements of their daily work, designers are demanding key-turn tools and methods that are ready to be used immediately. The benefits of using a design method must be obvious, since while designing there is no time at all to *play* with some abstract proposals on how a design might be done better.

It is a fact that convincing designers of the benefits of using a design method is mostly a matter of showing them impressive results. If the use of a method generates an unexpected concept, which overcomes a competitor's patent and cuts costs in half, then designers logically conclude that the method used to generate these results must also be good. In transferring methodical work in design departments, one can say that surprising and sustainable solutions could act as a Trojan Horse, which motivates even sceptical designers into being interested in a design method. It is the successful solution and not so much the successfully carried out process which is credited to designers and contributes to their esteem within the design department and the company!

Unfortunately the potential for motivating designers to method-based work is limited. During a long-term design project in which the designers involved underwent intensive training in working methodically, an empirical investigation analysed how the methodical know-how increased during the projects (Schneider *et al.*, 2001). The initial sobering result was that only 32% of the designers from the co-operation partners had learned substantial knowledge about the use of methods. Especially designers with a positive attitude (39% of the designers) learned significantly more about the methods used (64%) than designers with a negative or neutral attitude (12%).

Inform designers appropriately

The presentation of design methods varies substantially as to content, style and volume. At the same time, one can see the same method presented by various authors using various terms and contexts. Thus, a designer has to leap that first hurdle to gain access to an appropriate method.

Moreover, the presentation of design methods mostly imparts knowledge, but does not impart the ability to use them properly in an industrial context. Neither abstract descriptions of design methods nor highly formalised procedures with a step-by-step approach will support designers in using methods successfully. Didactic elements such as application-oriented explanations, a reference guide for frequently occurring mistakes, and detailed hints on how to adapt a method to a specific design situation are rarely pointed out.

One can understand the prescriptive nature of most presentations of design methods, as the main target group for paper-based descriptions in literature seems to be the scientific community and not designers in industry. This statement might be validated by the fact that an author's esteem within the science community depends chiefly on citation indices and publication rankings. A practical guidebook for requirement-management or a company-specific manual for FMEA-application that is broadly accepted in a design department has noticeably less glamour within the science community.

As already mentioned, there is a big gap in software tools for systematic design methods which might be integrated in an industrial soft- and hardware environment. The management of requirements, a functional model or a combination of working principles set up in a morphological box is supported only by a few tools, which are often designed for individual use based on standard software like Excel-databases. Due to missing links to other tools used before and after, they normally produce isolated results that cannot be transferred to other tools or databases. For example, there is no known tool which supports all the early phases whose results could be transferred to a widely spread CAD-system!

The successful use of methods requires a clear concept of product and process models, a linguistic consciousness and the ability to recognise the important and urgent aspects within a component or product (abstraction).

Last but not least, speaking of designers as a homogenous class of people is an oversimplification. We have to recognise the many types of designers from the beginner to the expert, from a technical draughtsman to the design manager, from the aircraft specialist to the expert in designing cutting tools. It should not be at all expected that all these designers use the same method description presented in one book. Perhaps the approach of a 'specialised design science' (Birkhofer *et al.*, 1996) may be a step forward in tearing down some information barriers in the future.

Coach designers in their job

Winning over designers for the sustainable use of design methods also requires the intensive involvement of trainers in the current design work.

Standard design seminars cannot normally be adapted to the specific tasks and needs of the participants due to the heterogeneity of the audience. The main objective of such seminars, the transfer of methods, is also hindered by the audiences' effort to understand the design examples, which are often much removed from the designers' background.

Therefore, a problem-oriented way of learning 'on the job' is needed, applying methodical work in the current design situation. An approach to overcoming the barriers in the transfer of methods to industry could be 'transfer-workshops' (Schneider, 2001). In contrast to seminars, the training in transfer-workshops takes up a current design task of the designers involved. The participants work on this problem while being coached by the trainer. The designers are able to use methods while solving a concrete problem in their field of expertise. No transfer from strange product examples is needed and designers can immediately see how methods work in their own environment. One can say that creating and presenting a method like functional decomposition is one task. But quite another and maybe a more challenging task is to get systematic design methods used by designers in industry – continuously and successfully.

Perhaps the approach of a 'specialised design science' may be a step forward in tearing down some information barriers in the future.

On the one hand, transfer-workshops have a high potential to optimise the transfer of design methods in industry. On the other hand, they demand a great effort from the coaches. Managing a transfer-workshop requires not only a methodically experienced trainer but also a person competent in the special field of design. It demands that a trainer has remarkable product knowledge and an understanding of the company's internal processes and its market situation. Otherwise there could be a considerable risk of failure because the trainer does not understand the current design problem and hence cannot contribute to the development of solutions.

Besides the challenge in coaching a design team, the benefit of the methods used is often played down after the first application. New training concepts with a separate unit of reflection on one's own work (Wallmeier, 2001) could support designers in improving their own approach and style of design work.

Promote designers continuously

Education and training of designers alone cannot guarantee the continual use of methods in their daily work. Experience shows that product development projects are not necessarily carried out methodically after designers have visited a seminar or training course, even if the course was considered to be successful. As mentioned earlier, the use of design methods depends strongly on the design situation and on the environment of the company. Three major influences can be seen at work here:

- Organisational embodiment of method-based work in the company, e.g. in a development guideline.
- Attitude of the management and the way they look at method-based work.
- Atmosphere of the company which has to be open for innovations and for promoting project and team work.

Working methodically in product development is not a task given only to designers. It influences the whole development process, as methodically carried out design creates many more documents than only drawings and part-lists. The correct documentation of these documents and their classification within a design framework is a basic requirement for an efficient and effective reuse. It would be inefficient to let things ride on individual documentation and to trust in a knowledge management based on search-machines. A framework of well-classified documents has been proven as a plentiful source for solutions, their advantages and disadvantages, their risks and chances. This kind of knowledge documentation must be demanded by the management throughout the entire company and basically implies a distinct culture of communication and co-operation. It is not only a specific department within the company that a member of staff is responsible for, rather it is the prosperity of the whole company, to which everybody must contribute.

... the use of design methods depends strongly on the design situation and on the environment of the company.

But even prescribing the application of methods 'by law' is no guarantee that designers will attach great importance to them. It may be that designers use methods, but only superficially and formally and without profiting much from them. In order to firmly establish design methods, the support of the management is also needed. Executives have to demonstrate that method-based development is taken seriously. This is extremely important during the phase of change and initial training where mistakes occur. Processes may last longer than before and designers have to be motivated to continue their efforts. Overcoming initial difficulties and problems must not be delegated to designers themselves but must be the continuous responsibility of the design department and the company in total. The management can show their positive attitude towards method-based development by supporting the project manager, stimulating project and teamwork, and participating in meetings, thus emphasising the importance of a methodically carried out development project.

Summary

Teaching and learning design methods strongly depends on the specific situation in which designers are working as well as on their individual behaviour. Experience shows that the wide spread use of design methods cannot be achieved by isolated and uniform seminars. The proper use of methods is not only a question of having access to a description of methods. Experienced trainers with a wealth of work and product-specific knowledge as well as open minded designers, keen to improve their design behaviour, are key factors in the successful transfer of methods. Even if there are powerful software tools, based on a well-defined and modularised concept of contents, the role of the trainer remains an important one. As with internet-based teaching and learning systems, where we find a big potential for imparting knowledge and improving faculties, the most promising approach seems to be the concept of 'guided by experts'.

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Chapter 4

Teaching engineering design research

Lucienne Blessing
University of Technology Berlin

Mogens Myrup Andreasen
Technical University of Denmark

The importance of engineering design as an industrial activity, and the increasingly complex and dynamic context in which it takes place, has led to the wish to improve the effectiveness and efficiency of engineering design in practice as well as in education. Although attempts have been made to improve design for centuries, it was not until well in the second half of the 20th century that engineering design became a research topic (see Pahl and Beitz (1996), Heymann (2004)) for historical overviews). Engineering research, such as research into thermodynamics, mechanics and materials, has a much longer tradition, as can be seen from the establishment of many technical universities in the second half of the 19th century. However, despite 30 years of design research, the field is still not a well-established scientific discipline. Furthermore, the effects on industrial practice and education are far less than expected. According to Suh (1998) "the most significant changes in design practice will occur when the field of design is fully endowed with a firm science base".

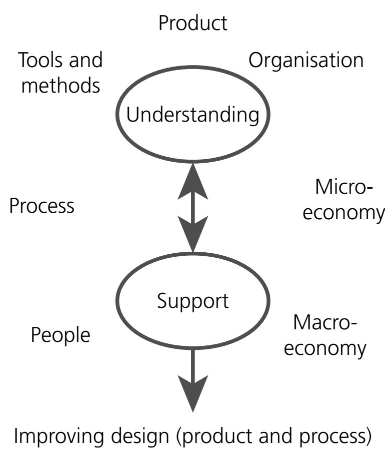
Today, due to the organisation of our universities and the path to a university position, a substantial part of all research effort is created by PhD students. This has created the demand for a clear, efficient way of learning the craftsmanship of doing design research, a demand which is in strong contrast to the state of design research in general.

This article reflects the authors' efforts in running a summer school on engineering design research to support young PhD students.

Design research

The aims of design research differ from many other traditional areas of research. Design research not only aims at the formulation and validation of models and theories about the phenomenon of design, but also the development and validation of knowledge, methods and tools that are founded on these theories, to improve the design process. One of the challenges is that the topic of study, design, is a purposeful, complex and strongly dynamic activity, involving artefacts, people, tools, processes, organisations as well as the micro- and macro-environment in which it takes place. Figure 4.1 illustrates the aims of engineering design research and highlights the various aspects that are involved in design and that therefore should be studied or at least be taken into account in design research. Typical of engineering design research is that usually a combination of factors is studied.

Sadly, although design is one of the fastest growing areas of research, the status of research into its own research methodology is, with a few exceptions, poor. Few publications on design research methodology exist and little is



4.1 Design research aims and aspects involved in design

written in research papers about the methodological issues that are involved. In effect, little guidance exists as to how to do design research, leaving it to the individual to find an efficient, effective and rigorous approach. Many different methods can be, and have been, used to address the various issues involved in design research. Analysing engineering design literature led us to conclude that research is fragmented, rigour is often lacking, the impact on industrial practice is very limited, no clear subsets of research topics exist and the issue of research methodology is not addressed (Andreasen, 2002; Blessing, 2002). According to Cantamessa (2001) "it is no simple matter to define the contents, the research approach or the community behind research in engineering design". The reasons he mentions are the relative youth of the discipline, the involvement of researchers of different disciplinary backgrounds and the fact that there is no specific field of the natural sciences of which it can be viewed as a natural offspring, and from which research methods and tools have been inherited. This makes design research a particular challenge for young researchers.

Design research must be scientific in order for the results to have validity in some generic, practical sense. For this, design research has to develop and validate knowledge systematically. This requires a research methodology. The characteristics of design and the aim of design research, to change the present for the better, require design research to have its own methodology (Blessing, 2002; Blessing and Chakrabarti, 2002).

The need for teaching engineering design research

The status of design research may be described in terms of three related issues, which characterise the situation confronting a design researcher: the lack of an established overview of available research results, the lack of scientific rigour and scientific justification within much of the research, and the sparse use of results in practice (Blessing, 2002). This is the situation in which young researchers have to identify and understand what they are studying, how research should or could be done, and what conclusions can be drawn from the actual research effort.

In an effort to improve this and to support the researchers in this messy situation, the authors have been offering a summer school for several years to make the participants (PhD students) better qualified and equipped for research on topics related to design science, by presenting the latest thoughts and theories; by helping to select a theoretical foundation and develop a research approach; and by encouraging discussion and collaboration.

It was the following questions from PhD students that gave rise to the idea of this summer school:

- How do I make my work scientific and not just a consultancy report or a report of my own learning?
- What are the methods/approaches to be used? How to do empirical research? Is it sufficient to do only theoretical research? How to prove or justify my results?
- How to obtain insight in the state-of-the-art, to find a theoretical foundation and to judge competing contributions?
- How to actually plan my research?

We have found, throughout all the years that we have been running this summer school and have been supervising and examining PhD students, a clear lack of clarity about what constitutes engineering design and how to go about it. None of the universities we are aware of have courses giving an overview of the theories and methodologies in engineering design, nor does an interactive environment for intensive discussions exist. The reason is the usually small number of students involved in engineering design research at any one university. Furthermore, no research methodology specifically for engineering design research exists, leaving it up to the students to adapt approaches from other disciplines.

4.2 Participants at the summer school

Origin and objectives of the summer school

The origins of the summer school date back to 1990, when it used to be a course for PhD students in the Scandinavian countries organised by the second author and financed by NordForsk until 1997. Gradually the course began to attract other European PhD students. Since 1999 the first author has been involved, focusing on research methodology and methods. In 2000, the course duration increased to two full weeks (one in May/June and one in July/August) in different European towns, hosted by local colleagues. The summer school does not receive financing: the fees cover full-board accommodation and handouts. By using down-to-earth accommodation in 'concentrating' surroundings – a monastery (Figure 4.3), sport centres out of season, a castle in the woods – and the support of the local hosts, costs are kept down to a minimum. The objectives are to provide the participants with:

- insight into existing design theories and models to enable them to select a suitable theoretical foundation
- an overview of design research methods to enable the most appropriate approach to be chosen

4.3 Monastery Lichtenthal, Germany, summer school 2004

- an interactive environment in which individual research topics are presented and intensively discussed with the other participants and the lecturers
- the opportunity to get to know and learn from others and develop long-term collaborations.

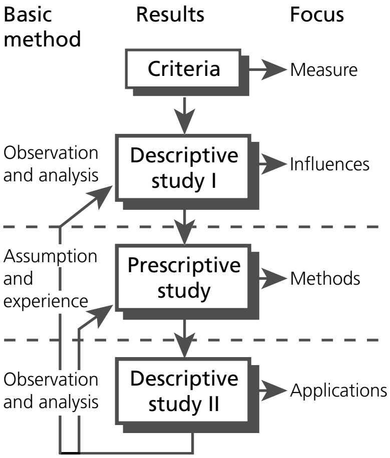
To achieve the objectives, participants are actively engaged in the summer school: the emphasis is as much on providing knowledge as on discussions and exercises based around the research projects of the participants. For this reason, the students need to have finished at least one year of their PhD project.

Topics and approach

The topics that are covered during the summer school can be grouped under the following headings:

- Theories – the nature of theories, modelling, systems theory.
- Design theories – artefact and process modelling, theory of technical systems, design process theory, theory formulation.
- Design research topics – definitions and topics of design research, the use of computers in research.
- Design research contributions – types of results, design schools, methodologies and methods, the phenomena of design, models.
- Design research methodology – types of design research, focusing, planning and executing design research. A backbone is the design research methodology by Blessing and Chakrabarti (2002), the framework of which is shown in Figure 4.4.
- Design research evaluation and communication – evaluating the research process and its outcomes, dissemination of results.

The summer school is kept up-to-date by adding and discussing the latest theories and models as presented by the lecturers, as well as current research issues presented by the participants, hosts and guest speakers.



4.4 Design research methodology framework

Involvement of participants

The summer school is a highly intensive course, building upon the research projects of the participants. Prior to the first week, the participants prepare a short introduction to their research project describing topic, objectives and an outline plan to be presented in Week 1. Before Week 2, the participants use the material of the first week and the comments on their presentations to prepare a poster of their research approach and theoretical foundation for presentation in Week 2. Experience in the last two years showed that many modifications to contents and presentation are made, resulting in a much more focused, realistic and convincing research approach. After the second week, the participants prepare a feedback report for the organisers. A summary of this is returned to the participants.

Nearly every day, discussions are triggered through questions that challenge the students' attitudes towards their own research and to design research in general, in an attempt to encourage a questioning approach and more scientific rigour. Examples of these questions are: What is research? What is engineering design research? What do you believe are important research questions in engineering design? Do the questions have to be important (for mankind, for me, for whom), can they not *just* be challenging and interesting? Why do you think your approach is scientific? Literature from which domains is useful for your topic, and to which domain will you contribute? The participants also discuss their own work in pairs or small groups, forcing them to develop a critical, questioning approach and to be able to explain and summarise their work. An additional result for non-native English speakers is the considerable improvement of their command of the English language.

What we as teachers learned

Meeting with 20 or more PhD students every year and discussing their research, their views, their worries and experiencing their excitement about the things they learn – in particular from each other – confirms our view of the current situation in design research, and that of others, such as Cantamessa (2001), Horvath (2001) and Samuel (2001). As described earlier, structure, contribution, coherence and research methodology are rather poor: the design research area shows fractioning and islanding and there is no tradition for highlighting valuable theoretical contributions. Partially this is due to the relative youth of design science, but it also highlights the need for consolidation, building a theoretical foundation and establishing a research methodology (Blessing, 2002).

Concerning the students' research and the way the research subject is treated, we and the other teachers observe the following problems (Andreasen, 2002):

- Some of the students have no 'ticket of admission': they do not know about design practice and/or they (and their department) have no focused theoretical insight.
- Many projects are impossibly broad or multiple in their goals: it takes numerous rounds of cut-down to make them feasible and many questions and hypotheses cannot be answered or justified with the chosen research methods.

- Students are often not able to articulate arguments for the research questions and hypotheses.
- Many projects have no proper formulation of the metrics, which makes the verification soft or false, or makes the conclusions false.
- The students (and the department) do not know state-of-the-art in research results.

We can also observe that the concept of a PhD-thesis has very different interpretations, covering a large variety of contents. Often engineering and research are confused, leading to consultancy reports and engineering reasoning. Some schools do not expect a chapter about scientific approach and the conclusions do not reflect on contribution or validity. Other schools have very high demands on a thesis, two or more supervisors and several reviewers are involved and the work is evaluated for scientific rigour. Unfortunately, students have a tendency to follow their department's patterns and traditions without questioning whether these are appropriate for the given topic. Illustrations are often sparse and examples are not given, because 'they are not proofs'. In other cases, the examples are too simple to convince.

The discussions that take place during the summer school weeks and the questions the students ask inevitably lead us to become involved in supervision activities. Although our suggestions may not be in line with the supervisors' goals and approaches – we know of research that has fundamentally changed – conflicts have not been reported. Our colleagues continue to allow their students to attend the summer school and offer to host one of the weeks.

As teachers we have gradually become conscious of our own agenda, which is:

- to contribute to the development of the paradigms for design research
- to understand the nature of multi-disciplinary and multi-theoretical research and advise how to manage it
- to influence the design society's research agenda and endeavour to raise the rigour of researching and create consolidation
- and last but not least, to bring inspiration for our home-research.

Reactions of the participants

After the last week of the summer school, students are asked to write a short report reflecting not only on the summer school's content and organisation, but also on how they experienced and were affected by the summer school. The quotations confirm our observations:

- "There are inevitably points and issues that need to be questioned and answered during the course of my research and yet, taking the easier option, have always been set aside to be answered when either the answers appear or are given. However, the course has forced our specific research questions upon our heads and forced me to awaken and at least start the process off explicitly so that my focus becomes more directed and refined at an earlier stage during the course of my PhD."
- "Knowing that I am not alone with common research problems and how to go about addressing and solving them is supportive."
- "It is interesting to see how many projects have a similar content but very different approaches, and seeing this will help you open your mind and maybe to get a different angle to your own project."
- "What triggered me to apply for the course, was that I have been confused about my focus (research questions), validity and methodology. I hoped that I would get at better focus on these subjects and as well that I would be in a forum where there would be a lot of discussion about design and development. … I got what I came for."
- "I changed my approach after the course (more rigour, focus, use of literature, start writing now)"
- "I have self-confidence now and I can structure my research"
- "Now I know that creating something is 'not science'; the reasoning must be scientific"
- "I thought I could be original by not reading the literature …"
- The students find the summer school 'hard', they express the need for breaks, for sport and walking, as well as time for reflection. Many students get tired from daylong thinking and talking in English. But overall they enjoy the intensity of it and at the end ask "Give us a third week after half a year".


4.5 Time to relax and reflect

These statements and a paper about the summer school written by two former participants Flanagan and Jänsch (2004) show how the students get some of their needs satisfied, and absorb and utilise the insight and skill obtained from the summer school. Furthermore, a working group has been established by former participants, who focus on design methodology. In a recent two-day meeting, each PhD project was presented and discussed. Then the group discussed the various issues that still needed addressing and how each of the research projects could proceed. A second workshop will follow. These are the type of development that we hoped for and we allow ourselves to conclude that the summer school reinforces the students' craftsmanship in design research, their research approach and their communication and networking.

Conclusions

Design research can be considered to have passed through three overlapping phases: experiential, intellectual and experimental (Wallace and Blessing, 2000), but in all phases, a theoretical framework has been largely missing. This fact, together with a fast growing number of researchers, has led to increasing concerns about the efficiency of design research and the effectiveness of its outcome. No overview of research results exists, most results never find their way into practice, either directly or indirectly, and research is often lacking the required rigour. One of the main focus points in the near future has to be the improvement of our research. Only then may we enter the next phase in design research: the theoretical phase (Blessing, 2002).

On the basis of the discussions we had with the PhD students and from their feedback reports, we conclude that the summer school supports this development by:

- broadening the students' view and developing their ability to argue and present their research
- creating awareness of consciousness about the craftsmanship of research and training in the core methods
- supplying the student with a network for discussion, co-operation (joint articles) and friendship, as well as a more international view by providing insight into the different European university and PhD systems.

This, however, is not the only reason for us to continue organising and teaching at this summer school. Nor is it the fact that every year we learn much from the PhD students and are being forced to sharpen our thoughts and improve our teaching material. Our main driving force is the tremendous joy of being allowed to spend two weeks discussing design research with an international group of intelligent, enthusiastic, critical young researchers.

Acknowledgements

Our thanks go to Prof. Dr.-Ing. Christian Weber and Dr.-Ing. Ralf Lossack for their continuous support and involvement, and to all other people who have enriched the summer school with interesting lectures. Also thanks to the students for being so engaged and for teaching us so much, as well as to those colleagues who have hosted the summer school and given the participants great experiences. And finally thanks to the supervisors, who shared confidence in our teaching, even if it raised disturbing ideas in the mind of the researchers.

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Chapter 5
Some thoughts on definition, influences and measures for design creativity

Amaresh Chakrabarti
Indian Institute of Science, Bangalore

Creativity is an essential element in designing. Definitions of creativity, however, are multiple and varied, and factors influencing creativity myriad and various. Moreover, the definition, the influences and their measures are not linked in a systematic way. Consequently, metrics for estimating creative potential of agents or methods are few and only as sound as the theories on which they are based. The goal of this chapter is to provide a broad and quick overview of work in this area and analyse it to speculate on what should be reasonable as the:

1. essential aspects of a creative idea or solution
2. essential factors influencing development of creative ideas or solutions
3. relationships between these factors and conventional measures of creativity
4. metric for evaluating methods for their potential in supporting creativity.

Characteristics of a creative idea or solution

Literature has seen multiple attempts at qualifying and quantifying the main characteristics of a creative idea. Many authors take novelty as the sole essential characteristic of a creative idea, e.g. Newell, Shaw and Simon (1962; cited by Davis, 1999) who argue that creativity appears simply to be a special class of psychological activity characterised by novelty; or for Rhodes (1961; cited by Davis, 1999) "creativity... is a noun naming the phenomenon in which a person communicates a new concept".

Contrary to these, many other authors argue that an idea must have novelty as well as some sense of appropriateness, value or social worth (Davis, 1999) for it to be considered creative. For instance, Perkins (1988; cited by Davis, 1999) states that a "creative person by definition ... more or less regularly produces outcomes in one or more fields that appear both original and appropriate." Hennessey and Amabile (1988; cited by Davis, 1999) argue that "to be considered creative, a product or response must be novel... as well as appropriate." In earlier papers we defined creative outcomes as new as well as interesting (Chakrabarti, 1998).

The specific proposal made in this chapter is that for an idea to be creative it ought to be novel, purposeful and resource-effective. This is more of a summary of others' work; the only claim to novelty is in clarifying the characteristics that should constitute what is 'appropriate' or 'interesting'. The definitions of these are:

- Novelty – degree of difference from other existing ideas (the higher the better).

- Purposefulness – degree of satisfaction of the task, or solution of the problem (the higher the better).
- Resource-effectiveness – amount of resources used (the less the better).

A novel idea becomes creative in one of the following cases:

- It is as purposeful and resource-effective as existing ideas (enabling competition with protected ideas).
- It is more purposeful than but equally resource-effective as existing ideas.
- It is equally purposeful as yet more resource-effective than existing ideas.
- It is both more purposeful and more resource-effective than existing ideas.

Illustrative examples explaining novelty, purposefulness and resource-effectiveness

The following three sets of examples explain primarily these three aspects of a creative solution:

Examples of novelty: tunnelling accelerometer and SMA key ring. While existing concepts of accelerometers are based on principles of capacitance, inductance and resistance, this new accelerometer is based on a tunnelling effect in the way the movement of a mass in response to acceleration is electrically sensed; it also has comparable performance characteristics to the existing accelerometers (Chakrabarti *et al.*, 1997). As another example, take the concept of a key ring made of shape memory alloys; when heated to its transition temperature it would assume its 'memorised' shape, thereby allowing keys to be inserted.

Examples of purposefulness: adjustable steering column and brush with soap filled handle. In both these cases, the concepts are not only novel, but also more purposeful. An adjustable steering column (Terninko *et al.*, 1998) can be used by users of a wider range of dimensions than a single size steering column. A brush with a handle for filling with soap supports scrubbing as well as dispensing of the soap during scrubbing. Both utilise similar amounts of resources to those used by their competing concepts.

Examples of resource-effectiveness: engine 'nose' concept, acid tester concept. The first example is from Ken Wallace (1990). The pointed front 'nose' of some Rolls-Royce engines acts as a nucleus for snow and subsequent ice formation that leads to breakage of the ice and pitting of the surface of the turbine blades. The common and not so resource-effective solution to this problem is to heat the 'nose' continuously. A more creative solution is to consider the 'nose' as a separate element, periodically wiggled by a motor, so that snow has no time to become ice but breaks away with no harm to the engine blades. In the acid tester concept (Terninko *et al.*, 1998), a common problem for an acid bath in which material specimens are dipped for a given time to measure their susceptibility to corrosion by the acid is the corrosion of the bath walls. Common solutions to the problem are replacing the bath or repairing its surface – neither is resource-effective. Another solution to this problem is shaping the specimen as a small bath in which to pour acid, thereby eliminating the use of the acid bath altogether – a far more resource-effective solution!

Similar ideas of choice of the simplest (interpreted here as more resource-effective) among competing proposals have often been an unwritten rule followed in many natural science disciplines. Occam's razor (by William of Occam, a 14th century logician, circa 1300–1349 AD) is one such rule: "Given two competing solutions to the same problem, the simpler one is the better".

... ideas of choice of the simplest (interpreted here as more resource-effective) among competing proposals have often been an unwritten rule followed in many natural science disciplines.

Sometimes purposefulness is implied within the concept of novelty – a proof is no proof if it does not prove the point in question, and a solution is not one unless it solves the problem. In such cases, the characteristic of purposefulness should focus on whether the task accomplished by the novel concept is done better than or in addition to what already is done by the current one.

Essential factors influencing creativity

A wide variety of factors are cited in literature as influencing creativity. Rhodes (1961) grouped over 50 definitions of creativity into four Ps: product, people, process and press, the product characteristics being influenced by the characteristics of the other Ps. Afterwards, various authors identified various factors related to each of these Ps, for example strong motivation (people), incubation (process), or relaxed work environment (press).

Rhodes (1961) grouped over 50 definitions of creativity into four Ps: product, people, process and press, the product characteristics being influenced by the characteristics of the other Ps.

Several authors describe creativity as a special kind of information or knowledge processing (e.g. McKim, 1980), and argue that information or knowledge must be a prime ingredient for creativity. For instance, Gluck (1985) sees as essential the possession of tremendous amount of raw information, as does Read (1955; cited by Davis, 1999) who describes this as 'scraps of knowledge' in describing creative people who "juggle scraps of knowledge until they fall into new and more useful patterns". Note the act of juggling in this description – one proposed to be described here by the generic name of 'flexibility'. Also note the mention of 'new' and 'valuable' patterns – the two aspects of creative outcomes. Various authors have also stressed the importance of flexibly processing knowledge. McKim (1980) speaks of flexibility in levels, vehicles and operations, and argues that seamless use of and transfer between these are important in creative thinking. Gluck (1985) describes as essential

We propose knowledge, flexibility and motivation ... as the three factors essential for creative thinking.

in creativity the ability to combine, order or connect information. In C-K theory (Hatchuel *et al.*, 2004), the authors distinguish two different kinds of creative ideas: those that are dominated by knowledge requirement, and those that operate within existing knowledge but require imagination for conception. We interpret the first category as primarily requiring new knowledge while the second primarily requires flexibility of thinking. In TRIZ (Terninko *et al.*, 1998), children are described as capable of connecting all ideas to each other, while commonly adults connect only a few – that too in the existing ways. In the light of flexibility and knowledge requirement for creativity, children can be interpreted as having great flexibility in thinking with little knowledge of the constraints among them, whit adults having far less flexibility with far more knowledge. In the four stage model of the creative process by Wallas (1926; cited by Davis, 1999), the first stage – preparation – is interpreted here as accumulation of knowledge, the 'scraps' as described by Read (1955). The second stage – incubation – is one of transferring the task to the hand of the subconscious, a sign of flexibility (McKim, 1980). The third stage – illumination – is when these two come together to create the idea, and the fourth – verification – is where the ideas are verified. Note that 'mental blocks' (Adams, 1993) are blocks against using knowledge in a flexible way.

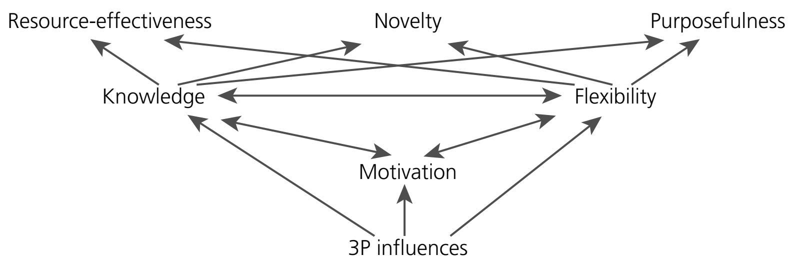
We propose knowledge, flexibility and motivation (*i.e.* encompassing all motivational factors and indicators such as challenge, energy-level, single-mindedness and aggression) as the three factors essential for creative thinking. McKim has spoken of similar factors for 'productive thinking' – information, flexibility and challenge. Perkins (1988, cited by Davis, 1999) describes creative people as motivated, having creative patterns of deployment or personal manoeuvres of thought (both of which are interpreted here as flexibility) and having raw ability in a discipline (seen here as knowledge). Echoing similar notions, Torrance (1979; cited by Fox and Fox, 2000) argued that 'prime factors' in the creativity of people are their abilities, skills and motivation. The specific ideas proposed here in this regard are the following:

- Motivation, knowledge and flexibility are the broad, primary factors influencing creativity.
- The factors are not independent of each other. Knowledge influences motivation, motivation may lead to acquiring of new knowledge; flexibility leads to development of new knowledge that may lead to more flexibility; motivation to utilise knowledge in a flexible way may lead to further flexibility leading to more motivation, etc. This idea of interdependence of factors is influenced by Lewis's (1981) model of influences on intelligence

in children. Lewis sees intelligence as the ability to see and solve problems – at a broad level, not very different from designing. In his model, motivation, self-image and attitude are all linked to a child's problem-handling skills, and vice-versa.

- Among these factors knowledge and flexibility are the ones that directly affect the outcome of a creative problem solving process, motivation assuming an indirect influence. Other factors from the categories of people, process and press influence one of these factors, which in turn influence the novelty, purposefulness and resource-effectiveness of the product. This proposed model of influences is shown in Figure 5.1.

Sometimes it is difficult to see the influence of knowledge as separate from that of flexibility. An instance where their separation is quite clear is the acid tester example – no additional domain- or solution-specific knowledge not already provided in the current product is necessary for creating the novel 'specimen as bath' concept – as long as the current knowledge is processed in a flexible way!

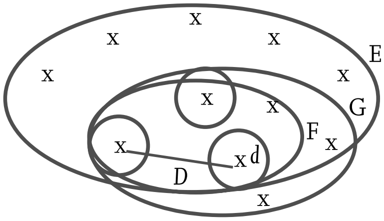


5.1 Proposed model of influences

Relationships between knowledge/flexibility and some conventional measures of creativity

Some relatively common conventional measures of creativity are: originality, fluency, novelty and quality (Shah *et al*., 2003). Originality and fluency are concepts popularised by Torrance (1979) to measure creative effectiveness of the outcomes. Originality of a set of ideas is measured by the variety of the ideas produced, *i.e.* how different the ideas are from one another. Fluency is measured by the number of ideas generated. Novelty is measured by how unusual or unexpected an idea is as compared to other ideas (Shah *et al*., 2003). Quality is the feasibility of an idea and how close it comes to meet the design requirements. How do these metrics relate to the two major influences identified here – knowledge and flexibility?

As a first attempt at doing this, we make some assumptions. The first assumption is – flexibility can be deployed only around (or from) known



5.2 Existing (E), familiar (F) and generated (G) solution spaces

or familiar ideas; knowledge of these ideas provides the nuclei around which flexibility can create new ideas. The second assumption is, the existing solutions familiar to the creative agent are the most directly influencing pieces of knowledge around which flexibility can be deployed. In a graphical sense (Figure 5.2), let E be the entire space of existing concepts for solving a given problem, and F be the concept space within E that is familiar to the agent.

Let each cross in space E or F represent a concept or idea for solving the given problem, the distance shown between them representing the degree of difference between these ideas. The longer the distance, the more different the ideas are from each other. Let the number of ideas in F be n, and the average distance between two ideas in F be D. Now, let the agent create an average of k ideas around each concept, the conceptual dissimilarity between these being given by an average diameter d around each familiar concept. Let the new set of ideas generated by the agent be represented by G. Assuming that originality is measured by the spread of ideas in the concept space generated, and taking the average largest distance possible between ideas in two clusters as a measure of this, originality of the agent generating G is:

$$\text{Originality} = f(D, d) \qquad \ldots 1$$

Intuitively, originality should be more when both D and d are more; one possible expression for function f is $f(D, d) = D+d$. Fluency of the agent, in terms of number of ideas generated in set G, is given by

$$\text{Fluency} = g(k, n) \qquad \ldots 2$$

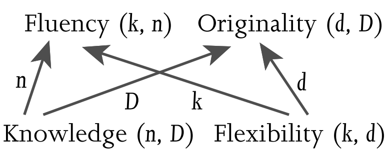
Intuitively, fluency should be more when both k and n are more; one possible expression for function g is: $g(k, n) = k.\, n$. Since knowledge necessary to generate these ideas was given by F, knowledge could be represented as a function of the number and spread of ideas in F, where knowledge is more when both n and D are larger:

$$\text{Knowledge} = h(n, D) \qquad \ldots 3$$

Flexibility could be represented by the average number and spread of ideas possible to be generated by the agent around each existing idea familiar to the agent, and should be more if both k and d are larger:

$$\text{Flexibility} = q(k, d) \qquad \ldots 4$$

If these are now put together into a relationship diagram (Figure 5.3), it can be said that both knowledge and flexibility influence both fluency and originality of the agent. However, the aspects of influence are quite different: while the number components of both knowledge and flexibility are likely to influence fluency, their spread components together are likely to influence originality. Novelty and quality of ideas are, however, relative to the set of ideas in E:



5.3 Relationships between knowledge, flexibility, fluency and originality

novelty is the difference between the new ideas and the existing ideas, while quality is the difference in their purposefulness and resource-effectiveness.

Evaluating creative impact of methods

Knowledge and flexibility – the two major direct influences on creativity – could be used to intuitively explain where the major impacts of a creativity method could be. For instance, brainstorming should primarily influence flexibility of idea generation, though it indirectly provides some knowledge by being a group method and by displaying the knowledge created. However, the method does not help clarify or solve a problem for more purposefulness or resource-effectiveness. Hence, while it may help develop ideas with novelty, these have no more than a statistical chance of being purposeful or resource effective.

Contrast this with synectics – another group ideation method (Prince, 1970). In this, several steps are used to first clarify the problem, and then systematically generate ideas analogically connected to it, and eventually use these ideas to solve it. Apart from some degree of help in clarifying the problem, solving it focuses on finding solutions to particular aspects of the problem, and it is likely to provide more novel and yet purposeful or economical solutions rather than merely associative ideas as in brainstorming. Here too, knowledge is primarily provided by the group, while flexibility comes from the method.

Take yet another case – using 'contradiction method' for solving problems in TRIZ (Terninko *et al.*, 1998). It is an approach for developing alternative formulations of the problem, providing support to flexibility in clarifying the purposefulness of a problem, followed by use of contradiction tables, which provide both knowledge and flexibility in resolving contradictions in the problem. The result is a space of concepts that are novel and purposeful. A further illustrative case is 'ideal design' approach in TRIZ – supporting the ideal definition of the problem (*i.e.* solving the problem with no resources!), and gradually compromising to the extent necessary to find a close-to-ideal solution. Here, the primary focus is on finding novel and resource-effective solutions, and the method provides knowledge and flexibility for solving such problems.

How can we categorise these intuitive evaluations into a common, overall evaluation framework? We propose to do this by putting together three areas of evaluation: 1) A creativity enhancement support might be useful in exploring the problem or generating solutions, since both these have a bearing on the eventual necessary creative value of the solution. 2) A support may be helpful in enhancing flexibility or knowledge. 3) A support may enhance novelty, purposefulness, or resource-effectiveness. Putting these three aspects together, we have an evaluation matrix (Table 5.4). Within this matrix, we could now place a given support by highlighting the areas of its likely influence, and the relative strength of these influences; it is an extension of the matrix proposed in Chakrabarti (2003). We assume here that the influence of all creativity methods has the goal of finally providing either flexibility or knowledge in exploring problems or generating solutions for novelty, purposefulness or resource-effectiveness. Creative synthesis agents must provide both in some form or other.

5.4 Creativity evaluation matrix

	Novelty		Purposefulness		Resource-effectiveness	
	Problem	Solution	Problem	Solution	Problem	Solution
Knowledge	...	...	...	...	...	...
Flexibility	...	...	...	...	...	...

Conclusions

The thoughts reported here are largely speculative; many are based on analysis of product cases and findings by other creativity researchers. The main points proposed are:

- A creative idea or solution has three related aspects: novelty, purposefulness and resource-effectiveness. Novelty is only important in as far as it impacts the other two aspects.
- Creativity has three mutually related major influences: knowledge, flexibility and motivation. Only knowledge and flexibility are direct major influences. All other influences found by researchers influence these two directly or indirectly (e.g. by influencing motivation).
- Knowledge and flexibility are linked to fluency and originality in specific ways such that both influence both fluency and originality.
- An evaluation matrix is proposed for positioning the influences of a creativity support in terms of whether it affects problem or solution generation by enhancing flexibility or knowledge necessary so as to influence novelty, purposefulness or resource-effectiveness of the solutions generated.
- Creativity methods are taken here as divergent methods that assist in finding problems or solutions.

- Since flexibility also requires knowledge of how to be flexible, an issue is how this knowledge is distinct from what is considered 'knowledge' here. Our position is: flexibility requires knowledge that is generic and guides change in a domain- and solution-neutral way, while 'knowledge' is largely domain- and solution-specific.
- With further development of this understanding of creativity, it might be possible to clarify, for instance, why creative style differs from creative effectiveness (Kirton, 1994), or how to measure 'individual' and 'social' creativity.

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Chapter 6
Inclusive design

John Clarkson
University of Cambridge

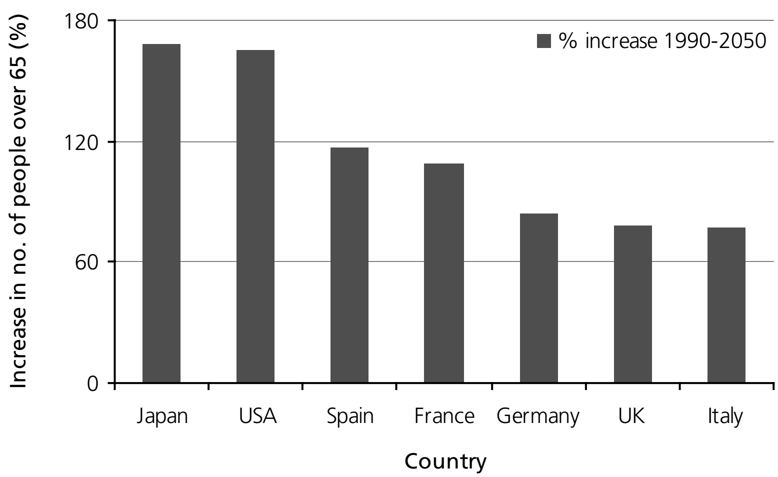
I thought it appropriate, given Ken Wallace's contribution to the first published part of British Standard BS7000 – Guide to managing product design, that a chapter in this book should reflect on the most recently published part of the same standard, BS7000-6:2005 Design management systems – managing inclusive design (BSI, 2005).

Part 6 of the standard was written as a direct consequence of an ongoing research initiative between the Helen Hamlyn Research Centre (HHRC) at the Royal College of Art, the Cambridge Engineering Design Centre (EDC) and the Design Council. The research aims to provide business decision makers and designers with the tools required to design more inclusive products.

The EDC remains the only engineering group researching in the area of inclusive design and has made a significant contribution to this emerging research field, building on earlier work on rehabilitation engineering initiated by Ken Wallace. Much of this success has been the direct result of the support provided by the EDC in nurturing new research in this area.

Background

Studies show that by 2021, half the adult population in the UK will be over 50 (Coleman, 1993) and that similar trends are observable elsewhere (Figure 6.1). Such ageing populations are known to exhibit an increasing divergence in physical capabilities (Clarkson and Keates, 2003), where in general the population becomes less capable. At the same time, the products that we use each day seem to become ever more complex, making increasing demands of their users.



6.1 Worldwide population trends

The principles of Universal Design
1 Equitable use
2 Flexibility in use
3 Simple and intuitive
4 Perceptible information
5 Tolerance of error
6 Low physical effort
7 Size and space for approach and use

6.2 Universal design

For example, a mobile phone demands that its users can read the legends on its keys. If the size of the keys is reduced, with a corresponding reduction in legend size, to meet a marketing need for a smaller, lighter phone, then the demand made on the users' visual capabilities is increased. When such demands exceed the capabilities of the user, then the user will find it difficult or, at worst, impossible to use the product, thus leading to exclusion. Hence, as populations age and users' capabilities fall, it becomes increasingly necessary for products to support a wider range of physical capabilities (Cooper, 1999).

Legislation such as the UK 1995 Disability Discrimination Act (DDA, 1995), the US 1990 Americans with Disabilities Act (ADA, 1990), and Section 508 of the US 1998 Workforce Investment Act (WIA, 1998) also provide a case for designing for the widest possible population.

Whilst a vast amount of literature exists in the area of human factors and ergonomics (for example, Norman, 1988; Nielsen, 1993; Green and Jordan, 1999), little mention is made of the full range of potential user capabilities. Most design approaches deal only with the 'average' user. Even anthropometrics, which seek to describe the full range of users, often succeeds only in encouraging design to the 90th percentile, hence excluding less able, or 'extreme', users.

There are, however, a number of design approaches that are targeted at specific population groups or impairment types. For example, transgenerational design (Pirkl, 1993) focuses on design for the elderly, while rehabilitation design (Hewer *et al.*, 1995) focuses on specific impairment types. Universal design (Figure 6.2) dominates the US and Japanese approaches to inclusive design (Bowe, 2000), whereas Europe has tended to develop other methods, such as the user pyramid (Benktzon, 1993) (Figure 6.3). When combined, the existing approaches can offer complete coverage of the population needs. However, such an approach is not easy (Clarkson and Keates, 2003).

Design exclusion

Inclusive design is a process whereby designers, manufacturers and service providers ensure that their products and environments address the widest possible audience, irrespective of age or ability. It aims to include the needs of people who are currently excluded or marginalised by mainstream design practices and links directly to the concept of an inclusive society.

One of the steps to ensuring that designs are as inclusive as possible is to provide metrics for defining the level of inclusivity attained for a given product. However, while it is useful to know who and how many can use

6.3 The user pyramid

the product, that information will not provide guidance on how to include more. Conversely, knowing who and how many people cannot use the product and why they cannot do so immediately highlights the aspects of the product that need to be improved. This forms the basis of an exclusion audit. For example, if a product excludes a significant proportion of the population because the users either cannot hear or cannot see the output from the product, then designers know to re-design the features involved in providing the output to the users.

The underlying principle of the exclusion audit is that by identifying the capability demands placed upon the user by the features of the product, it is possible to establish the users who cannot use the product irrespective of the cause of their functional impairment. Consequently, by re-designing the product to lessen the demand, users from a wider range of user groups can potentially be included. Levels of exclusion can be estimated if the prevelance of capabiliy within the user population is known.

The underlying principle of exclusion is that by identifying the capability demands placed upon the user by the features of the product, it is possible to establish the users who cannot use the product

User data

In order to identify populations who can (or cannot) use products there is a need to assemble relevant data describing prospective users. Fortunately, there are many sources of such data available, each tailored for different purposes, including, for example, descriptions of:

- physical characteristics – the size (and strength) of the user
- socio-economic studies – the educational/social background of the user
- disability data – what the user cannot do
- capability data – what the user can do
- medical conditions – the health of the user
- longitudinal studies – the variation of health/abilities of the user with time
- market surveys – the likes or dislikes of the user.

Any, or indeed all, such data may be relevant to product design and much of it is certainly related. However, in terms of understanding whether users are physically excluded from using a particular product, the disability/capability and physical data are more important. Indeed, anthropometric data provides the predominant source of physical data used in product design, allowing designers to knowingly accommodate users within extremes of physical size.

Such data is usually assembled from a variety of sources with no single group of users providing all the data. The data can also be age related, as is the case with data available in the UK for children (Norris and Wilson, 1995), adults (Peebles and Norris, 1998) and older adults (Smith *et al.*, 2000).

In order to identify populations who can (or cannot) use products there is a need to identify relevant data describing prospective users

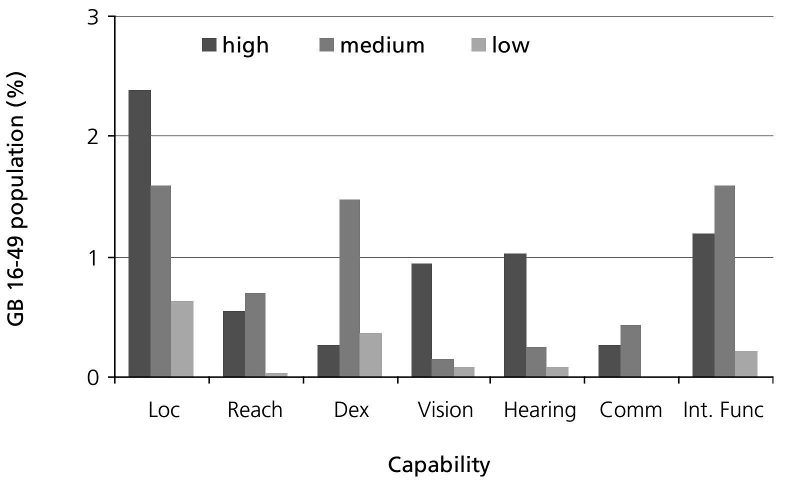
The prevalence of capability losses

The Survey of disability in Great Britain (Martin *et al.*, 1988) and the Disability follow-up (Grindy *et al.*, 1999) to the 1996/97 Family resources survey (Semmence *et al.*, 1998) aimed to provide up-to-date information about the number of disabled people in Britain and their domestic circumstances. The purpose of the surveys was to provide information to allow the planning of welfare benefits and services provision.

The results showed that an estimated 8 582 200 adults in Great Britain – 20% of the adult population – had a disability according to the definition used. Of these 34% had mild levels of impairment, 45% had moderate impairment and 21% had severe impairment. It was also found that 48% of the disabled population were aged 65 or older and 29% were aged 75 years or more.

The surveys identified 13 different types of disabilities based on those described in the International classification of impairments, disabilities, and handicaps (WHO, 2001) and gave estimates of the prevalence of each. They showed that musculo-skeletal complaints, most notably arthritis, were the most commonly cited causes of disability among adults living in private households. Ear complaints, eye complaints and diseases of the circulatory system were also common. For those living in communal establishments, cognitive complaints, particularly senile dementia, were mentioned most often, followed by musculo-skeletal (arthritis) and nervous system (strokes) conditions.

For the purposes of product assessment, seven of the 13 capabilities identified by the surveys are of particular relevance. These may be grouped



6.4 Capabilites for GB 16-49 population

into three overall capability categories:

- motion – locomotion, reaching and stretching, and dexterity
- sensory – seeing and hearing
- cognitive – communication and intellectual functioning.

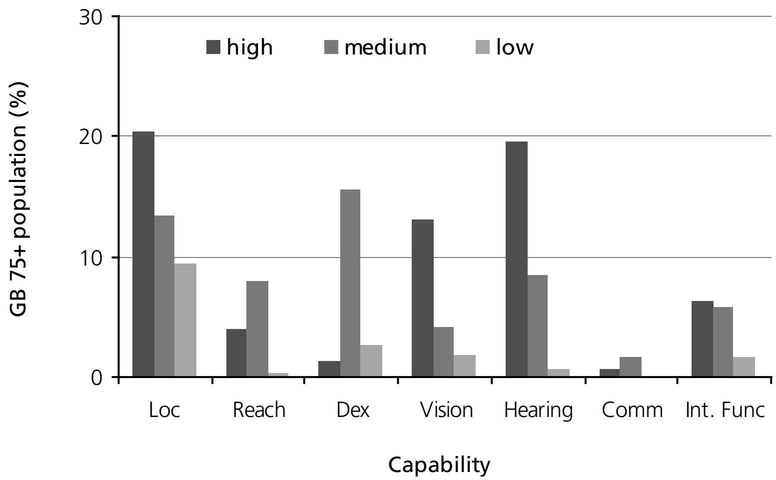
A summary of the capability data is presented in Figures 6.4 and 6.5 for the 16-49 years old and 75+ populations. Perhaps the most striking feature is the order of magnitude difference in the scales used for each figure. While the graphs have similar distributions, the percentage of those with a loss of capability in the 75+ age band is 10 times higher than for the 16-49 band.

The analysis of capability data generates useful information for designing for a wider range of user capabilities. However, multiple capability losses present particular challenges for designers and if their importance is to be fully appreciated, comparable capability data is essential. Again, the capability data, taken from a single sample, are able to provide some insights in this area.

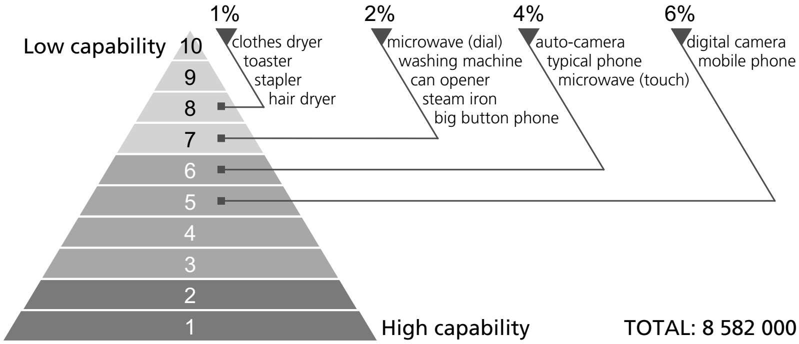
Case-studies of design exclusion

A range of domestic products have been assessed to quantify typical levels of design exclusion. In each case, the demands made by the product were estimated using the seven capability scales; an overall demand was calculated as a weighted sum of the three highest demands and the number of users unable to meet the demands was evaluated, taking account of multiple capability losses. The results are shown in Figure 6.6 superimposed on a pyramid.

The product demands are divided into ten levels, with the lowest band (1) corresponding to the highest capability demand and the top level (10)



6.5 Capabilites for GB 75+ population



6.6 Product demands and exclusion for those over 15 in Great Britain

to the lowest. Different shading is applied to differentiate high user capability (score 1-2); moderate capability (score 3-6); and low capability (score 7-10). The whole user pyramid represents 8 582 200 adults with functional impairments. The percentages shown represent exclusion in Great Britain for those over 15 years of age.

The kettle

A typical 1.7 litre stainless-steel kettle is shown in Figure 6.7. Assuming that the kettle is positioned to suit the height and mobility of the user, the basic actions required are: to pick up the kettle; carry it to the nearby water tap; fill the kettle with water; return it to its base; switch it on; and pour the boiling water into a cup. A level of user exclusion can then be calculated by assessing the levels of each of the functional capabilities required to undertake these actions and estimating the number of users unable to meet these demands (Table 6.9). In Great Britain 5.3% of those over 15 would not be able to use such a kettle.

One could argue that the predominant purpose of a kettle is to provide hot water for making drinks and, in that context, an ideal kettle might be one that is no more difficult to use than drinking from a cup. The target population for an ideal kettle could therefore be all those users who can safely drink from a cup full of hot drink.

Further analysis shows that those excluded from this task number less than 500 000 for those over 15 in Great Britain (Table 6.9). In fact, the results suggest that there are over two million people in Great Britain who can drink from a cup, but are unable to use a typical metal 1.7 litre kettle to boil water. An inclusively designed kettle (Figure 6.8) has the potential to include many of those excluded by the heavier metal kettle (Table 6.9). However, at the time of writing, such a product is not available.

6.7 A typical 1.7 litre stainless- steel kettle

6.8 A more inclusive kettle

Digital television

Digital terrestrial television (DTV) equipment and services are significantly different from their current analogue counterparts, often using a separate set-top box with its own, additional, remote control (Figure 6.10). Based on an assessment of current equipment undertaken for the UK Department of Trade and Industry, two million people in Great Britain (4.4% of those able to access analogue television) could be excluded from viewing the new digital services using digital television set-top boxes.

A further 700 000 people (1.6% of those able to access analogue television) would be excluded from using advanced features such as digital text and interactive services. This problem is compounded by the fact that providers of different parts of the system (television, set-top box, interactive television services and digital teletext) all use different interaction approaches.

The integration of the set-top box electronics with the television (iDTV) provides the means to solve a part of the first problem, but much effort is required to co-ordinate the design of the whole system to ensure that the new digital technology remains at least as accessible as analogue television.

Kettle	Total excluded (%)	(people)
Typical	5.3	2 506 000
Inclusive	2.6	1 229 000
Ideal	1.0	486 000

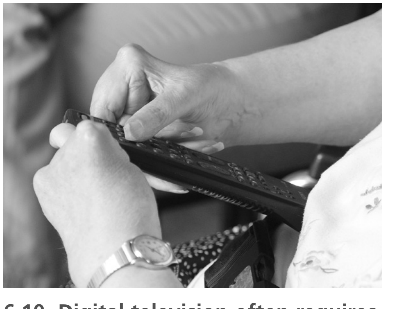
6.9 Total exclusion for the GB 16+ population

Countering design exclusion

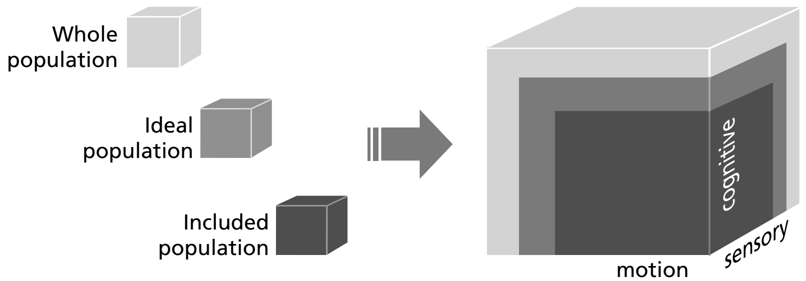
Assessing capability demands is only a part of a larger process required to counter design exclusion. There is a need for a range of tools and techniques to help designers and design managers with this task. The inclusive design cube (Figure 6.11) was proposed to assist in the visualisation of the scale of exclusion and the resultant design task (Keates and Clarkson, 2003). The axes represent motion, sensory and cognitive capabilities. Hence, the cube conveys a sense of the overall level of exclusion and some indication as to its source.

The concept of an exclusion audit has also been developed to combine the exclusion analysis described above with an expert analysis of the product interaction process and trials with actual users. This approach has proved to be particularly successful if the users involved in the trials are 'boundary' users, *i.e.* those who are right on the limit of being able to use the product. However, there remains a need to develop the means to train the expert assessors and provide guidance on the selection of suitable users for the trials.

In addition, trials of the exclusion audit have highlighted the shortcomings of the existing user data and research is underway to develop a new database specifically for use in inclusive design that would integrate the capability and anthropometrics-based views of the user.



6.10 Digital television often requires the use of a second remote control



6.11 The Inclusive design cube

Conclusions

Product design has the potential to exclude users, a fact that is sadly all too prevalent in an age of increasing technological advancement. The current generation of mobile phones, for example, includes more features than the previous generation and as a result is potentialy much more difficult to use.

Recent research has also shown that exclusion is also no longer the preserve of those with reduced capability. A recent US-wide web-based survey by Philips (2004) of 1 501 Internet users, aged 18-75+ concluded that "two-out-of-three Americans report having lost interest in a technology product because it seemed 'too complex to set up or operate'," and that "only 13% of the American public believes that in general 'technology products are easy to use'."

A further US-wide survey by Microsoft (2003) of 15 477 working-age adults and computer users asked questions about levels of difficulty with ordinary daily tasks (such as reading newspaper print and using the telephone) as well as direct questions about impairments and their impact on employment. Their findings show that the majority of working-age adults are likely to benefit from the use of more accessible technology.

It appears that the principles of inclusive design have the potential to significantly advantage the able-bodied as well as less able users. Contrary to many universal design and design for all approaches, inclusive design incorporates a description of user capability that does not configure an 'average' user or specify 'one product for all', rather it promotes a more acute awareness of design exclusion and the impact of product development decisions on levels of exclusion.

The publication of BS7000-6:2005 and a recent initiative by the DTI to promote awareness of inclusive design is ensuring that this new focus on accessibility will, in time, become part of everyday design practice. Already there are signs that this research is having a significant impact on UK industry and on product users worldwide.

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Chapter 7

Perspectives on knowledge management in design

Steve Culley and Chris McMahon
University of Bath

The word knowledge is used a great deal today in an industrial context. Politicians stress the importance of the knowledge-driven economy, especially from the perspective of the global economy. Engineers suggest that the way companies use their knowledge is a key factor in determining competitiveness. For example, Dieter Frank, Head of Research at BMW, noted in a keynote address at the ICED'99 "Knowledge is the resource of the 21st century . . . those with advanced knowledge management will also be market leaders" (Frank, 1999).

Knowledge management (KM) is particularly important in engineering design for a number of reasons. Economies have developed from dependence on "a lot of material held together by a little bit of knowledge" to "a lot of intellectual content in a physical slipcase" (Stewart, 1997). With this transformation from primarily industrially based societies to those more reliant on the exploitation and use of accumulated knowledge the productivity of the 'knowledge worker' has become a crucial issue (Drucker, 1993). Creating and sharing knowledge is essential to fostering innovation, and is the key challenge of the knowledge-based economy (Chan Kim and Mauborgne, 2003).

The importance of knowledge management is reflected in the interest displayed by the research community. At the ICED'99 about 20% of papers were primarily about information and knowledge management (McMahon and Culley, 2000). In 2001 knowledge and information management was one of the key topics of the conference, and the topics have been widely discussed at other conferences worldwide (e.g. Benson and Terpenny, 2001).

The term knowledge management encompasses a very wide range of issues. It has come to be associated in particular with a number of computing techniques, but it is much broader than just sophisticated information technology. A key distinction is between a 'commodity view' and a 'community view' of knowledge (Stenmark, 2002). The commodity view considers knowledge as an artefact which can be collected, and managed. The community view, by contrast, considers that it is impossible to define knowledge universally, suggesting that it can only be defined in practice, in the activities of and interactions between individuals. We propose (McMahon *et al.*, 2004) that both views are important in the context of design, and that Hansen *et al.*'s (1999) distinction between 'codification' – the careful capture and storage of knowledge in data stores of various types – and 'personalisation' – knowledge sharing through people and teams – is particularly pertinent in design. Codification corresponds to the commodity view of knowledge, and personalisation corresponds to the community view. We suggest that both are needed in design, but that the relative balance between the two approaches depends on the application context: small and *ad hoc* teams need informal means, based on personalisation, to work together on deliverables, share information, locate necessary expertise and communicate progress with one another. Large work-groups with more structured and formal processes require different knowledge management systems in which codification is more important.

In this chapter we build upon the distinction between codification and personalisation with three perspectives on knowledge management in design. In the first we present a reflection on patterns of design knowledge and an associated typology, which is considered in the context of the codification-personalisation axis. In the second we expand upon the notion of codification by exploring the knowledge classes that are likely to be required, in this case for a design automation system. Finally, we reflect on how design heuristics and knowledge may be captured and make a case for the exploitation of automated approaches.

Patterns of design knowledge

The nature of engineering product development within modern organisations has altered dramatically over the last few decades as products have become more complex and as engineering has become widely geographically distributed. In the automotive and aerospace industries a little over a generation ago design teams would reside on a single site and would deal principally with local suppliers and, often, local customers. Today, the teams may be distributed through multiple countries, as will the suppliers and customers.

The knowledge embedded in a modern product has also grown dramatically in only a short time. The knowledge needed to achieve state of the art performance of a modern aircraft, automobile, computer or suspension bridge (coming from for example internal and external sources and internal research and development (R&D)) demands engineering teams that may number many thousands, and the effective operation of these teams is critical for engineering success.

Through the design and associated development processes, engineering communities learn about the characteristics of the artefacts that they have designed, how they match the goals of those who use them, the nature of their form and structure, and how they interact with their environment. They learn also how to predict and assess various product characteristics at the design stage, and what to test and measure in development and prototype test stages.

Individuals in the communities develop specialist skills and knowledge to allow assessments to be made in the various scenarios chosen as examples above. This knowledge, and the information on which it is based, is always incomplete and uncertain, and so the community together seeks new or improved knowledge and information to fill the gaps, to reduce uncertainty and to develop new understanding. In the next section the knowledge and information that is developed by the designing communities will be characterised.

A typology of design knowledge

Many categorisations of knowledge have been proposed, and a number are particularly apposite in the context of design. Ryle (1949) distinguished between two different types of knowledge – 'know how' and 'know that'. He noted that learning about a subject primarily involves the accumulation of 'know that' – principally data, facts and information. Learning about, however, does not produce the ability to put 'know that' into practical use (*i.e.* knowledge as some type of competence notion). This, he argued, calls for 'know how', which does not come through the accumulation of information. Learning how to do something can only be carried out in practice, which explains why the same information (a manual, book, verbal instructions, etc.) directed at different people (with different backgrounds and experiences) does not result in the same knowledge in each – practice and context shapes the assimilation of information by individuals. To explain this, Polanyi (1966) was the first to distinguish between the 'explicit' and the 'tacit' dimensions of knowledge. He suggests that human beings acquire knowledge by actively creating and organising their own experiences – "we can know more than we can tell". In making the distinction between the tacit and explicit dimensions, he argues that no amount of explicit knowledge can provide individuals with the tacit (and trying to reduce one to another is not possible). This resembles Ryle's view that 'know that' does not produce 'know how'. These arguments suggest that information is not enough, on its own, to produce actionable knowledge.

We can see similar distinction in Blackler's (1995) typology of knowledge shown in Table 7.1 with additions by the authors (McMahon *et al*., 2002). In the context of design, it is suggested that encoded knowledge describes that knowledge and information recorded in books, manuals, codes of practice, specifications and so on, together with recorded information concerning materials, manufacturing processes, machine elements and other components and so on.

The reports, catalogues and other documents in a company's document archives constitute 'encoded knowledge'.

'Embedded knowledge' is concerned with knowledge and information about the processes used in design – for example the processes of design analysis and assessment and the formal processes of interaction between the participants in the process. These may be documented in codes of practice, design guides and the like, but they will also be embedded in the collective memory of the members of the design community. Encoded and embedded knowledge are both explicit knowledge in Polyani's terms.

'Embrained knowledge' by contrast describes the implicit or tacit ability of people to work with complex ideas and concepts, and in the context of design may describe the ability to process complex interactions and trade-offs – the ability to build a holistic view on the artefact.

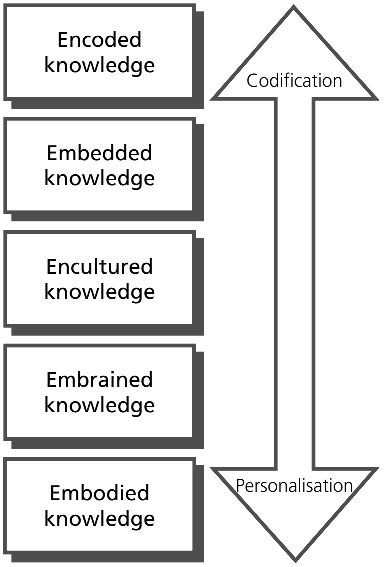
'Embodied knowledge' is also in general tacit (although some of the efforts of artificial intelligence seek to make it explicit) and describes the general problem-solving approaches and attitudes of mind found in design. Embodied knowledge also allows the community to know the limits of its knowledge and where it breaks down.

Knowledge type	Knowledge dimension	Definition	Example
Embedded knowledge	Explicit	Systematic routines, procedures and practices	Company documents on design procedures and sign-off
Encoded knowledge	Explicit	Knowledge represented by signs and symbols in books, manuals and recorded works	Engineering text book on the principles of aerodynamics
Encultured knowledge	A combination of the two	Knowledge from the process of achieving shared understanding	Personal log-book of experience on design project
Embrained knowledge	Tacit	"Knowledge about" - the ability to work with complex ideas and concepts	Personal experience of a variety of design projects
Embodied knowledge	Tacit	"Knowledge how" - practical thinking; problem solving	Personal ability to plan and execute a design project

7.1 A typology of design knowledge. Adapted by permission of Sage Publications Ltd. from Blackler F. © Sage Publications, 1995

Finally, 'encultured knowledge' may describe the implicit 'shared memory' (Konda *et al.*, 1992) that exists in the design community of practice concerning the shared beliefs and values of the community.

In terms of the distinction between codification and personalisation, codification strategies clearly involve encoded knowledge. They also involve embedded and encultured knowledge to the extent that these two aspects are recorded within an organisation, although they are predominantly concerned with personalisation. Embrained and embodied knowledge are primarily the result of, and nurtured by, strategies of personalisation. In Figure 7.2 the knowledge types are mapped onto the personalisation-codification axis.



7.2 Knowledge types mapped onto a codification-personalisation axis

An example of codification – a design system for conceptual design

Design is an example of the kind of complex and ill-defined task that requires intelligence to perform successfully. It involves the translation of some abstract statement of need into the description of a concrete artefact or plan that meets that need. The key to performing a design task successfully is the proper application of correct knowledge. Execution of a particular design task requires the organisation of and access to particular knowledge as dictated by that task. This section considers in more detail the knowledge involved in the design process by exploring the knowledge needed in a design system to support machine configuration design.

Codification can involve the organisation of design knowledge in order to make it accessible to designers, but it can also involve the embedding of knowledge into design systems developed for the purpose of automating design. Since, for many domains, conceptual design is the most difficult stage, most benefit would be gained from its successful automation. We list below the knowledge classes used in design systems for machine design and for fluid power systems as discussed in Kota and Lee (1993a, b) and on issues associated with populating these classes. The five knowledge classes are based on the knowledge classification scheme proposed in Schreiber *et al.* (1994) and Wielinga and Schreiber (1997) and have been used in a configuration system in Potter *et al.* (2003). It is useful to devise such classifications because the knowledge for complex tasks cannot be assumed to be of some uniform nature – classifying the knowledge into groups displaying similar traits or performing similar functions in the task can assist in the process of precisely identifying the knowledge that must be represented, and can suggest schemes for its representation.

Knowledge classes

'Domain knowledge' class contains knowledge of the entities which constitute the domain. For configuration design, this group includes knowledge of:

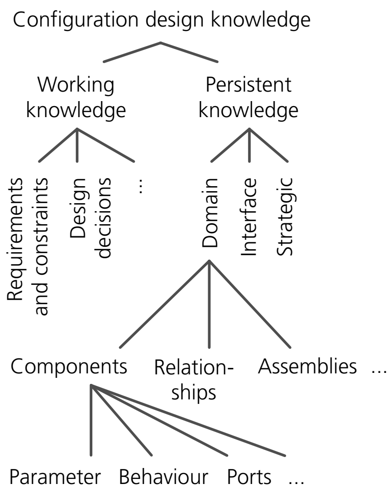
- The physical elements (and their behaviours) which may constitute a solution.
- How these elements can be combined.
- How groups of related elements (up to and including the system level) behave, component parameters, and so on.
- A description of the design requirements that the system understands. This category would seem to consist primarily of declarative knowledge – these elements correspond in some way to the external evidence of the design task.

'Inference knowledge' is 'reasoning knowledge' that allows an abstract element of a design to be made 'more concrete' according to the requirements specified, the intermediate abstractions already formed, design choices made elsewhere.

'Strategic knowledge' is knowledge of how elements of inference knowledge can be arranged and controlled so as to provide a complete strategy for producing a design. This amounts to a set of high level methodologies for controlling the search for mappings from requirements to solutions. This is procedural knowledge of the design process.

'Working knowledge' is unique for each design episode and contains the specific requirements, design choices made, knowledge of the reasons for the modifications to a design, feedback from the customer about the application of the designed system, etc. This category represents a 'pool' of knowledge about the current design process, from which elements may be retrieved when they are necessary for invoking or applying elements from the other categories of knowledge.

'Common-sense knowledge' is in addition to the above. This category includes knowledge which is not specific to the domain of the task in hand, but which, nevertheless, is brought to bear on the current process. For example, it contains the basic deductive, inductive and abductive reasoning 'rules', experiential knowledge of the world we inhabit (e.g., gravitational effects) and so on. The structure and content of this type of knowledge are open research issues.



7.3 The hierarchical relationships of design knowledge. Adapted from Wielinga and Schreiber, Configuration-design problem solving, IEEE Expert Magazine. © 1997 IEEE

Figure 7.3 shows the static relationships between the first four classes of knowledge and Figure 7.4 shows the relationships between the categories that exist in a design system. These categories are still quite loosely defined, and will vary from domain to domain, and may even vary within a domain when, say, different design strategies are applied, so this description cannot be considered as a generative definition for a design system. However, all these categories *must* be embodied and recognisable in some form within such a system, and as such, they offer some measure of the completeness of any proposed system.

Heuristic knowledge

Another view on knowledge in this area comes from Coyne *et al.* (1990). They suggest that the range of design knowledge covers such things as laws, rules, and formulae pertaining to the behaviour of people, materials, objects and spaces. Knowledge may be axiomatic and unequivocal, or casual and more approximate in nature. It can represent different levels of control during the design process, knowledge about "appropriate actions to perform in producing configurations, and knowledge about strategies". To produce intelligent design systems, they say, it is necessary to "be able to represent and manipulate knowledge of this kind".

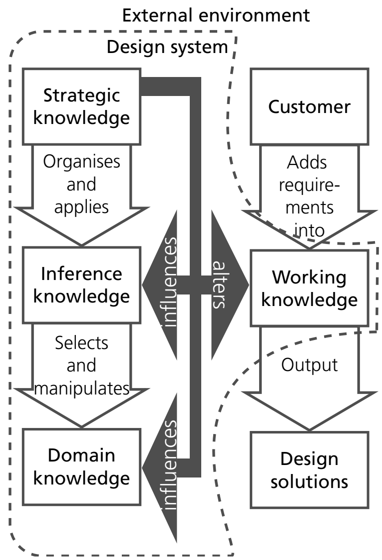
The knowledge employed during conceptual design, and in particular, that knowledge used to synthesise design solutions has some special characteristics. The synthesis of solutions rarely follows an explicit algorithm; rather, solutions seem to be generated through the application of 'heuristic' knowledge. According to Fox (1996) heuristic knowledge is that which:

> *expresses rules of thumb, which is not guaranteed to be precise or correct, but nevertheless useful when …the field lacks a comprehensive body of theory and most practical knowledge is empirical.*

Clancey (1986) says:

> *A heuristic relation is uncertain, based on assumptions of typicality, and is sometimes just a poorly understood correlation. A heuristic is often empirical, deriving from problem-solving experience; heuristics correspond to …'rules of thumb'...*

In order to automate the conceptual design stage, then, it would seem to be necessary to capture this heuristic knowledge in some manner and incorporate it within a computer system.



7.4 The relationship between the knowledge categories during the design process

The capture of heuristic knowledge

The final perspective is the issue of capturing knowledge so that it may be codified and made available for access or use in whatever situation is appropriate. This section will reflect on capturing heuristic knowledge as this is what is particularly used in the emerging knowledge based engineering (KBE) systems.

Buchanan and Shortliffe (1984) identify three ways by which knowledge (in general) may be acquired for intelligent computer systems:

- *Handcrafting* – human experts at the task in question also have the ability to code their knowledge directly
- *Knowledge engineering* – knowledge engineers work with human experts to acquire and organise the required knowledge
- *Machine learning* – the system automatically acquires knowledge.

In general, handcrafting can be discounted for the acquisition of design synthesis heuristics, since a domain expert with the right combination of skills is unlikely to be found, and an unreasonable amount of time would be necessary for an AI practitioner to acquire the necessary expertise in the task. This leaves two approaches – knowledge engineering and machine learning.

The majority of approaches to the automation of design have relied on knowledge engineering to acquire this knowledge (e.g. McDermott, 1982). Knowledge engineering is the extraction of useful knowledge from domain experts (Winston, 1993). A number of techniques have been developed or adopted to assist in this task; these include interviews, protocol analysis (Ericsson and Simon, 1984) and a number of domain-structuring methods adopted from psychological research.

On the whole, however, these techniques are extremely time-consuming. If an elicitation session is to be exploited to its fullest, a great deal of preparation must be made by the knowledge engineers. Typically, they will have to become familiar with the domain and, to a certain extent, with the task itself in order to control the acquisition process. Furthermore, once the interaction with the expert has been completed, there still remains the laborious and difficult task of transcribing and analysing all that has been said and done, extracting from this the appropriate knowledge, and then deciding how this may best be represented and encoded within the system. Quinlan (1986) remarks that, given typical rates of acquiring knowledge in this manner, "it is obvious that [this] approach to knowledge acquisition cannot keep pace with the burgeoning demand for [intelligent] systems …"

However, the problems with knowledge engineering run deeper. As Winston (1993) observes, "knowledge engineering is an art, and some people become more skilled at it than do others". In other words, the time and effort of the knowledge engineer may not, by themselves, be sufficient.

Another essential ingredient in every case is a willing and able expert – and, for one reason or another, such an expert might not be available. Furthermore, as Gillies (1996) observes:

> *… in some cases, the experts may simply not know how they perform their skilled task, even though they perform it very well. In such cases, [knowledge engineering techniques] will have no success in producing a knowledge base for the computer to use.*

This knowledge of how to perform the task is precisely that heuristic knowledge of the sort required for conceptual design synthesis. This inability to articulate heuristics has also been documented by others (e.g. Berry, 1987; Hart, 1988) and raises doubts about the accuracy of all heuristic knowledge acquired in this fashion: the heuristics that the experts supply may reflect how they think the task ought to be performed, rather than how they actually do it. The difficulties encountered are known collectively as the 'knowledge bottleneck' in intelligent system development (Lenat, 1983). It should be evident that this bottleneck imposes serious limitations, both practical and theoretical, on the development of systems in this fashion, although more recent approaches such as the MOKA methodology (Stokes, 2001) are improving the situation because they cover all the elements of the process in a rigorous and procedural manner.

So, with the knowledge engineering approach being far from satisfactory, attention turns to the third suggested approach, that of machine learning (ML), as a possible source of design heuristics. As Reich and Fenves (1989) remark, the use of ML 'has the potential of alleviating the knowledge acquisition bottleneck'. This realisation has stimulated research into ML in the past (e.g. the work of Michie (1982) and Lenat (1983)). The critical consideration is that, if design synthesis heuristics could be acquired automatically from examples of their application in specific design episodes, this would reduce, or even remove, the need to 'knowledge engineer' the heuristics.

Inductive machine learning algorithms

Inductive algorithms operate using a set of training data, consisting of a number of examples of some concept. If the learning is supervised, an example comprises an input pattern and a corresponding output pattern: the learning task is one of inferring the relationship that holds between the two. If the learning is unsupervised, an example consists of an input pattern alone: the task is to search for the relationships implicit in the data.

In general, each example is expressed in terms of the values that it possesses for each of a number of attributes that serve to describe the problem. Since the task of learning knowledge may be viewed as one of recognising consistent relationships amongst these attributes, given the current state of machine learning technologies this is only possible if the attributes are themselves described consistently. Consequently, each example must be described using these attributes, and their values, in a consistent manner.

Successful inductive learning algorithms must be able to generalise appropriately over their training data. It would not be acceptable, for example, simply to produce a look-up table of the example inputs and their corresponding outputs: this involves no learning beyond memorisation by rote, and would not be able to respond to new examples which lie outside the training data. However, the algorithm alone does not determine the quality of a learned generalisation; a number of other factors also have a strong bearing on this. For instance:

- the training data must be truly representative of the problem
- the training data must be of sufficiently high quality – errors in the data can hamper, or even prevent, learning
- the problem must be described using an appropriate set of attributes and it must be 'learnable', in that consistent relationships do indeed exist amongst the attributes.

Conclusions

The combination of large and distributed teams, high intellectual content, product complexity and risk has led to a significant emphasis on knowledge management in engineering design. Approaches to knowledge management include those that are largely concerned with the human capital of an organisation – the personalisation approaches – and those concerned with the capture and organisation of knowledge – the codification approaches. This article has considered a typology of knowledge types in engineering design, and has mapped these into the personalisation/ codification classification. It has also examined in more detail the design knowledge that may be incorporated into a design system for the support and even automation of conceptual design. These considerations show that design knowledge support is characterised both by the range of approaches that are required and also by the breadth of classes of design knowledge topics that need to be considered.

Just as the calculator and computer free the engineer from much of the difficulty and drudgery of calculation, so we must look to information management systems to do the same for information access, and thus to allow the engineer to concentrate on interpretation of the trends and patterns shown in the information. As the knowledge in a domain becomes more complete and more thoroughly formalised, it may be embedded in systems for the complete automation of aspects of the design. Most design tools, however, will provide support to the human designer rather than take over his or her role.

It is not possible to reflect on knowledge management in design without the consideration of designers' tacit knowledge. There are problems associated with an organisation (or indeed an individual) being over reliant on tacit knowledge. This is largely associated with the way it is disseminated verbally in social environments (e.g. over cups of coffee or 'around the water-cooler'). Tacit knowledge is not only difficult to communicate (and prone to being modified in that communication) but might be wrong or have been superseded – it tends to become stubborn and locally entrenched (Stewart, 1997). To counter this we need a systematic approach to human-centred knowledge management based on a continual re-examination of the core beliefs and assumptions in a domain, and supported by careful examination of patterns and trends in the underlying information (perhaps ultimately supported by routine use of data mining). This is emphasised by Drucker (1993) in noting the need to develop methodologies that allow the conversion of "…*ad hoc* experience into system … anecdotes into information, and skill into something that can be taught and learned".

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Chapter 8

Design process and performance

Alex Duffy
University of Strathclyde

The nature of designing has evolved over the decades encompassing different eras from craft based, 'design by drawing', system designing, and design as a socio-technical activity (Jones, 1979). We are generating and carrying out a considerable amount of effort upon design but do we apply what we have learned to design the design process? This notion is not new. Jones (1979) described 'designing designing' as:

> *the conscious direction of part of one's activity and energy, while designing, into the meta-process of designing the process of design. At any one point one should be aware of 'what you are doing' and 'why'.*

The focus of Jones's proposition is upon individual designers being more aware and creating their design process as they are designing, that is, real-time design of the design process. The work at the University of Strathclyde builds on this basic idea by taking a broader and more proactive, tactical, operational and strategic approach than just focussing upon the activity of designing. That is, 'designing design' for process improvement.

This chapter presents ongoing work being carried out at the University of Strathclyde to model, manage, control and improve the design development process. Design co-ordination was the impetus and foundation upon which much of the work was developed and has illustrated savings of over 50% reduction in process execution time, the identification of a lack of resources (two electrical engineers) with 28% reduction in process time, and in team modelling a 45% resource cost reduction and over 50% time reduction (Coates, 2001). The fundamental aspects of performance, efficiency and effectiveness, are discussed along with the distinction between goals, activities and tasks. The need for NEAT measures, 3B targets and SMART performance objectives is then outlined. A fundamental model of a design activity is described that defines the relationship between the activity of design and its management. This forms the basis to determine and design the behaviour in order to meet the processes' functional and performance requirements. The chapter then provides an overview of some of the activities being carried out to improve the design process. Craft, parametric performance and process optimisation approaches are outlined to illustrate the need for continual improvement.

Performance analysis

Although there is widespread use of efficiency and effectiveness to describe performance there are a variety of interpretations of these terms when applied in design and development. Efficiency (η) and effectiveness (Π) are fundamental elements of performance that may be used to fully describe the phenomenon. That is:

$$\text{Design Performance} \equiv \text{Efficiency } (\eta) \text{ and Effectiveness } (\Pi)$$

The E^2 model has been defined to clearly formalise the phenomenon of design performance and allow efficiency and effectiveness to be distinguished and related (Duffy and O'Donnell, 1998; O'Donnell and Duffy, 2005). Efficiency is related to input, output and resources, while effectiveness is determined by the relationship between output and goal(s). That is, the degree to which the result (output) meets the goal may be described as the activity's effectiveness.

In practice a variety of metrics are used to determine efficiency, reflecting different aspects of the input, output or resource knowledge. For example, the cost of using a designer within an activity may be measured to reflect the amount of financial resource used in utilising this knowledge source. Efficiency of an activity is considered here to exist irrespective of whether it is measured or not, *i.e.* it is an inherent property of the activity. The selection and application of metrics to determine efficiency allow particular views of efficiency to be created, e.g. cost or time based efficiency. That is, the determination of efficiency facilitates the measurement of an activity's performance effectiveness.

Relating efficiency and effectiveness

Efficiency and effectiveness focus on related, yet contrasting performance elements. The efficiency is inherent in the behaviour of a particular activity/resource combination. It may be measured without any knowledge of the activity goals, although the goals may influence the behaviour of resources used in the activity and consequently the level of efficiency that results from their use.

Efficiency is related to input, output and resources, while effectiveness is determined by the relationship between output and goal(s).

Effectiveness, in contrast, cannot be measured without specific knowledge of the activity goals. As is the case in measuring efficiency, the measurement of effectiveness involves the analysis of the activity output (O). However, effectiveness is obtained through analysing a specific element of the output knowledge, *i.e.* that which relates to the goal(s) of the activity.

In certain cases there exists a direct relationship between effectiveness and efficiency. This relationship exists when the specific element of the output knowledge, which is evaluated to establish effectiveness, also describes an element of the resource used.

NEAT measures, 3B targets and SMART objectives

Having a basis such as E^2 to model the elements of performance still requires appropriate measures (or metrics) to be defined, targets set and performance objectives determined. The initial steps in improving process performance are to determine the activity goals, define appropriate metrics, determine their corresponding measures (the actual data used to populate the metrics), gather data, specify targets and set objectives.

Measures are the only means to tell if performance is improving or not.

Measures are the only means to tell if performance is improving or not. Metrics and their corresponding measures (metric values) should reflect the defined efficiency and effectiveness requirements. Metrics can be considered as three basic types:

- Accumulative: individual, e.g. cost, time. For example, the accumulative cost of particular activities e.g. total cost = Activity A cost (£2k) + Activity B cost (£4k) + ….
- Derived: calculated, e.g. cost of non-conformity in quality. For instance, an activity cost goal is impacted by the duration of the activity, the desired level of quality and the level of complexity associated with the product; e.g. activity cost = $2t \times (2.3Q \times 0.5C)^2$.
- Independent: direct input, for example, number of x. That is, where the value is directly measured from data and can be used in other metric types.

Metrics should also be NEAT:

- Numeric – the measure should be quantitative as opposed to qualitative in nature.
- Explicit – it should clearly and directly indicate achievement.
- Appropriate – is applied in a consistent manner, relevant to the defined goals and corresponding activity(ies) and is coherent with E^2.
- True – in accordance with fact, *i.e.* objective as opposed to subjective in nature and therefore open to impartial analysis.

Targets are quantifiable required values of measures that define desired performance/progress. As such, they should be bounded in some way to reflect continuous improvement. Thus, to be realistic, targets should be 3B:

- Value-bound – the target should indicate the level of performance to be attained; that is the required value.
- Time-bound – it should indicate the date by which the required performance is to be attained.
- Benchmarked – given the 2Bs above it should indicate the required standard of performance to be achieved based on an identified datum. That is, it should be based on past performance, data gathering and an objective basis.

It is generally known in marketing and business management that objectives should be SMART: specific – objectives should specify what they want to achieve; measurable – you should be able to measure whether you are meeting the objectives or not; achievable – are the objectives you set achievable and attainable? Realistic – can you realistically achieve the objectives with the resources you have; time – when do you want to achieve the set objectives? For performance and process improvement the interpretation of SMART objectives has been modified to:

- Stretching – reflects a substantial increase in improved performance that will stretch current resources to an acceptable level.
- Measurable – clearly indicates an appropriate metric, the value of which can be determined
- Achievable – falls within the known scope of responsibility and has a greater than fifty percent probability of being achieved.
- Results oriented – indicates performance improvement in ability to do things 'better', 'faster' and/or 'cheaper'. That is, focus on results and not the means.
- Target bound – possesses a target that is bound by time and value, and has been benchmarked.

An example of the above may be:

- Goal: Satisfy user requirements (SUR).
- Metric: Satisfied user requirements per month.
- Measures: 1. Number of user requirements scheduled per month; 2. Number of user requirements satisfied per month; and 3. Number of new user requirements per month.
- Units: No/month.
- Formula: 100 × 2 / (1+3).
- Target: SUR of 95% by 31st Dececember 2002.
- Performance objective: To improve our user satisfaction from 92% to 95% by 31.12.2002.

Design activity management

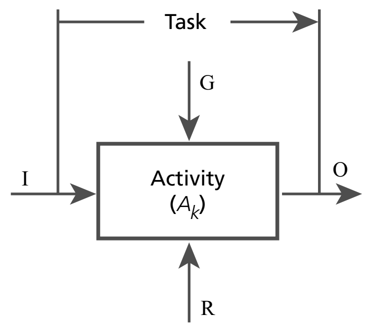
Goals, activities and tasks

For clarity it is worth presenting here the relationship between a goal, an activity and a task. A goal reflects a desire, need and/or requirement, for example, a customer's requirement.

An activity is taken to be a physical or cognitive action that creates an outcome. Thus, it has a starting state, condition or input, and an outcome.

An activity is carried out by a resource of some kind. In some ways an input and a goal can be considered resources. However, the distinguishing feature is that the resource is the means to carry out the activity while the other inputs provide the conditions or elements upon which the means act. That is, the resources facilitate the activity whereas the inputs and goals are used in the activity.

Definitions of tasks often become entangled with activities and goals. A task is not considered here as an activity or a goal, though they are closely related and hence possibly one of the reasons they are often confused. A task is taken to be an undertaking specified *a priori* (Coates, 2001). It reflects the desired or expected output or outcome that is required to meet the goal. It is not in itself the goal, as the output shall meet the goal to a degree of effectiveness. Of course there is a strong relationship between the goal, output and task. The desired output reflects the goal and consequently defines the task. Neither is a task an activity, as the activity is the action carried out to create the output or outcome, and consequently meet the task. These relationships are depicted to a degree in Figure 8.1.



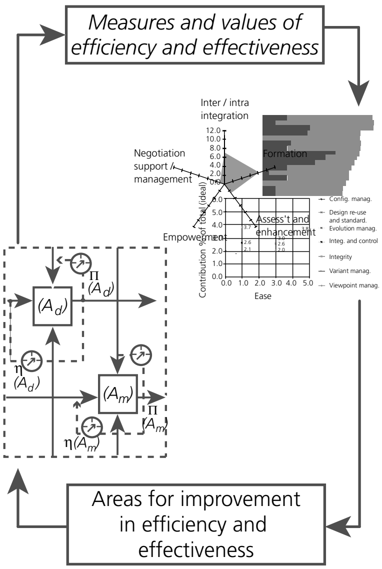
8.1 Goal, activity and task relation

The difficulty or degree of a task depends on the relation between the activity's input and output. The more inappropriate the input the more difficult it becomes to achieve the desired output or outcome. Similarly, the less appropriate the resource, for carrying out the activity in order to meet the task, the more difficult that task shall be for that resource to complete.

A managed activity

The knowledge goal (G) may be related to either the design artefact (DG), e.g. reliability, aesthetics, or the design activity (DAG) involved in creating that design, for example, time consumed, labour costs, resources consumed. The designer may manage the design and design activity goals intuitively in what has been presented above as one activity. However, there are two types of activity taking place; design activities (A_d) and design management activities (A_m). Design activities are focused on the design goals (DG), while design management activities are concerned with design activity goals (DAG) and managing the trade-off between achieving design and design activity goals to ensure best overall performance.

At a design project level these activities are often defined separately and are generally carried out by different people, e.g. the designer or design team and the design manager. However, the distinction between these activity types exists even at the level of individual design activities. For example, during



8.2 Craft oriented performance improvement

sketching a designer may glance at their watch to evaluate the time elapsed in relation to an implicit or explicit time goal before proceeding.

The managed activities described above are the fundamental elements of the design process. That is, the design process consists of a number of managed activities with relationships such as those based on information dependencies. The overall effectiveness of designing is composed of design effectiveness, illustrating how well the design goals have been met, and design management effectiveness, indicating if the design activity goals, such as resource cost, have been met.

In an informal sense, designers will continually evaluate the effectiveness of their activities, e.g. checking their watch to assess time elapsed (design management effectiveness), or evaluating the aesthetic strengths of a particular concept (design effectiveness), as intimated by Jones in the beginning of this chapter. More formally, effectiveness may be reviewed through simulating product behaviour and evaluating results at specific stages of milestones.

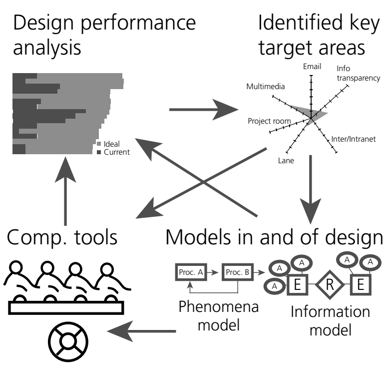
Process improvement

The understanding gained from the performance analysis work is being used to define, implement and measure design development metrics with industrial companies. These metrics can then be used for craft, parametric or optimisation oriented process improvement.

Craft oriented

Having an understanding of the customer requirements and performance metrics it becomes possible to carry out craft type improvement by analysing the needs, implementing changes and measuring the results, on an iterative basis as depicted in Figure 8.2.

In the approach illustrated in this figure the E^2 model is used to measure the efficiency and effectiveness of the actual design development activity. A PERFORM analysis is then carried out to determine the process improvement needs and the most appropriate means to meet those needs. Areas for improvement are then identified and corrective design and implementation actions taken. Thus, new design process models, methods or computational tools can be designed, developed and implemented, as reflected in Figure 8.3. These are then introduced back into the company and any improvements measured through the performance metrics. Iterative cycles of this approach supports continual performance improvement. Figure 8.4 illustrates improvements to a company's design process made over a three-year period using this approach.

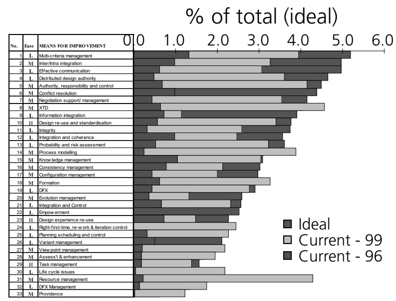


8.3 Craft oriented continuous improvement

Parametric oriented

As in parametric product design, parametric process improvement needs a model that not only defines the parameters (descriptors) but also their behavioural relationships, an additional challenge in determining the most appropriate and reflective performance parameters (metrics) is not only how to define their relationships but to do so in such a way as to predict their behaviour.

Our approach is to employ knowledge data discovery and data mining techniques (Haffey and Duffy, 2001). Within industrial companies we have been gathering the necessary data for extracting implicit behavioural relationships to define process 'performance models'. These models are going to be used to design, primarily through parametric analysis, new solutions to design processes. It is intended that a number of the solutions shall be implemented and tested. Their actual performance will then be compared to that predicted, and a process of continuous improvement adopted (see Figure 8.5).



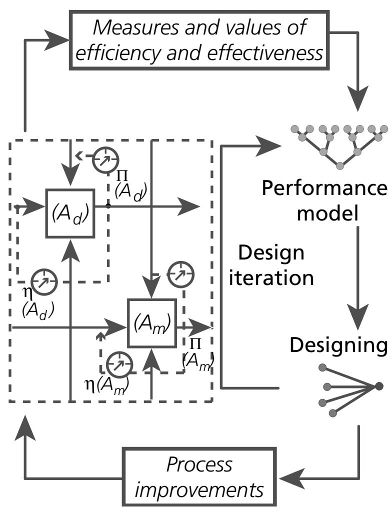
8.4 Required improvements

Optimisation oriented

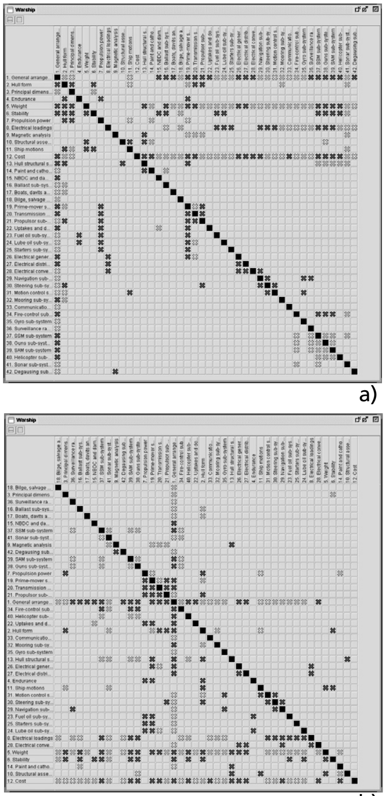
Optimisation algorithms such as simulated annealing, genetic algorithms (GA) and tabu search tend to have a number of parameters that affect their performance and are intrinsically linked to the problem domain (Whitfield *et al.*, 2003).

The dependency structure matrix (DSM) (Steward, 1981) has been used to model dependencies due to its generic applicability, ease of representation within a computer-based system, and, its quantifiable nature. The DSM, also known as the design structure matrix, consists of a list of concepts (e.g. activities, tasks, components) that are represented in the same order in both the row and column of the matrix. The matrix part represents the dependencies between the concepts. A DSM modelling and analysis system was constructed with the focus of providing mechanisms to enable the optimisation of the order of tasks with respect to a pre-determined optimisation criterion (Whitfield *et al.*, 2003).

The order of the activities within the matrix may be managed manually by dragging either of the rows or columns into a new position. The value for the clustering criterion is simultaneously re-calculated, assisting the user in the determination of an improved design process. Alternatively, the design process may be optimised using one of the optimisation algorithms available within the optimisation module. The system can simultaneously manage



8.5 Parametric oriented design



a)

b)

8.6 Optimised pre-contract design process

the optimisation of multiple design processes although this will obviously take longer on a computer with a single processor.

Applied within a warship pre-contract design process, involving 52 activities, the DSM achieved a 75% reduction with respect to the Scott criteria (Whitfield *et al.*, 2003). The before (a) and after (b) matrices are illustrated in Figure 8.6.

Similarly within a design and drawing process, involving 54 activities, the system achieved an 83% reduction with respect to the same criteria. Work is currently ongoing to translate this into performance metric improvements through the implementation of new processes within the industrial company. Thus, a similar continuous improvement approach to that indicated above shall be carried out.

Conclusions

Over 20 years ago Jones (1979) highlighted the need for designers to design their design process. The work at the University of Strathclyde has adopted this concept. Performance is defined to consist of efficiency and effectiveness. Efficiency is seen as the relationship between what has been gained and the level of resources used. Effectiveness reflects the degree to which a goal has been met. Corresponding measures, targets and objectives need to be NEAT – numeric, explicit, appropriate and true; 3B – value bound, time bound and benchmarked; and SMART: stretching, measurable, achievable, results oriented and target bound.

A design activity and a design management activity are presented as being inextricably linked and grouped within a managed activity. A distinction between a goal, activity and task was presented. A goal is considered to reflect a need, an activity an action with a resulting outcome that can meet the goal to some degree, and a task as *a priori* specified undertaking. The inter-relationships, performance and control links within the managed activity were considered outwith the scope of the paper and are presented elsewhere (O'Donnell and Duffy, 2002).

A number of cyclic approaches of design process improvement are presented as craft, parametric and process optimisation. The craft oriented approach is a trial and error iterative process, with significant improvements witnessed within industrial practice over a three-year period. Work is ongoing to build a performance behavioural model that can be used as the basis for parametric design of the design process. Two industrial processes, each with over 50 activities, have been optimised using a genetic algorithm with reductions of 75% and 83% (with respect to an iteration criteria).

Acknowledgements

The work presented in this chapter is the fruit of discussions, working with others and a summary of other published work. I am particularly indebted to Mogens Andreasen, Graham Coates, Mark Haffey, Bill Hills, Frank O'Donnell, Dave Rimmer and Ian Whitfield. I also express my appreciation to the staff members in DePuy International Thales Optics, Thales Optronics and Babcock Engineering Services for their support and close collaboration. This chapter is an update from my paper presented in 2002.

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Chapter 9

Adding value to design research

Crispin Hales
Hales & Gooch Ltd.

The value of academic and industrial research in helping to advance existing knowledge and to develop improved practices in technical endeavours is well recognised. However, when it comes to engineering design it is surprising to find an apparent disconnect. Despite years of design research with well documented results on how to do things better, many projects still exhibit the same unfortunate characteristics typical of similar projects decades ago. Late delivery, underestimated costs, poorly specified systems and aggravating detail design errors are commonplace, with occasional spectacular failures indicating a disregard for the most basic of accepted engineering design practices. Such weaknesses emphasise the continuing need for academic administrators, researchers and managers in industry to make sure that the full value of design research is recognised, understood and applied in practice.

Design research – developing a critical mass

For over 50 years motivated individuals have had a keen interest in the notion of design research, with the ultimate aim of improving the way we do design (for example see Allen, 1965). During much of that time there has been scepticism regarding these notions, especially within university academic departments steeped in the traditions of hard engineering and science. Indeed, why reject strong research proposals within accepted disciplines in favour of vaguely defined projects in fuzzy areas with a lesser chance of funding and a greater risk of having no tangible outcome? The frustration of potential design researchers during the 1950s and early 1960s may be sensed through the personal proposals and papers of forward thinkers such as David Marples (1960). His published paper on decision-making in design became a key reference for early design research projects in universities. Indeed, it is still often referenced on the Internet over 40 years later. He tried to gain acceptance for a research program on the management of design work in 1965 but without success. Others, whose focus was more towards organisational management or 'research and development' than on the 'design process', fared better. Indeed, they were able to carry out worthwhile research programs in areas that were closely related to design (Payne, 1963; Rubenstein, 1984). Looking back from the multi-disciplined, culturally diverse and geographically dispersed perspective of today, the attempts of early design researchers to gain acceptance can be seen as important steps in developing the necessary critical mass for design research to become established.

By the end of the 1970s, all around the world there were individuals and small groups engaged in some form of research on the engineering design process, but with little interaction amongst them. The cultural, language and design terminology differences were so great that it was difficult for any common understanding or meaningful discussion on design research issues to emerge. However, things were changing. In Britain the Feilden Report (Feilden *et al.*, 1963) had focussed national attention on engineering design issues. The effect of this report, together with further subsequent national reports on design (Barlow *et al.*, 1984), was to strengthen the case for design research and improved design teaching (Pugh and Smith, 1978; Wallace, 1979a). At Cambridge it not only led to revisions in the way design was taught but also to two important initiatives that would prove to have a far-reaching influence on design research internationally. The first of these was an exploratory series of visits to six universities in the U.S.A. and the second was the translation into English of 'Konstruktionslehre', a comprehensive book on systematic engineering design authored by German Professors G. Pahl and W. Beitz (1978).

The visit to six American universities was undertaken by Ken Wallace (1979b), and it resulted in a detailed report, which provided valuable insights into the differences between ways of thinking about design in the USA and the thinking in other countries. More importantly, it established a series of new links between isolated groups of design-orientated individuals with quite different approaches to design. From this grew broader and more substantial communication channels, eventually leading to collaborative ventures and the mutual appreciation necessary for creating an international research community involved with design issues (Rabins *et al.*, 1986; Dixon, 1991a, b).

Similarly, the translation of 'Konstruktionslehre' promoted mutual respect and a better international understanding of German approaches to design. During the 1960s and 1970s there had been great efforts and advanced development in design thinking within the German-speaking areas of Europe, but the language barrier was such that much of the real intent was lost to those with only an English language background. The progressive translation of Professor Hubka's (1982) work from German to English by Ernst Eder was one of the few such communication channels at the time, and it highlighted the need for more than simply the literal translation of written words. Professors Hubka and Eder had a longstanding personal relationship and mutual understanding in their design thinking, which enabled them to present their work consistently in either language (see Hubka and Eder, 1992). However there was no equivalent bilingual relationship for translating the work of Professors Pahl and Beitz, despite the recognised value of their book in bringing together much of the German design thinking up to that time. The Design Council in Britain wished to publish an English translation of 'Konstruktionslehre' and this was encouraged strongly by a number of faculty members at Cambridge University (for example see Reddaway and Wallace, 1981). The project was started, but proved far more difficult than originally anticipated. It became clear that technical translation skills were simply not enough, and that a real understanding of the intent, nuances and detail from a design perspective in German was essential before trying to present it in English. Ken Wallace (1982) accepted this role in the project and his tireless efforts were instrumental in providing us with a most wonderful engineering design reference book from the German perspective, presented accurately and readably in English (Pahl and Beitz, 1984, 1996). The personal relationships that developed during the course of the project have continued to strengthen and broaden ever since, providing new communication channels and opening the way for collaborative ventures based on mutual appreciation and understanding.

These two initiatives and the tangible outcomes from them gave new impetus to the idea of multi-disciplinary design research and its acceptability within engineering institutions (Gatiss, 1981). They led directly to the first formal research project on the engineering design process within the Cambridge University Engineering Department, starting in 1982 (Hales, 1987). From then on there was the steady growth of an enthusiastic team and a new Engineering Design Centre (Wallace and Bauert, 1992; Clarkson, 2005), now recognised throughout the world for the quality of its design research.

It might appear that the frustration of those keen to improve the teaching and practice of engineering design five decades ago has been alleviated; design research is accepted, funding can be procured and researchers are available! However, many questions remain. Why, with all this research effort and enthusiasm, is design education still sidelined in many otherwise respected institutions? Why is the design process often still carried out so poorly in industry? How can the results of all this research be applied and utilised more effectively?

...the introduction of improved approaches still depends largely on the enthusiasm and persistence of individual educators.

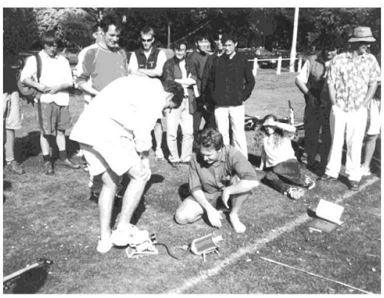
Design education – key to the future

There is no doubt that the teaching of engineering design has improved beyond all measure in many places during the past twenty years, but the introduction of improved approaches still depends largely on the enthusiasm

As design issues become more complex, it is important ... to... be able to produce designs that will meet the expectations of the user within reasonable time and cost constraints.

and persistence of individual educators. From the perspective of one who deals with the aftermath of design failures and engineering disasters on a day to day basis, it is most disturbing to see so many engineering schools and university departments offering students such a perfunctory design education that it may be more of a danger than a help. There still needs to be a more universal appreciation by educational administrators and senior faculty members that without design there can be no engineering, and that an engineer without a good grasp of engineering design fundamentals is a liability to an employer rather than an asset. A systematic approach to the engineering design process provides the core structure for progressive development of the students, and an emphasis on project assignments and teamwork encourages an attitude attuned to the needs of future employers. For example, Ken Wallace used a combination of what he had learned from Pahl and Beitz and his American visits to implement a revised approach to the teaching of design at Cambridge (Wallace, 1988a, b) that has since been used as a model for improving the way design is taught in numerous other engineering educational facilities around the world.

With the advantages of electronic communications, computer-based design assistance, Internet information retrieval and web-based project facilities, it is now possible for students in different cultures and countries to work on projects together (Gooch *et al.*, 2001) and the future possibilities for 'geographically-dispersed' design teams look promising. However, it is still critical that basic design skills, knowledge and attitudes are instilled individually, by means of a design education that includes a systematic and rigorous approach to the engineering design process. Without this it is easy for students with poorly developed design skills to graduate with a false sense of capability in design: a recipe for disaster. How best to combine the exciting new possibilities for working together with the necessary understanding of basic engineering design principles and practice is a matter for further design research.



9.1 Moment of truth for student designers, Canterbury University, New Zealand

It is the responsibility of educational leaders and administrators to better understand the need for improved engineering design education, and it is up to design researchers to help them address the issues.

Design practice – improving the engineering design process

The ultimate aim of design research is to help improve the way design is carried out in practice and the quality of designs produced. This is not a matter of trying to make a naturally brilliant design team even more brilliant, but more of trying to make sure that a less brilliant design team does not fail completely. As design issues become more complex, it is important that ways are developed for the average design team to address all the issues without becoming overwhelmed, and to still be able to produce designs that will meet the expectations of the user within reasonable time and cost constraints.

It could be argued that improved ways of doing design work evolve naturally over time within each specific industry, and that the results of any third party 'design research' would lag behind, would be too general and would provide no practical benefit. While it certainly is true that different industries have evolved different design approaches and techniques, adapted specifically to their own circumstances, it is also true that there is always room for improvement in the design process (Engineering Council, 1986; Andreasen and Hein, 1987). Not only that, but new ways are needed for handling the increased number of negative influences on the design process that are beyond the control of the design team and are outside the scope of traditional company design approaches. For example, the destructive effect that company takeovers, buy-outs and restructuring can have on design team capability is rarely appreciated or even acknowledged by those whose focus is on immediate financial gain or business survival. Yet for any company dependant on design for the outcome of its business, the effectiveness of its design capability is crucial to its future survival, and the design team should be treated as a valuable asset rather than as a disposable liability. It can take years of painstaking management effort to pull together an effective and productive design team (Frankenberger *et al.*, 1998), all of which can be lost within minutes by cost cutting without adequate appreciation of the real consequences.

It is time for managers in industry to recognise the potential benefits from understanding and implementing design research findings, and it is up to the design researchers to present their results in a convincing and useable format.

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Forensic analysis – who did what, what went wrong and why?

A poor quality design team and a flawed design process are a fatal combination for any company in the business of developing engineered products and equipment. Costly failures in service will happen, accidents are likely and the penalties may include debilitating lawsuits and bankruptcy.

When there are problems with a product or piece of equipment in service it is usually rather obvious, and even a user with little technical knowledge may offer personal opinions on 'what the designer did wrong'.

9.2 1999 Ford power plant explosion, Dearborn, Michigan, USA. Courtesy Dearborn Fire Department.

9.3 Inspecting details of boiler explosion, Dearborn, Michigan, USA

However, it is not often so easy to identify exactly what went wrong during the design process and what specific factors contributed to such a problem. In the case of legal disputes, it is especially critical for any expert analysis of the design process to be carried out in a systematic fashion, with reference to accepted guidelines and criteria. The credibility of expert witnesses is often challenged during cross-examination and any issues perceived to be 'fuzzy' are choice targets for quick lawyers. Fortunately, systematic approaches to engineering design such as that defined by Pahl and Beitz are now mature enough to be used as an excellent foundation for analysing what happened during a design process (Hales and Gooch, 2004). They can provide a simple structure for developing conclusions and opinions, robust enough to withstand the most withering cross-examination. In addition, the results from different types of design research provide ways of investigating a wide variety of contributing factors once considered beyond the scope of engineering analysis (Hales and Wallace, 1988). For example, the practical application of phase diagrams to analyse the distribution and effectiveness of work effort during a full-scale design process has been demonstrated in a detailed case study by Whybrew *et al.* (2002).

As another example, consider the company that had designed, manufactured and remanufactured specialty dynamometers successfully for many years, but suddenly started to have service problems due to bearing failures (see Hales and Pattin, 2002). As they were unable to identify the source of the problem themselves, they engaged an independent consulting engineer to analyse the bearing failures. The investigation started in the usual engineering way, with a review of available drawings, photographs, reports and other documents associated with the bearing design, followed by an inspection of some failed units at the company's manufacturing facility. However, when the questions became more focussed on the design process, rather than the component failures themselves, it became clear that the problem involved many contributing factors, including a severe personality clash between two employees. One designer, a long-service employee, had been assigned to a 'sales engineer' position and felt that his perceived role as the technical expert in the company had been usurped by the arrival of another designer. Without any open malice he was able to undermine the effectiveness of the 'new fellow' simply by withholding selected pieces of his own technical 'know-how' on the channelling of lubricant in the bearing housings of dynamometers that were being adapted for a new application. It had reached the point where the 'sales engineer' was faced with upset customers demanding emergency warranty field repairs at enormous cost to the company, a situation which had never happened before. He had started to blame the perceived inexperience of the 'new' designer, but the real problems were identified during the design process analysis and a workable resolution was developed. What started as a bearing failure analysis ended with a company-wide seminar on improving the engineering design process through team building, followed by a convivial dinner at a leading restaurant!

Summary – increasing the return from design research

A large number of exceptionally dedicated individuals have spent years of personal effort investigating various aspects of the engineering design process as carried out in different companies, cultures and countries. Although it has taken far longer than expected to convince the more science-orientated community of its importance, design research has now become an established part of the work carried out at many universities and other institutions. However, the outcome still tends to be undervalued and under-utilised. An essential part of the work is to develop simple and more effective ways for the results of ongoing design research to be introduced into the teaching and practice of engineering design. It is not sufficient merely to report findings at a conference or in a journal paper and then to expect that somehow this will influence those outside the design community. To have real engineering value the results need to be transformed into a format directly applicable to industry problems and tailored to the needs of potential users.

9.4 Forensic investigation team

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Chapter 10
Design, art and science

Geoff Kirk
Rolls-Royce, Civil Aerospace

Design affects all aspects of life and has done ever since man decided to fashion his first tools. It covers a wide range of articles and processes from clothes to computers, banking to bridges, chemicals to cars, furniture to films, textiles to theatre and advertising to aeroplanes. It is surprising therefore that it is not more widely understood.

There are many misconceptions about design. The popular press frequently use the word design to denote style and fashion, bordering on the artistic. This gives rise to the view that design is about form and aesthetics. Equally, scientists are reported to have designed things with the implication that design is about discovery and technology. There are elements of truth in both views but neither gives the whole picture. An understanding of design could be formulated by considering what features all these things have in common: the relationship with art and science can then be explored.

Products of design

The products of design are numerous and various. They reflect society's needs and technology. The following illustrate the breadth.

1. The Great Wall of China was built about 200 B.C. by the Emperor Qin Shi Huang to prevent invasion by the nomadic tribes to the north. It was reputedly initially 5 000 kilometres long and then rebuilt and extended in the Han Dynasty, stretching 10 000 kilometres. Its role as a defence mechanism rose and fell along with the fortunes of China. It is now preserved as a national monument and provides a tourist attraction. The type of construction changed to make use of the available materials. In the eastern part stone and lime mortar were the basic constituents but in the desert compressed earth and reeds were used.
2. The Gem, the most successful paperclip, is the classic design, which has been available since the late 19th century. It was never patented in its own right, the original patent being granted to William Middlebrook of Connecticut for the machine to make it. Since then there have been several hundred patents relating to paperclips. The design is optimised to hold a number of sheets of paper with the minimum length of wire without being overstressed.
3. A ladies fashion boot. This is patent leather boot decorated with a silver chain, aimed at the fashion market in the late 1990s.
4. A company logo. This represents a number of company logos designed by John McConnell of Pentagram for major companies and institutions.
5. An aero engine is a modern civil engine installed on a aircraft. It is a further evolution from the original engine designed by Frank Whittle in the 1940s.

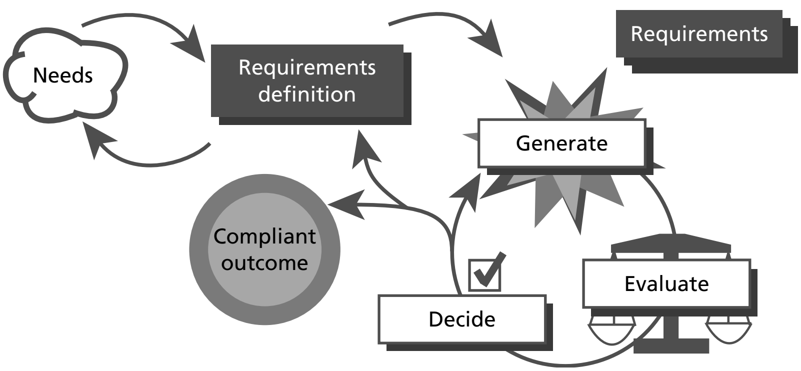
10.1 Products of design. FF-logo reproduced by permission of Faber and Faber Ltd. Aeroplane © Rolls-Royce plc 2005.

6. An aero engine turbine blade. This is a component designed to operate at very high speeds and temperatures, beyond the material's melting point. The aerodynamic shape is crucial to its performance. All the surfaces are defined to perform a function.
7. The Royal Crown Derby Globe Barometer and Thermometer. There are two globes, a barometer and a thermometer, decorated in 1 128 Old Imari style and made as a limited edition. They are working instruments but clearly their major value is their great aesthetic quality.

It is clear that for some of the products the form is dominated by appearance, for others, by the need to perform a function and to provide utility: all, however, are the products of the design process.

What is design

A definition: *to devise the optimum artefact, component, system, or process to satisfy customer needs*. The design process is distinct from the product life cycle whereby a product is brought from an initial idea, through realisation, manufacture, service and ultimately disposal. It is a fundamental and is the same irrespective of which phase of the product life cycle is being pursued. Figure 10.2 shows a diagrammatic representation of a generic design process.



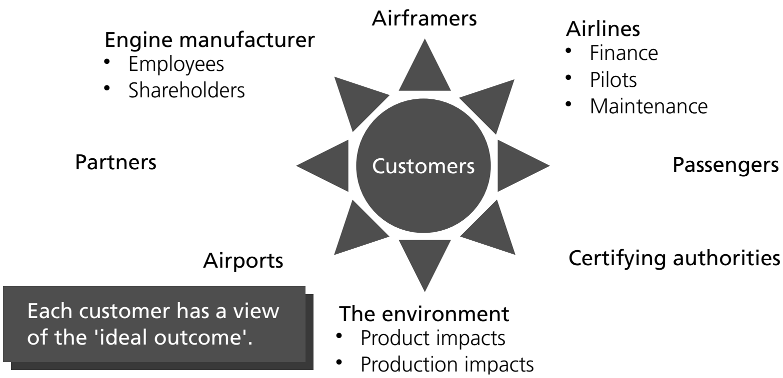
10.2 The generic design process

Customer needs

Each product has a customer or a user. The customer may be an individual, an organisation or a socio-economic group. Needs may be clearly defined and very specific or quite loosely expressed aspirations. A single product may have a number of customers with conflicting needs. It is designer's task to understand these needs, reconcile the conflicts and formulate a statement of requirements. Figure 10.3 shows the customers for an aero engine.

Defining requirements

There are two stages in defining requirements, the initial activity of capturing them by interpreting the customer's needs and the longer-term management during the design process, where progress towards a compliant product can be tracked.



10.3 The customers for a civil aero engine

Requirements are defined in terms of the product's attributes, its function, mass, unit cost etc. It should be noted that appearance is a product attribute, one that can take precedence in consumer products where aesthetic appeal may be the major selling point.

Requirements are conditional statements about attribute quantities, and are often expressed as inequalities, for example the performance of the product must have at least a certain value whilst the cost may not exceed another. It is possible to have a requirement that is bounded by an upper and lower limit. There may be occasions where attributes can be traded. If one attribute over achieves then another may be allowed to deviate from the initial requirement. The customer is the arbiter of these trades.

Constraints need to be considered very carefully before being invoked during the requirements capture. They are limiting statements on the requirements, which if exceeded or not achieved by the smallest amount render the design solution not viable.

Once defined, the product attributes can be agreed with the customer and provide the basis for demonstrating compliance.

Generating ideas

The generation of concepts consists of two phases called concept creation and concept capture. Concept creation is the activity that distinguishes the design process. Individuals are observed to be 'naturally creative' and there are many examples throughout history from Leonardo da Vinci to Sir Frank Whittle.

There are barriers to creativity: psychological set, experience, pressure, self imposed limits, conformity, fear of being wrong, lack of effort in challenging the obvious and the belief that there is always one correct answer. Non-scientific surveys have indicated that young children display a level of creativity that diminishes with age. There are a number of creative techniques that try to open new views on things that were previously dealt with using traditional, closed perspectives and try to reproduce the childlike quality.

Industrial experience (Knott, 2001) has shown that creativity can be enhanced by the use of these various techniques such as structured brainstorming and more latterly TRIZ. These particular techniques have been shown to be powerful when used in team situations but also are productive for individual work.

> *To live a creative life, we must lose our fear of being wrong.*
>
> Joseph Chilton Pearce

> *Every child is an artist. The problem is how to remain an artist once he grows up.*
>
> Pablo Picasso

In concept capture, the concepts need to be captured in order to record them – either to communicate them to others or to record them for future use. The methods used range from freehand sketches to complex computer models.

Evaluation

The concepts then need to be evaluated to provide data, in order to demonstrate compliance, provide data to the customer and provide a database for service support and product improvement. Progress towards design objectives can be monitored. In large projects the results of the subsystems evaluations are used to integrate them into the main system.

There are many evaluation techniques ranging from basic hand calculations to sophisticated rigs or full concept tests as in the case of an aero engine or aeroplane. The more sophisticated the evaluation the greater the confidence – but at the expense of time and resources. Modern computational tools enable the design space to be explored to find where the optimum solutions may be.

Decide

Decisions need to be made on the next course of action: which concepts to take forward, which to eliminate or which to combine. There are a number of tools available to make rational choices based on the requirements and the results of the evaluation studies.

The iterative nature of design

Considering the generic process in Figure 10.2, in practice it is rarely possible to proceed from assessing customers' needs to generating solutions without an iterative loop. In many cases, armed with some primary customer needs, concepts need to be generated to establish the remaining ones or to test the initial assumptions. Generate, evaluate, decide is the classic iterative loop whereby knowledge and information gathered is used to refine the designs on subsequent iterations.

Capability acquisition

Capability in the form of knowledge, process, technology, facilities and people is needed for a successful design project. The need to acquire further capability may become apparent as the project progresses. This can be time consuming and expensive and delay the project completion. It is the designer's role to anticipate capability acquisition needs for current and future projects.

Determinate and indeterminate designs

Not all designs have the same level of complexity or degree of novelty. Some design tasks follow an essentially linear process where the needs and process map is fully understood and so the outcome is determinate. If it is required to define a bolted flange where the loads are known, then there is a clearly defined process for determining the proportions of the flange and the number of bolts in order to avoid separation of the flange and fatigue of the bolts. If two or more designers attempt this task there is a high probability that the outcomes will be the same and therefore the designs can be considered determinate.

However, many designs are indeterminate. There are ten distinguishing properties for wicked problems (Rittel, 1973). These can be modified and adapted to define the characteristics of an indeterminate design task, in that:

1. there are few solution constraints
2. there is no definitive road map to a successful outcome
3. there is more than one possible outcome
4. there is no pre-ordained right outcome
5. the outcome is novel

6. outcomes and an understanding of the true needs co-evolve
7. the needs are a subset of a higher set
8. the process stops when resources of time, money or patience run out.

There are obviously design tasks that meet all of the criteria; but many have only some of the characteristics, so there is a spectrum of tasks between determinate and indeterminate. There is a pressure for businesses to try to turn indeterminate tasks into determinate ones by parametric modelling, key systems etc. This gives lower risk and cost and a more assured outcome: the approach however carries the attendant risks that all outcomes become stereotype.

What is art?

Finding a definition of art is not a simple task. There appear to be as many definitions as there are people prepared to offer one, not all complimentary. This is compounded, as there are many forms of art – visual, fine and performing arts – each with its own characteristics. The visual arts have a link to product design, as there is a common theme of appearance.

Commercial influences have been present in art circles for many years. The benefactors of the artists in Europe of the Middle Ages were the church and the nobility accounting for the great religious paintings and portraits. These were intended to demonstrate the individual's or institution's wealth and importance. There was the practical side; portraits would be used as photographs are used today, for example Holbein's paintings.

Rembrandt, Constable and Turner's work represents a style of art which has been appreciated for many years. Artists like Picasso, Léger, and Warhol moved art to the more surreal form, which causes the viewer to consider the work not simply on the basis of immediate appearance.

There is rarely an acceptance of the 'status quo' and modern artists such as Hirst with The Pharmacy and Emin's My Bed continue to extend the boundaries of what is generally recognised as art.

Artists are generally their own customer and judge of compliance. However, there are some commissions, especially works which are to be used for permanent display, where a customer needs to be convinced that the result is compliant. This can lead to difficulty if there is no objective statement of requirements. It seems that there are a few themes that seem to be generally agreed:

- art is directed at human emotions and senses
- like beauty, art is in the eye of the beholder
- the only attribute of art is its appearance
- art ceases to be art if it has utilitarian value.

A good example of the last is Marcel Duchamp's The Fountain which is a gentleman's urinal placed on its back. Displayed in such a manner in Tate Modern it is art; placed on a wall with pipes attached it clearly has utilitarian value. A fan blade is the same. Within a set in an engine it has a function, placed on a mahogany plinth with the correct lighting, called 'Reaching for perfection', it is art!

How can art, which tries not to have utilitarian value in order to exist, possibly have any relationship to the design process, whose objective is to provide utility? One explanation is that it is all about satisfying the customer's needs. The customer for art does not want the outcome to be useful and utilitarian but to exist as an art form.

Some works of art involve a great deal of engineering evaluation. The Angel of the North sculpture, for example, required a great deal of analysis to ensure a safe and lasting structure and a close liaison with the manufacturing team, practices which are common to any engineering design task.

So art objects are in fact the result of applying the design process; there is a customer even if work is done by artists for themselves; there is certainly a creative phase. There is an evaluation phase and artists can be extremely critical of their own work.

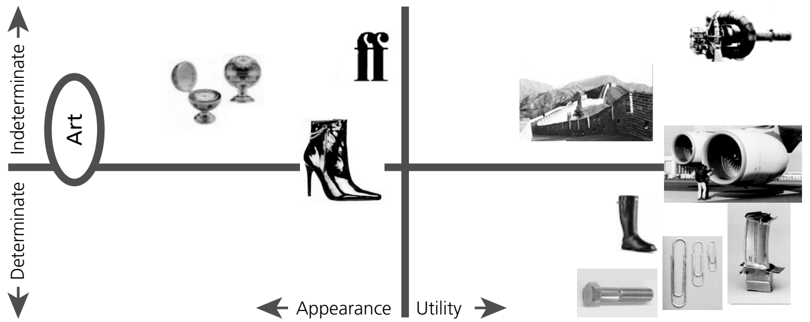
Form obviously plays a large part in art but this is a shared value and is present in most design tasks. In engineering there is a concept that if things are right they look right – the eye ball test – and there are many guidelines such as the golden ratio.

The taxonomy of designs

Of the products described earlier there are those that have appearance as a primary attribute. Others are designed to function, and have utility value, where appearance is not a requirement and any aesthetic quality is fortuitous. Products may also be classified according to their determinacy. So products may be arranged according to their form, defined by appearance or function and their determinacy. Figure 10.4 shows the original six products arranged on such a chart: however, the positions are subjective.

The basic Wellington boots and the fashion boot illustrate a comparison of how two similar objects may be placed. Both have the same function but the fashion boot has clearly been designed to achieve a high aesthetic quality and is more indeterminate.

When Whittle designed the W1 it was highly indeterminate as judged by the criteria defined earlier. There was no prior art and it was claimed as an



10.4 The taxonomy of designs

invention. The modern aero engine is designed to fulfil the same basic function but is more determinate as the processes for defining such machines have been developed and refined. Therefore there is a progression from indeterminate to determinate as a product matures

Where to place art on such a chart? Clearly some works of art are valued for their great aesthetic quality and they would be positioned as shown. Some of the modern works of art are not intended to be beautiful or display a high aesthetic value but still depend on their appearance for their impact.

The same landscape scene done by two different artists will be very similar and recognisable as the same place and is therefore somewhat determinate. However, it cannot be fully determinate as there is still the individual interpretation of the scene. The more modern works of art are clearly indeterminate and are based on the individual artists' desires and inspirations.

What is science?

Science is an endeavour to construct an accurate, reliable, consistent and unarbitrary representation of the world. It uses the scientific method: observe some aspect of the universe, create a hypothesis that is consistent with the observation, use the hypothesis to make predictions, test those predictions by experiments or further observations and modify the hypothesis in the light of the results. These steps are repeated until there are no discrepancies between theory and experiment and/or observation.

A process model, Figure 10.5, can be used to define the relationship between design, science and evaluation. Given the input, the device and the output, then the laws of nature can be determined; this is science. Given the laws of nature, the input and the output, then the device can be defined; this is design. Further, given the input, the device and the laws of nature, then the output can be deduced; this is evaluation. However, the purely fact based approach is tempered by a sense of the aesthetic.

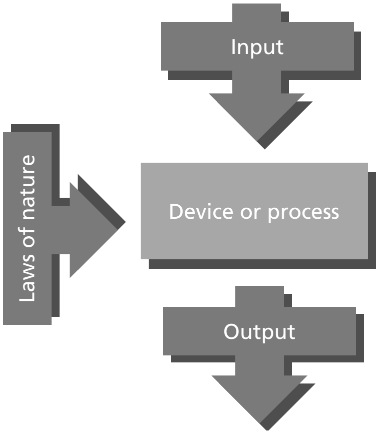
The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful. If nature were not beautiful, it would not be worth knowing, and if nature were not worth knowing, life would not be worth living.

Henri Poincaré (1854-1912)

Science and design – a symbiotic relationship

There is a view that designers are scavengers of science and technology, but this implies dead or discarded technology. As human beings have progressed from scavenging, so have designers. Modern design is not content with that which is immediately available, but designers are at least hunter-gatherers, in that they seek the most succulent and appetising technology and have progressed even further in many industries, to be the cultivators. Capability is set and technology acquisition is seeded ready to be harvested when ripe for exploitation. Science also provides designers with the basic building blocks in that it provides the rigour required in analysis and understanding of problems.

There are many instances of scientists inventing and designing. In those cases although primarily scientists by training and occupation they become designers using the design process.



10. 5 A process model

Summary and conclusions

- the design process is a fundamental process common to many roles and industries
- art objects result from the use of the design process
- the design process is used by many who would not normally describe themselves as ‘designers’
- an objective taxonomy chart could be a useful tool in design planning
- the unstructured creativity of artists has something to offer more functional designers
- science provides the basic building blocks for design capability and the rigour required for analysis
- designers should always look to the future and never be satisfied with the status quo.

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Chapter 11

Intelligent strategies for structuring products

Udo Lindemann, Maik Maurer and Matthias Kreimeyer
Technical University of Munich

Nowadays, offering a wide variety of variant models and releases of one and the same product is most common. This may be due to an increasing saturation of markets, more differentiated customer requirements or the general transition from a supplier-controlled to a purchaser-controlled market paradigm. Whatever the reason, the increase in variant models induces rising operating expenses. These costs, in return, motivate the use of diverse strategies, mainly to control or reduce complexity of a given range of variant models (Ericsson and Erixon, 1999; Schuh and Schwenk, 2001). An increasing need for individualised products (Pine, 1999) appears to be a trend that will continue in the future. This leads to a severe problem: further combination of the given number of parts does not forcibly produce a fully individualised product. The core problem in offering a wide number of variant models is that it does not fully accommodate the customer with a product which is fully suited for his needs but which the customer has to choose from a range of goods on a given market.

Requirements on design variants

Approaching the above problem with the proposals of structural analysis and synthesis will enable the developer to verify the potential for individualisation of his product during the early stages (Lindemann *et al.*, 2003). Ultimately, these are therefore the key to developing the attribute of individuality in the product. They empower the developer to identify compatibility of parts and modules as well as potentials and limits of individualisation based on an analysis of structures either already existing or actually being created for a new product. By doing this, the developer sets the boundaries of individualisation and opens up the room for design. In addition, a quick check whether a customer's desire can be catered for can easily be accomplished; as a result, costs, complexity and effort for the adaptation can be assessed.

Upon recognising possible problems within the structure of a product, different scenarios of optimised ones could generate suggestions and focal points for a new design, which then lead to a technical implementation different from the prior one. This is possible as a result of systematically making use of algorithms taken from graph theory, which are applied to the structure of the product.

The use of deterministic algorithms often results in unsatisfying output and calls for immense computational power; this is why the approach about to be presented uses heuristic search and evaluation algorithms to overcome this downside of prior proposals (Rich, 1985; Goldberg, 1989).

Implementing this approach can drastically reduce the required amount of time to develop each single variant model of a product range, which in turn leads to reduced expenses for development and a more competitive time-to-market. It also caters for the need to develop only those products actually requested by the market.

In practice, finding the existing interrelations between different components is a most difficult undertaking, especially for highly complex structures. It would thus be wise to support the developer during the preliminary planning of the conceptional product model.

The information processed to build such a model is manifold. Whereas modern software systems with a focus on the product's structure are able to manage multifaceted product data, they offer little flexibility towards the goal described above. Product data management (PDM) mainly addresses large amounts of data. However, the emphasis is rather on accessing product related data via a predefined product structure rather than computing and modifying this structure based on the data within the system. Configurators, often offered successfully as b2c web-based systems, only map existing product topologies and do not allow for their modification.

Modern CAD systems are much better suited for adapting a product model to the customer's individual requirements. Nevertheless, they do not offer the possibility of adapting the product's structure, either. However, features like knowledge-ware and parametric product design indicate the actual trend towards the problem sketched out above. All the same, the existing tools, not being designed for this particular purpose, remain little ergonomic, difficult to handle and time consuming.

Requirements for software tools

Efficient handling must hence be the focal point when developing a tool to support flexible work with product structures. It must furthermore be apt to handle and modify different types of elements (such as components, functions and requirements) and interrelations between them (Lindemann and Pulm, 2001). The outcome must be visualised in several different views to supply the user with the full picture of the outcome of his work.

The data that the model is built up on would be a semantic network of the conceptional product; common representations such as graphs, matrices and tables need to be at hand as most developers are familiar with the use of these.

Even structures built up from just a few components may often be represented by a most complex product model. The means of viewing the generated data thence need efficient filters, which can be used concurrently. Highly flexible viewing is a crucial point in working with and adapting the product structure, as this will give the necessary room to come as close as possible to the ideal solution of a given problem.

To develop new configurations even further, the design and comparison of different scenarios will be desirable. Their evolution over the progress of modifications needs to be logged in and represented by a history management module; with this, the impact of each change can be evaluated with respect both to the original solution at the starting point and to each modification in between. Going back within the history of changes will offer an easy means of navigating the evolution of changes and modifications.

A glance at the process of interacting with the product structure reveals that in most cases it starts with an existing, often invariant product. This then is modified to create individual variant models to plan and extend the product range to optimally fit the market's demands. Also, an idea not yet put into effect could be the starting point. Based on either one, a preliminary product structure can be generated from the underlying fixed and variant elements. Furthermore, the nature of interrelations between those elements needs to be defined. Once this information is gathered, the tool will support the user in analysing it and the semantic network created thereby, leading him to define measures and modifications of the product as a second step.

During the computer-based analysis both chances and risks of possible changes within the product structure are determined through the application of algorithms taken from graph theory. The algorithms are first applied to the database of elements and their interrelations, then the result is visualised in a suitable manner and finally the results are interpreted with the aid of a set of rules. In a following step these interpretations are used to modify single elements or interrelations; this will eventually enable the developer to better use the product's potential, to resolve possible conflicts and to circumnavigate or avoid critical parts. These modifications, however, only relate to structural optimisation – yet, these almost always directly relate to one or more characteristics of the product.

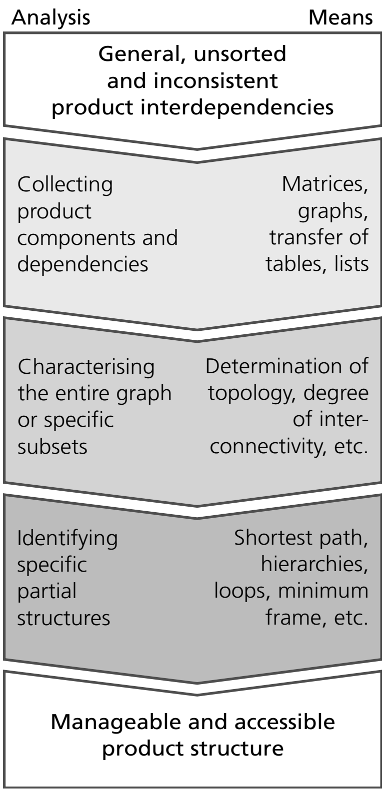
In summary, the tool is a means of generating suggestions on how to possibly use the potential of a set of components. The viability of each suggestion, however, needs to be scrutinised thereafter by the developer.

Structure analysis

The analysis of the product's structure is made up of three consecutive phases, whose sequence is shown in Figure 11.1. Starting point is usually the collection of mostly general and little structured or inconsistent data about the correlations within the product. Supporting this first step with computer aid helps access it with more structure and generates a more easily manipulable semantic network.

At first, the correlations normally exist in the form of documents, tables or lists. To transfer these into a graph structure the tool supports both the representation of the data as and entering the data in the form of a matrix or a graph.

As a second step, the tool is used to scrutinise this now consistent product model with regard to the global qualities of the graph as well as the qualities of any subset of it (both identifying and analysing them). A very concrete way of globally studying the graph would be, e.g. a topological determination, *i.e.* to describe the correlations within the model through a weighted arrangement in a graph representation. In this, the most important elements or groups of elements will concentrate in a central position; the less important ones will stand out at the borders of the graph. The same applies to the less integrated elements. This allows one to judge the interconnectedness and the number of subsets with little effort (Maurer *et al.*, 2004).



11.1 Steps of analysing a product's structure

The identification of subsets of the global graph deserves special interest with respect to deduction steps and measures for adapting the global structure. More specifically, finding subsets means identifying groups within the product structure that show particular properties that can be directly broached (Kusiak, 1999).

An important instance for identifying sub-structures is finding circular correlations or loops. Structurally, these have a heavy impact as two or more elements interlock and influence the product reciprocally. If, for instance, these circularly correlated elements are components and their geometrical dependencies, the outcome might be negatively self-energising (such as resonance of a lathe). In the outcome, this may lead to the necessity of redesigning the very sequence of elements as to make sure the do not interact in a negative way.

Another rather obvious example would be the hierarchy within the data set, given for example by a correlation such as 'element B relies on element A'. The very element that is on the highest level of a hierarchy created by these dependencies will induce if changed a whole cascade of changes on all subsequent levels (in our example B depends on A). Therefore, elements on the lower levels of the hierarchy are much better suited for changes (A is independent from B). As simple as the example may seem, it is yet very difficult to detect these dependencies within a complex product structure (Kusiak, 2000).

Currently, there are a number of tools on the market to visualise dependencies within and configurations of products (Browning, 2001). All these use matrices to represent the semantics of it; however, matrices are only useful when it comes to representing complex correlations.

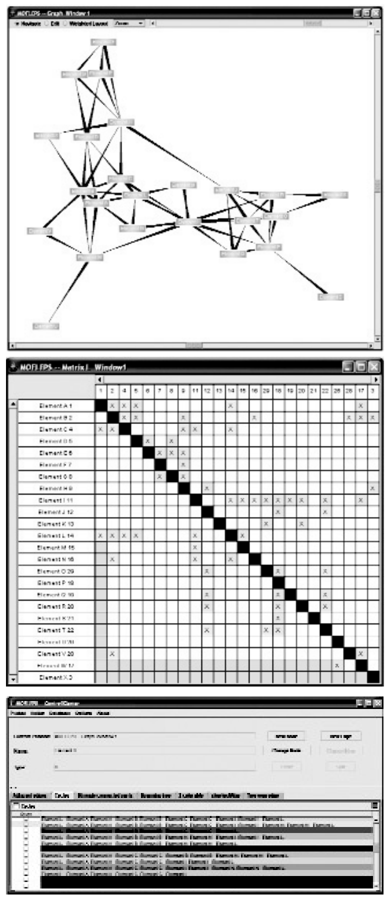
This is where our tool Mofleps (modeling flexible product structures) comes in, which has been developed to answer the needs sketched out above. Figure 11.2 shows the three main windows, which are the control center, the matrix representation and the graph representation.

The control center is used to access basic functionalities such as loading and saving data sets and to control the general settings. Also, available algorithms and filters (Maurer and Lindemann, 2004) can be selected here. A separate part of the control center window is used to represent results of the application of algorithms and filters. These are arranged in lists, from which the product designer can easily chose specific information to be visualised in graph or matrix representations.

Generally, the control center offers all available means of manipulating and interacting with the data, *i.e.* creating, relating and deleting elements and dependencies.

The representation as a matrix is most efficient for any kind of analysis used in the study of design structure matrices (also known as DSM). These have been described and validated in various publications (Steward, 1981, Browning, 2001). The matrix representation is universally compatible with drag and drop handling and offers context sensitive functionalities by use of a context menu. Analyses of the structure can also be executed manually by rearranging the elements on the abscissa or the ordinate on the matrix, for each of which the other one is automatically rearranged accordingly. In addition, elements can be excluded from any further processing by fixing their position. Facilitation for the comprehension of interconnectivities permits the accentuation by coloring specific matrix cells (representing e.g. directed interdependencies or loops).

The graph representation and the matrix representation access the same data of the product structure, but the information accessible within each window is considerably different. For example the switching of an element's position in the matrix representation (as it is executed for DSM analyses) does not cause any change of the graph representation, as no changing of element interdependencies is carried out. Thus, the rearrangement of elements in the matrix is only a visual support for product designers to identify specific subsets (e.g. clusters). The graph representation is particularly useful for



11.2 The three main windows of the software tool Mofleps

visualising overall coherences or partial graphs of strong interconnectivity due to its strength-based description of the structure (Lauer, 1998). In contrast, the identification of strong interconnectivity in matrix representations requires an experienced product designer and can only be carried out with structures of low complexity. Figure 11.2 shows as example a simple spectrum, for which advantages of the graph representation are easily recognised. Due to the strength-based modeling highly interconnected elements are arranged in the center of the structure. This comes along with the common understanding and allows intuitive interpretations. According to this, elements possessing only one single interdependency within the structure are pushed to the border of the structure. This also matches the common understanding as such objects are usually of lower interest and possess less impact on the entire structure. Furthermore, the rules of graph composition result in distinct concentrations of elements ('packages'), if multiple highly interconnected subsets exist in the structure. The (mostly important) elements and interdependencies, which generate the linking between these packages, can easily be identified. Both the matrix representation and the graph representation offer convenient means for accessing and adapting the structure and context sensitive functionalities for interaction. Analyses and filter results, which can be visualised in both representations, are displayed simultaneously, e.g. the consideration of an interdependency loop is meaningful in both representations. The content displayed is fully dynamic, so that adaptations in one representation will instantly cause a change in the other one.

Once a product structure is available in Mofleps, the first step is to identify overall attributes of the structure, e.g. the existence of subsets or strongly interconnected element packages. Usually, this will be executed by examining the automatically generated arrangement of elements in the graph representation. Often, this already leads to selecting structural subsets for closer consideration. Furthermore, this first approach of characterising the entire structure (e.g. strongly interconnected, highly dissected, mostly linear arranged) helps to focus on the appropriate attributes during the follow-up. Then, the product designer can initiate an intensive, algorithmically supported analysis of the structure. The results represent the input for the deduction of interpretations and possible measures for the adaptation and optimisation of the product structure.

Figure 11.3 shows a list of ascertainable structural content (subsets) and the possible interpretation within the product's context. The context-specific semantic meaning of the interdependencies is of major importance for the interpretation. In the example given below the interdependency is described by the general meaning ‘has impact on’. The measures shown in the right column of Figure 11.3 correspond to the consideration of product structures for customisable products.

The possible interpretations and derived measures for the interaction with product structures in Figure 11.3 are explicitly kept at a conceptional level in order to permit their applicability onto different product structures. Therefore these statements can only serve as suggestions for the product designer, who has to verify their aptitude for his specific scenario.

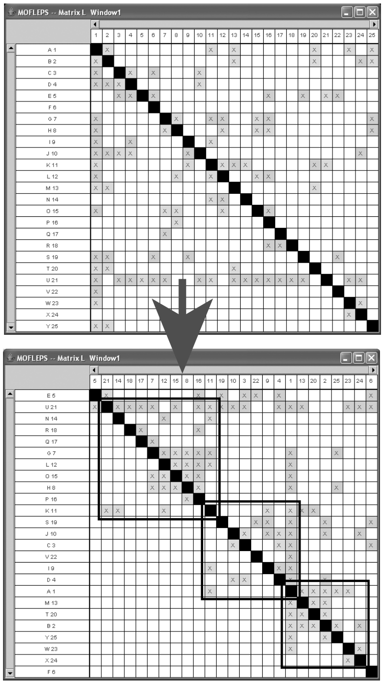
Structural content	Interpretation	Exemplary measure
Dependent/independent areas of the product	Changes can be executed parallely without any interaction	Release or block product areas for individualisation
Degree of inter-connectivity,loops	Estimation of range, moderation of impact from adaptations	Integrated editing of elements in loops; block highly connected areas for individualisation
Structural intergration of exposed elements	Estimation of possibilities for implementation	Rearrange structurally relevant elements
Specific subsets (hierarchies, complete interconnectivity, etc.)	Depending on structure in question: robustness, propagation of errors	Review of attributes by choice/adapting suitable structures
Structural similarities to known structures	Assignable behaviour, assignable characteristic	Review of attributes by choice/adapting suitable structures

11.3 Structural subsets, interpretations and measurements

Structure synthesis

Alongside extensive functionalities for analysing purposes Mofleps also offers means of structure synthesis. In its current version, Mofleps is able to tweak clustering (Kaufmann and Rousseeuw, 1990) by removing single interdependencies. To achieve this efficiently, a genetic algorithm (Goldberg, 1989; Yu *et al.*, 2003a; Yu *et al.*, 2003b) is applied comparing the deviation of each possible cluster computed relative to a full cluster; *i.e.* the relative deviation from a full cluster is used for gauging the quality of the clustering.

This principle is shown in Figure 11.4, where the matrix representation of a modularly structured product is given. Each single product is slightly modified by the manufacturer before being delivered; experience has shown



11.4 Matrix representation and clustering

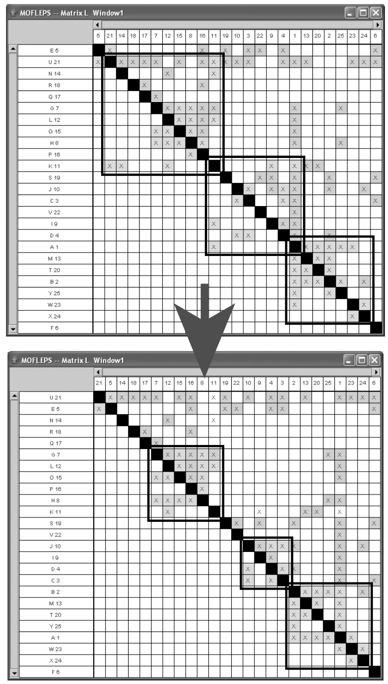
that in many cases such allegedly slight changes have caused unexpected impact onto the whole product. Hence, the goal was to determine and optimise the clustering of components, *i.e.* minimise loops and far-reaching interdependencies across multiple elements. The result of a first automatic clustering is shown in the lower left corner of Figure 11.4. Three clusters appear, extended over a large number of elements but not featuring a high density of dependencies within each one. With each cluster overlapping the next one, long chains of correlations and possible loops extend over almost the whole structure.

In a next step, the goal was to eliminate single dependencies, which in terms of technical design means eliminating the physical interdependency between the two formerly related parts. This was to achieve a reduced number of loops and to receive an optimised clustering by changing the structure the least possible. For the example given in Figure 11.5, the genetic algorithm was set to eliminate a maximum of four interrelations from the matrix – the result clearly shows an optimised structure. The density of each cluster is much higher and there is no more overlapping between them. The number of loops within the total semantic network is reduced by almost 40%, the number of indirect dependencies is decreased notably.

To verify this scenario, the outcome was communicated to the manufacturer. Although not all four eliminations could physically be removed in the machine, the scenario turned out to be an important stimulation for the engineers to enhance the product.

To advance the functionalities of the software-tool Mofleps in the future, a special focus will be put on improving support for creating scenarios, especially by weighted combinations of multiple structural criteria (Yu *et al.*, 2003a, Yu *et al.* 2003b). The automated means of clustering in order to reduce the number of loops within the semantic net will be expanded to a set of more comprehensive constraint definitions (e.g. by retaining specific elements or dependencies) and direct identification of e.g. hierarchical or linear subsets.

All development of Mofleps as hitherto has shown that efficiently interacting even with smaller product structures is almost impossible without computer aid. Manual adaptations of relatively small sets of dependencies are very difficult to manipulate. This is why there must be an important focus on offering the user the ideal means of interaction with the product's structure. By simultaneously visualising both graph and matrix representation a major step towards better comprehensibility could be achieved.



11.5 Structure optimisation (scenario)

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Chapter 12

Social responsibility and engineering innovation

David E Newland
University of Cambridge

A number of case histories illustrate the complex issues that need to be addressed by engineering innovators and lead to two questions. Can good innovation be encouraged? Can the bad consequences of innovation be recognised and, if recognised in time, prevented? The answers are complex, but designers need to consider what they are. As society becomes increasingly dependent on technology, those who understand technology must be willing to make their views known.

Preamble

A quarter of a century ago, I was a member of an Appointments Committee in the Engineering Department. Our task was to find a new lecturer in engineering design. We had two concerns. One was that not all members of our Committee were convinced that design should be a proper part of the engineering curriculum. The other was that good designers were still a rare breed in university engineering circles. How well we overcame those concerns in appointing Ken Wallace. Our success led to the department winning the original EPSRC block grant which led to the EDC being set up a few years afterwards. From the outset it was spearheaded by Ken, who was the lead principal investigator, with Mike Ashby and me as his supporters. The EDC's international standing, and the improvement in design teaching that came alongside it, became clear for all to see. Without Ken Wallace, this would not have happened. It is a great pleasure to have the opportunity now to contribute to a publication to mark his 60th birthday.

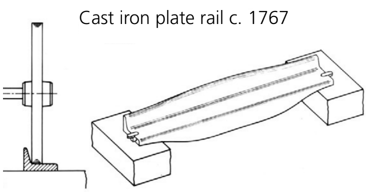
Ken Wallace's managerial and entrepreneurial skills have been a major factor in making many innovations in our department. In this chapter, I want to explore the responsibilities of innovators. There are many issues, but I have in mind two in particular. First, what makes for good innovation? How can it be encouraged? Secondly, because innovation is often not an orderly process, it may lead to unpredicted and sometimes unexpected results. Can we anticipate when change may lead to undesirable and unintended consequences?

Of course these are related questions. They do not have simple answers, but they are questions which design engineers need to consider. They raise important issues for the engineer in society. Because each new case is different, I do not think that general answers can be found. Rather there needs to be a continuing debate on specific questions. And sometimes these questions lead to answers which engineers have a responsibility to explain to an audience wider than just their professional engineering colleagues.

Railway track design

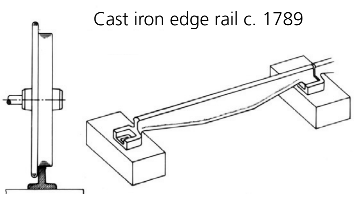
I begin with a case history. It concerns one aspect of railway design. The introduction of flanged iron wheels running on iron rails was a wonderful innovation in mechanical engineering design. But it was an innovation that would lead eventually to unexpected and undesirable consequences.

We take for granted that a railway train has steel wheels that run on steel rails. The rails are clipped to sleepers which are carried on a bed of ballast. This is a system that has evolved over 250 years and Britain led the world in its invention and development, a development that has been copied all over the world. How did this happen?



12.1 Original plate rails had vertical flanges to hold the wheels central

When William Jessop had the task of building a new wagonway from Loughborough to Nanpanton in the 1780s, for horses to haul coal wagons, he would have thought first of laying down a bed of rails with upstanding flanges to stop the wheels of the wagons falling off the rails. But it occurred to him that a cheaper, and perhaps better system, would be to take the flanges off the rails and put them onto the wagons' wheels. This would use less iron and the result would be the same. At first he put flanges on the outside of his wheels, but this proved unsatisfactory as the forces involved tended to push the flanges off their wheels and then derailments occurred. Instead he rebuilt his wagons with flanges on the inside of the wheels. Then cornering forces pushed the flanges further onto their axles and derailments did not occur, or at least not so frequently.



12.2 New edge rails rely on flanges on the wheels to hold the wheels central

This led to the flanged railway wheel that has been adopted ever since. It is a feature of railways everywhere in the world. And it is a system that worked very well – up to a point. To make the wagons run smoothly, it was found that the wheels' treads should be smooth with a gradual transition from horizontal tread to vertical flange. However, as speeds increased, instead of running steadily on straight track, the wheels had a tendency to move from side to side of the track at high speeds. An unstable hunting oscillation occurred which you may have noticed sometimes when travelling fast on a train. There is a rhythmical movement from side-to-side which shakes the book you are reading or slops the coffee in your cup. This hunting motion is damaging to the track and the rolling stock, as well as being uncomfortable, and a great deal of effort has gone into designing railway trains and track which minimise this undesirable feature of Jessop's innovation.

Even the very fastest railways in the world use flanged steel wheels on steel rails, when a better system could now be designed which overcomes the drawbacks that spring from Jessop's original design. But the investment in infrastructure and know-how is so great that a fundamental re-think is ruled out except perhaps for a completely new and separate railway that would not have to share traffic with the existing railway system.

The railway revolution has brought huge benefits to the world but now serious disadvantages are becoming apparent when an old system is having to be used in modern conditions that were never contemplated 250 years ago. Recent catastrophic accidents have been caused by the unexpected consequences of steel rails being unable to cope with much faster and heavier trains than were ever envisaged all those years ago. Now truly vast quantities of money have to be spent to upgrade and maintain what is essentially an old and unsuitable system for modern requirements. Short of a total rebuild of our complete railway infrastructure, we cannot escape from this undesirable legacy of past successes.

Technology revolutions

This railway example is not unusual in the history of design innovation. Two centuries ago the Industrial Revolution had seen the widespread adoption of steam power following James Watt's invention of the condensing steam engine. By his friendship with his business partner Boulton, Watt was able to lead the change from horse and water power to steam power, which altered the way of life of millions of people and of course made steam trains possible. The consequences were astonishingly far-reaching. Agriculture lost its importance as people moved to the cities. By the time of the Great Exhibition of 1851, Britain claimed to be the workshop of the world. But there were great disadvantages: enormous industrial and environmental pollution, dreadful working conditions, the gross exploitation of human resources, the dark satanic mills of Victorian Britain.

So often this is the case. The good exists alongside the bad. It is almost as though you cannot have one without the other. Has it not always been so when the enabling function of technology is exploited by innovation? Advantages that are perceived by some are not recognised by others. Or perceived advantages turn into disadvantages with the passage of years.

Where will more recent revolutions take us? The information technology revolution, a much more recent example, has changed how people work – changed how we interact with each other in a fundamental way. Now we buy books, cars and holidays on the internet – probably talking to no-one in the process, existing in our own private cocoon, isolated from our neighbours and self-sufficient within the technology. As well as isolation, this can cause a good deal of frustration and waste a great deal of time. How well have you found that 'help lines' work? It is hard to make contact with another human being. And what about Internet banking? The whole pattern of working and employment is changing as local branches close, the banks employ more computer engineers and fewer cashiers, and establish call centres thousands of miles away in another continent.

Now we are in the throes of a biotechnology revolution. There are huge opportunities to understand and conquer disease. At the same time there is the real danger that human life will be cheapened as replacement parts can be produced artificially and, quite soon, there is the possibility that life may be started in the laboratory without egg or sperm. Many people will oppose such a development, but will it always be bad? Can good outcomes justify the bad?

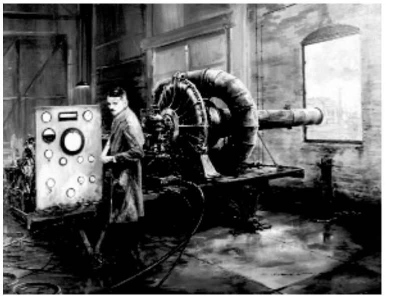
So change is not always for the better. The perceived advantages have to be balanced against disadvantages. Change comes gradually as new ideas become established and new working methods and procedures are introduced. Literally thousands of useful 'things' emerge as new ideas take hold. Most will be *good* in some sense or other, otherwise people will not want them and they will have no market. A small proportion may be *bad* because intentionally or unintentionally they may harm people or our environment.

Engineers need to be sensitive to these tensions. But can good and bad outcomes be anticipated? Are bad consequences foreseeable? How involved should engineers be in the consequences of their work?

Making innovation happen

When I began my career in the engineering industry in the 1960s, there was a clear pattern. I worked for a large engineering company, English Electric, which made power station equipment and electrical goods from aircraft systems to domestic appliances. When there was a call for a new power station, or when the company's marketing department found that a rival washing machine was outselling the company's product, a specification was drawn up to say what was required. The Design Department then had the job of using available technology to create the necessary drawings and specification, and the Production Department got on with making whatever it was. Finally the Sales Department had the job of distributing the product and satisfying the customer. All this activity was supported by a Research and Development Department who monitored what rival companies were doing and tried to keep product development ahead of the game.

It was all rather straightforward. We worked for a respected company. There was no need to question the consequences of our work. We knew what the company wanted, and by and large the designers were able to provide it. But, gradually, there came a growing realisation that big groups were slow to innovate. Large companies were often not responsive to truly new ideas. The inflexibility of a large organisation makes it an infertile environment for genuinely new things. To disrupt established manufacturing methods or processes for a new product of uncertain future is usually too hard for even the most enthusiastic entrepreneur to achieve.



12.3 Whittle's experimental jet engine, painted by Rod Lovesey © Rolls-Royce plc 2005

There was an archetypal example here in the Engineering Department in the 1930s. The greatest invention to spring from 125 years of engineering at Cambridge University is Whittle's jet engine. It is probably the most far-reaching engineering invention ever. But, at the time, the big aircraft engine companies were unable to recognise the huge prospects and untold advantages of jet propulsion, let alone foster its development. Whittle was an RAF officer studying engineering as an undergraduate when he developed his basic ideas for jet propulsion. Without the help and encouragement of two members of staff, nothing would have happened. As it was, patent cover expired before any progress had been made, and it was only when the Ministry of Defence reluctantly provided funding that slow progress became possible. A world war and the suspicion that Germany had a similar invention provided the impetus that eventually led to success. But the role of Whittle's two friends was pivotal to what happened. Whittle himself recorded this in generous terms. And a new company, Power Jets Ltd., had to be set up to do the first development work and trials. Existing aircraft engine companies did not have the resources, the inspiration or the foresight to foster this work, until it had already been proved successful. Even then, the successful development of jet propulsion in this country might never have succeeded but for the urgency of a war situation and recognition by Churchill that there was something here to be fostered.

12.4 First test flight of the Gloster E38/39 with Whittle's engine, May 1941 © Rolls-Royce plc 2005

To turn a really new idea into something useful is extremely difficult and it is often a hazardous financial undertaking. Some years ago, one of my ex-students, and a former member of the EDC, became R&D director of a new firm which had been formed to develop a new method of needle-less injection. This appeared to offer big advantages over existing methods, but it was costly to develop. Also an extensive programme of clinical trials had to be completed before the product could be put on the open market. Unfortunately the expenditure required ran ahead of predictions as results took longer to come in than expected and design changes had to be made. The upshot was that the company's financial backers lost patience and the share price plummeted the company into liquidation in 2003.

Sadly that story has become commonplace in high-technology industry. Probably it was always so. No doubt William Jessop and James Watt had funding problems that they had to overcome. We know that Whittle did, and without the help and encouragement of his colleagues, his invention would have foundered.

Perhaps surprisingly, developments in biotechnology may not need the scale of financial and entrepreneurial support that characterise engineering innovation. A relatively small laboratory can achieve profound results without necessarily having the huge infrastructure backup that is needed for successful engineering innovation. For example, to change the design of railway wheels is practically impossible for existing railways. The only option is to change the design for a completely new railway – at huge cost and with high risk. But to grow artificial tissue for 'spare-part' surgery and see this used is a practicable proposition which may bring great benefit to many people relatively quickly.

So in technology, as in other fields, the process of innovation is variable. It may be a long, hard route characterised by repeated failures and disappointments and only successful after years of commitment and determination, or it may be a short, simple process to turn someone's brainwave into a useful thing.

Trying to do good innovation

And now, turning back to my original questions, how should we judge whether innovation has a good or a bad outcome?

For those of us working in universities, our task is to advance knowledge and educate students so that innovation can happen. By encouraging creativity from a platform of sound fundamental principles and rigorous quantitative analysis, we strive to achieve good and useful outcomes. But the outcome of engineering innovation is not always predictable. There are risks with all technology.

In the UK, the Health and Safety Executive has a key responsibility to try to ensure good outcomes. Its early years were strongly influenced by public reaction to a massive chemical plant explosion at Flixborough in 1974. There was extensive legislation on health and safety issues. The upshot is that formal risk assessment is now used widely before new products are introduced into service. People independent of the original designers are required to follow an ordered procedure to try to identify what might go wrong and what its consequences would be. This often leads to design changes before a plant is built or a product is put into production and is definitely a contributor to a safer world.

Environmental risk assessment was led by the chemical industry and is widely practised across the engineering spectrum. Of course there is not always agreement on realistic environmental standards to aim for. For example, when leaded petrol was still being used, diesel engines were advocated as more environmentally friendly. Now there is concern about the very small soot particles generated in the exhaust of diesel vehicles.

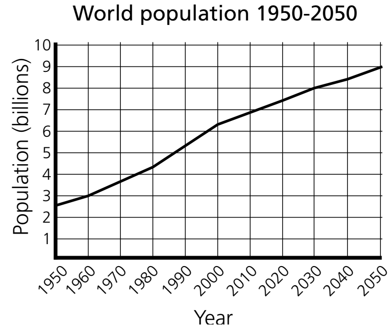
These issues can be extremely complicated and they may be difficult to grasp. The continuing debate on environmentally-friendly sources of energy is an interesting example.

Once their construction is completed, wind turbines generate clean energy. They help to meet national targets for reducing the emission of greenhouse gases. But they have disadvantages. They depend on the wind blowing, they are costly to make and run, and they are visually intrusive. Unfortunately their most serious disadvantage is none of these. It is a factor that is sometimes overlooked which is that, sadly, they are unlikely to make much impact on a world scale.

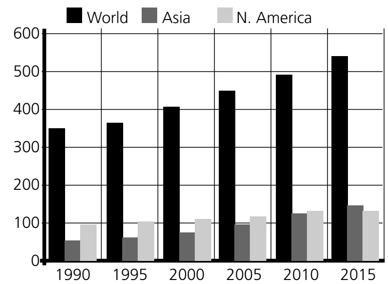
This is because pollution from energy generation is a world problem. When you consider that the world's population will increase from about 6 billion now to about 9 billion people in 2050 and that the two biggest countries, China and India, have 2.25 billion people now, the UK is a very small player on the world's stage. Our population now is about 60 million, or 0.06 billion.

Because both China and India have huge untapped reserves of coal, they will burn increasing amounts of coal to provide the extra energy they need. The generation of electricity from those vast untapped energy sources will bring enormous benefits to developing Asia, but it will come at a cost. The resulting release of huge quantities of greenhouse gases may have very serious bad consequences for the world.

How will we cope? We should encourage research and development to improve technology so that Asia's fossil fuels can be burnt without emitting so much carbon dioxide. Perhaps new technology for carbon sequestration will enable atmospheric carbon dioxide to be absorbed and returned to earth and sea. But, whether this happens or not, the improvement and extension of



12.5 Energy trends. US Census Bureau, 2002.



12.6 Annual energy outlook. DOE, Washington.

electrical power systems throughout developing Asia is undoubtedly a good thing while the resulting global warming is a bad thing. How do we reconcile those two opposites?

Probably the best long-term source of clean energy is nuclear energy, yet our nuclear stations are scheduled for closure with no new ones planned. Meanwhile we are happy to buy nuclear-generated electricity from France to use here. Has the nuclear alternative been resisted for too long? There are already over 400 nuclear reactors generating power around the world. And it has been reported that 35 new nuclear power stations are currently under construction, 17 of them in Asia. Their safe design and the security of their operation is a major engineering challenge.

Future dilemmas

In the end our response to nuclear power, like all innovation, depends on the views of members of the public and there are no absolutes. Politicians make laws, and politicians have to keep people happy if they are to be re-elected. Generally innovation is driven by commercial forces, but it is controlled by legislation which in turn depends on the public will. And the legislative process can be a slow one. The slow progress of genetically-modified crops is an example. People are cautious – sometimes more cautious than their elected representatives in Parliament.

It is important to understand that innovation is like a delicate plant which needs nurturing. This is not an easy task and, in its early stages, the innovative process is easily extinguished. Paradoxically, for initiating and perfecting new technology, small seems to be better than big. But once new technology has been developed, promoting and using it becomes a task where big companies are more successful than small companies. Whittle's company Power Jets Ltd. soon disappeared as jet engine development was taken over by the established engine manufacturers. How can the big support the small in these endeavours? And good innovation needs public support. People are wary of new technology. There have been well-publicised mistakes – the Challenger space shuttle disaster is an example. Inevitably new technology brings new risks and, initially, there are mistakes. But old technology can go wrong too. The Hatfield and Potters Bar railway accidents show the consequences of pushing old technology too far.

It is therefore right that university designers should address these wider issues of innovation. More than most, they should have the gift of expressing themselves. Too often the engineer's voice is not heard sufficiently loudly.

Members of the media generally do not listen, or, if they do, confuse engineering and science. By speaking out, engineers make a valuable contribution to society. As a group, we need to speak out more and speak more loudly. Whether on transport issues, the railways, roads, housing, aviation, energy, communications, nanotechnology, bioengineering, whatever it is, engineers, and particularly designers, have a duty to speak out.

The EDC has already started to play a part in that process. By raising the profile of engineering design in the university world in this country, our EDC has made a significant contribution to supporting the role of the engineer in society. Long may its success and its influence continue in this work. I hope that its programme will also not neglect the difficult, strategic issues of engineering innovation. And then may its members have the courage to speak out, when speaking out is needed, to help recognise the good and the bad in design innovation and to ensure, as far as is humanly possible, that engineering innovation truly benefits society.

Acknowledgements

In 2003, I took part in a meeting organised by the Revd. Dr. Brian Tompkins FREng on the subject Technology – master or servant? An account of my talk entitled 'Turning ideas into useful things' appeared in the proceedings, published privately under ISBN 0 9530360 7 3. This chapter is a development of that talk. Figures 12.1 and 12.2 were first published in my Inaugural Lecture at Sheffield University in 1967. The statistical data in Figures 12.5 and 12.6 are taken from the sources stated, and may be accessed via the Internet.

Chapter 13

VADEMECUM – recommendations for developing and applying design methodologies

Gerhard Pahl
Technical University of Darmstadt
Translated by Karl - H. Grote, Magdeburg and Long Beach (USA)

For some time several authors have discussed the methodical approach for product development. The VDI (Association of German Professional Engineers) standards VDI 2221, 2222 and 2223 present the most important aspects. Then there are several standards texts Roth (1994), Ehrlenspiel (2003) and Pahl and Beitz (2004). Pahl and Beitz (2004) discuss several concepts, procedures and specific methods for the practitioner and the student. Ken Wallace has edited and translated both editions of the book in the English language. Because several editions already exist in German, English and many other languages, it is recommended to find desired concepts and methods from their respective indexes and chapters.

The design methods presented were developed with the intent of securing successful solutions by adhering to a systematic approach. The procedure corresponds to a technical and 'mental logic' to achieve the anticipated goals, and is supported by practical experience. Regarding the applications, it became obvious that frequent uncertainties and misunderstandings exist particularly when methods are applied for the first time or in connection with others. The following 'VADEMECUM', being a short guide, hopes not only to contribute to the application of methods, but also to inform its users and others who are interested. Knowledge is helpful only when it is applied in accordance with the case at hand (Zhuangzi, 4th or 3rd Century BC). Replacing the term knowledge with the term method helps to better understand the purpose of this VADEMECUM.

13.1 TU Darmstadt's logo of goddess Athene is a symbol of wisdom

Development of design methods

- Explain for which design phase the method is proposed or is thought to be applicable, for the overall design process, or for individual design sequences such as target analysis and clarification of the requirements; operational understanding and analysis; search for solutions; and solutions analysis and solution evaluation, e.g. by selection comparison, or appraisal.
- Indicate what the method must achieve or should avoid.
- Explain the methodology necessary and any indispensable aspects, and allowances for individual margins and tolerances.
- Design methods should be simple to apply, in accordance with practice, and teachable.
- Avoid new or unclear definitions and wording. Use standardised and available definitions (VDI-Richtlinie 2221-2223, 2225; Pahl and Beitz, 2004) and only refer to new words and definitions when absolutely necessary. Newer references and definitions should be compatible with those already in use.

- Identify the method clearly and understandably according to its purpose.
- Results achieved by methods application must be directly obtained, *i.e.* without additional reference or effort.
- Indicate in which cases a methods application exceeds reasonable justified efforts, and therefore what should be abandoned.
- Indicate any limitations or areas of non-applicability of the methods considered.

Application of design methods

Adhere to the process of systematic engineering design, and proceed as follows:

- Start with the target analysis and examination of the requirements.
- Try to recognise the functions necessary.
- Start a solution search for the obviously most critical function to find its best and most effective solution principle.
- Only then look for further solutions for the other main functions and sub-functions.
- Examine these solutions and identify the weak designs.
- Improve the weak design solutions.
- Develop an all-supportive concept by embracing the above individual requirements and solutions.
- Evaluate this concept and improve it as needed.
- Then proceed to the configuration and detail design of the individual assemblies and look for interactions between them and the overall task.
- Examine the completed overall design for weak areas, errors, or flaws and optimise it.
- Proceed to a final examination and evaluation of all of your work towards the given task.

Keep in mind that the beginning of a new solution is frequently based on recognised and documented errors and shortcomings. Only a careful and complete analysis of a challenged solution permits us to completely recognise the shortcomings and will lead to a new insight on the necessary requirements. To this end, use the fault-tree type of analysis or a related procedure.

In these cases, the solutions search is limited to the particular design aspect of an existing product without always questioning the overall and entire concept. At this point, however, make sure that the existing concept appears to be sufficiently effective.

Plan your approach and establish a timeframe with clearly defined milestones corresponding to the design procedure (VDI-Richtlinie 2221-2223;

Pahl and Beitz, 2004). To this end, adopt individual methods as needed to meet the timeframe. The appendix in Lindemann (2005) contains a useful description of methods for that purpose. To a useful approach plan belongs knowledge of individual methods; otherwise their adoption could be questionable. Make sure you have sufficient and comfortable knowledge and ease-of-use with them. Develop a 'methods tool kit'. If possible, use only known concepts and nomenclature as per (VDI-Richtlinie 2221-2223, 2225; Pahl and Beitz, 2004). Avoid other names or designations, which could lead to confusion and unnecessarily complicate the work.

Begin with the simplest and least elaborate method. Doing so will often result in the lion's share of the correct answer. It is important to stimulate your own thinking, prevent mental blockages, set aside any prejudices, and ensure that a flexible interchange of several considerations exists. Use methods that stimulate the natural thinking process, and alleviate the failings of short-term memory. Strict over-working of methods does not benefit their intended application.

Procedures given in VDI-Richtlinie 2221-2223 and Pahl and Beitz (2004) are not of the 'straight sequence' type, but should be utilised only as guides for basic purposeful action. A useful approach in actual situations might be to choose either an iterative approach (*i.e.* with 'forward and back' steps) or by repetition using the next higher information level.

Systematic procedures are often avoided owing to a 'perceived' lack of required time. The engineer falls back on to what he knows from experience, or remembers. This is not unreasonable, although an optimal solution is then usually not obtained. Ehrlenspiel (2004) and Lindemann (2005) present some interesting aspects on the thinking process, approach, and cycles.

Management and consultants are inclined to see only methods offered by the outside as successful, and prescribe them. Notice that in principle, these do not offer more than those already given in VDI 2221-2223 and by Pahl and Beitz (2004) respectively. Observe the following recommendations for the principal design steps and detail design methods:

Target analysis and clarification of objectives

Begin with the best possible clarification of the objective and pertinent requirements. Discern required designs (demands) and wishes, set up a list of objectives, also called the requirement list. Use only requirements that are strictly defined, disregarding forgone conclusions. This assures a good start position and a permanent base for design reviews. The requirements list has different names, for example: a notebook of tasks, specification, etc. This is understood as a 'start document' which, after internal reviews, outlines the tasks to be met by the development and design engineers. Initially, the requirements list cannot always be complete or encompass every possible detail. Any 'cloudy' areas will become clearer as the work progresses. Accordingly, these 'cloudy' items must also either be corrected or have new requirements added to the list.

13.2 The symbol of Darmstadt.
The top of the tower represents the Duke of Hessen-Darmstadt's helping hand for artists and scientists.

The listing of the requirements must be orderly, but without excessively strict formality. Guidelines and checklists corresponding to product life cycle are helpful in finding requirements. These, though, are generally not substitutes for individual thinking in the respective problem areas. The requirements listing should include a production schedule, all cost limitations, responsibilities, and should be updated periodically.

Match the formal requirement listings to the format used by individual companies (or corporations) without ignoring their distinctions, requirements (demands), or desires (wishes) along with the possibility of incorporating changes later. Strive for consensus with all participating partners on the requirements. When differences of opinion remain, make a list describing them. Often these resolve themselves in the development process. By recognising requirements and listing them, solution ideas will usually come to mind in many instances. Use such instances to better understand the requirements and incorporate them in subsequent solutions searches. Analyse existing, known, or proposed solutions to recognise objectives and requirements to learn from and get additional inspiration.

Recognition of functions and their solutions

A function is the intended purpose of a solution. For example: The desired change(s) of input or output in (partial) a technical system. A function may also be a partial task and this is usually described by a noun-substantive and activity e.g. 'force increase'. This approach strengthens the ability to solve problems because it takes place on an abstract level without going into details.

Next after setting up the requirements try to discern the essential functions affecting the solution. Often a listing is very helpful. A task-specific formulation of the function is also very helpful. A subsequent new or re-formulation using generally applicable functions is a good means to recognise similar functions and helpful for systematics and catalogues. If possible, distinguish between principal and auxiliary functions. This assessment may vary with time. The principal functions are the core of the solutions problem while auxiliary or secondary functions are concerned with aspects of supporting and completion.

Setting up a function structure is helpful when the relationships between individual functions become recognisable. In other words, when relationships between partial tasks exist such as in cases that are of the 'when – then' type and in time or logical sequences. Initial function structures are incomplete, and completed and corrected only during the development process. Many conceivable function structures already offer a principal starting solution.

Functions to be satisfied are the basis of 'fault-tree-analysis' or 'error free design' and similar procedures. Possible non-compliance already reveals causes of errors. There are no important or unimportant functions. Unnecessary functions are disregarded. On the other hand, when considering functions in the various design phases, functions can be of first order or of second and higher or lower order directly affecting the solution. Distinguish between function and response. Therefore, avoid the terms 'failure function' or 'disturbance function' and instead use 'failure response' and 'disturbance effect'.

Solution search

A first spontaneous idea is very helpful and can be the beginning of stepwise correction (corrections solution search) or of a continued development, both of which clarify problems and possible ways of solution. Often, and especially during long-term product developments, the sudden and spontaneous idea does not suffice by itself. In that case, a systematic (generating) solution search is much more appropriate. Start the solution search with the principal determining function because it determines the kernel or the type of solution. Decide which search methods are best suited for the case at hand considering personnel and time limitations. If necessary, change the search method as required.

Hints for particular search methods

A thorough discussion among colleagues with pointed questions is very easy to do and very helpful to bring one's own understanding in to the right perspective and can yield surprising inspiration and new ideas. When no satisfactory solution comes to light and new approaches appear unavoidable, initiate a brainstorming session or use the method 635 (continuous development up to a given level of three initial solutions by each of the six participants of the session). Abide by the necessary rules and do not extend such sessions for too long. If no results surface it is better to set up another session with a new formulation, using analogies of the 'synectic type', as the case may be. Results are to be documented during the session. In cases of configurations or arrangements, use the gallery method.

Utilise the sketches produced as documentation of the results. Evaluate all sessions of the aforementioned intuitive based methods for the purpose of finding characteristics for supportive solutions, to request recommendations accordingly, as well as to find those characteristics that lead to the fastest optimal solution. Once these characteristics are discerned, it is worthwhile to proceed in a selective manner (discursive), *i.e.* to order these systematically, expand and complete them in an order-scheme or a matrix. Organising the ideas in such a matrix can be accomplished in many ways, for example, in the first column enter the partial function and then in the next enter the pertinent solutions. This is sometimes called a Morphological Chart. Such ordering schemes often yield new starting points for a solution. Follow this way only when sufficient experience with ordering schemes and enough available time are at hand. Utilise design catalogues (Roth, 1994) but do not expect to find complete information on the problem to be solved. Rather use them for inspiration in finding new or additional solution aspects and setups.

All search procedures often result in an excessive number of proposed solutions. Counter this plurality by a timely elimination of unsuitable and mutually incompatible solutions by means of formal or mental selection methods and referral to the requirements. Only formal handling will immediately provide a 'documentable' selection listing. In general, try to expand the solution area to the point of recognising successful characteristics ('divergence'), and then narrow the search to promising recommendations ('convergence'), followed by expanding these again with help of the recognised target tracking characteristics. The interchange between more abstract (function or characteristics oriented) and more concrete (configuration oriented) considerations helps to find successful solutions.

Solution analysis, selection and critical evaluation

A solution analysis must clarify the advantages and disadvantages of a proposed solution. Personal preferences may not be able to determine the decisions. For more objective consideration, several methods are helpful when appropriately applied.

Use a formal selection procedure, e.g. Pahl and Beitz (2004) with only a few selection criteria:

- mutually compatible
- listed requirements satisfied

- basically feasible
- effort admissible.

This allows a fast and effective selection of suitable proposed solutions. In cases of several positively judged solutions, test them for their significant aspects of safety and preference. If the number of positively judged variants is unsatisfactory, those solutions with certain information defects must be reconsidered. Any information that is lacking can be elicited by suitable research.

A pairing comparison, even when more than two variants are considered, is always mutually relative and does not constitute a final or all encompassing evaluation.

Only when proposed solutions have reached the maturity of a concept variant does the use of evaluation methods pay off. For that purpose the evaluation procedure given by VDI 2225 and the use-value-analysis (efficiency analysis) may be used. The last one requires a weighing of evaluation criteria and is therefore more time consuming.

Evaluation criteria must be comprehensibly specified with the help of guidelines and must be formulated independently of each other. The characteristics should be quantified, which is not always possible during the conceptual design phase. In that case, a qualitative estimate is better than nothing.

Individual evaluation procedures must be known and systematic instructions observed and exercised. A mix-up of evaluation methods or pairing comparisons is methodically incorrect and leads to wrong assessments.

Evaluate variants only on the same design and engineering level; otherwise erroneous assessments result due to only partial or lacking information.

Clarify the meaning of requirements and evaluation criteria respectively, before the evaluation procedure. A resulting 'weighting factor' must be well explained.

A weighting may be waived when not more than 10 or 12 rating criteria of nearly equal importance are selected. Excessive fear in this case is unjustified. A debate regarding weighting factors is often superfluous because weighting results will only differ when the weighting factors for the essential criteria are very different.

It is a serious systematic mistake to introduce weighting factors after a result has been obtained. That would be tantamount to manipulation for the desired result. The overall result and the individual weighting inputs are solely a means to recognise advantages and disadvantages.

The evaluation procedures must determine whether the project is altogether an adequate approximation to the expected goals. It should also consider if all of the economic aspects were attained. To base a decision solely on the calculated result could be a mistake. Other decisions could be justified by considering patent laws and company proprietary aspects.

Evaluation procedures clarify the value level reached and point to any existing weaknesses. Only after elimination of recognised weak spots should an advanced variant be further pursued. Weak spots are those characteristics given less, or only average, evaluation points.

Configuration or detail design phase

After a conceptual or principle solution is developed, the detailed configuration according to Pahl and Beitz (2004) begins. Accordingly, become familiar with and follow the design specifications for dimensions, arrangement, and materials. Always follow the basic rules of clarity, simplicity, safety and reliability.

Apply design principles such as force transmission, division of tasks, self-help, stability and bi-stability. Design principles can be mutually conflicting, therefore, use the principles that are most useful for the task at hand.

Observe the various design rules (Design for X) for development and the manufacturing processes up to and including the recycling phases that define the product life cycle. Often these rules must be simultaneously observed.

The detail design phase often requires more than 10 times the time that is required for a concept development and subsequent testing after the final design. The final detailed design must be subjected to a re-examination and evaluation also as regards the cost and scheduling.

Also required during the detail design phase are functional considerations for the purpose of finding errors and search methods for secondary or sub-functions, and for testing partial systems. The 'fault-tree-analysis', as explained above, has proven to be a good and practical error search method, especially so for partial systems. This method can often replace some more sophisticated and time consuming published procedures.

Use cost estimations given in Ehrlenspiel *et al.* (1998) and Pahl and Beitz (2004). The costs must be acceptable and technologically feasible. It suffices to consider only the varying costs. Even rough estimates of the expected material volume, the number and extent of machined surfaces, and assembly costs will help to avoid exceeding the cost target. Helpful are cost catalogues and elementary cost growth laws.

Do not forgo a systematic search for weak spots by an evaluation method after the final and detailed design is completed. All functions must be reliably satisfied and important properties in terms of evaluation criteria (e.g. the ratio of actual or expected value) should be greater than or equal to 0.7 or in other words, in the upper one-third of the value scale. Otherwise the design must be revised accordingly.

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Chapter 14

Simulation-based design practice

Asko Riitahuhta
Tampere University of Technology

Juha Sääski and Tapio Salonen
VTT Technical Research Centre of Finland, VTT Industrial Systems

Interest in a better understanding of how to study design arose around 1960 as the needs of designers in the engineering design area increased. The result was research work and method development, which produced droves of books on systematic design, like 'Theory of technical systems' by Hubka, 'Konstruktionslehre' by Pahl and Beitz, 'A short course in industrial design' by Tjälve, and 'Integrated product development' by Andreasen. Professor Ken Wallace from Cambridge University has worked in close co-operation with all these and is considered a groundbreaker although he is younger than the group of scientists above. Professor Wallace has developed and translated a central synthesis of German research into English, making it available for global use. He has edited the book 'Konstruktionslehre' by Pahl and Beitz into the book 'Engineering design', developing an exact English terminology that is accepted and widely used. Wallace's edition has been very popular in Finland, even though the book also exists in Finnish.

Professor Wallace has carried out research and successful researcher training at the University of Cambridge and in the Cambridge Engineering Design Centre (EDC). The Centre has developed into a leading ideal for the research centres of other universities: several Finnish technology development programmes have taken influences from the EDC.

Professor Wallace has created a framework in which a theory developed for individual products has been applicable to product families and series products; research on product configuration and modularisation achieved a high level at Cambridge. The Unit, under his direction, has been one of the first to apply knowledge-based systems in planning. In Wallace's research, the creative work of the designer has also been strongly considered. For example, team's research on the basis of knowledge-use provides a strong basis when considering the implementation of product data life cycle management.

Ken Wallace has been one of the most influential persons in Workshop Design Konstruktion (WDK) which is developing into a really international Design Society, a worldwide organisation. His work has been thorough but definitive, influential and future-oriented. The central influence of the WDK and Design Society are conferences, of which an International conference on Engineering Design (ICED) is one of the most particularly valued. Ken Wallace has belonged to the core group.

Ken Wallace's work as a scientist, educator, influential person and director is extremely important. The key is his personality: his lectures are always inspiring. I participated in an ICED Conference that was held in 1987, in

Boston, and since then his lectures have stayed in my mind and still guarantee that engineering design is an inspiring and valuable area to work in.

When we organised the ICED Conference in Tampere, the influence of Ken Wallace was very important through the long preparatory period. He was an ex officio keynote speaker and even participated in the sauna-evening of Finnish organisers.

I would like to relay the sincere compliments of the whole Finnish engineering design science community to Ken Wallace for the scientific ideal he has given. Personally, I would like to offer my warmest compliments for his unreserved support and friendship, and wish him the best success for the future.

Introduction

In the early 1960s, Ivan Sutherland developed the SKETCHPAD system (Sutherland, 1963), a milestone of research achievement in computer graphics. The evolution of computer graphics has since resulted in the development of computer aided design (CAD). Early CAD systems were essentially for two-dimensional drawing and drafting. Solid modelling techniques emerged to describe three-dimensional products unambiguously (Requicha, 1980), and there has since been an increase in solid modellers and three-dimensional CAD systems. Today, it seems that CAD tools support 3D modelling, FEM analysis, analysis of kinematics chains, man-machine interactions, and manufacturing and assembly studies. These tools are called virtual prototyping tools.

Research problems and goals

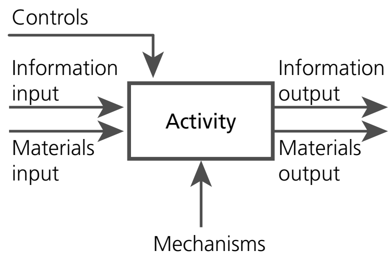
The research goal was to find out the product development process currently used in the Finnish heavy machinery industry and especially to see if the process supports the use of virtual prototyping tools. It was also the purpose to compare this process and different theoretical product development process models with each other. The research studied six different theoretical product development models with a standardised IDEF0-flowchart (IDEF0, 1993) in order to make them easily comparable with each other. These six models form the basis and are also compared with a synthesis model, which represents the product development process of mobile machinery companies. The synthesis model was composed after studying design processes and interviewing the design managers and project leaders of five different companies.

Research method

The IDEF0-flowchart used for modelling all of the product processes in this research is a standardised, purpose-built tool for modelling decisions, functions and actions in an organisation or a system. The models are very straightforward and, therefore, they are usually interpreted correctly even without prior knowledge of the semantics of the system. IDEF0 models only use a very limited amount of symbols and, with the decomposition technique, they can be focused to a suitable level of detail.

The two primary modelling components are functions (represented in a diagram by boxes) and the data and objects that inter-relate those functions (represented by arrows). Each side of the function box has a standard meaning in terms of box/arrow relationships. The arrows may represent inputs, outputs, controls, mechanisms or calls to other processes (Figure 14.1).

Every IDEF0 sheet may contain between three and six functions and every function can be decomposed to its own sheet as a new sub process. Decomposition can be continued until the subject is described at a level necessary to support the goals of a particular project. Therefore, the same model can be shown at a very detailed level or with a more general view to give a good overall understanding of the modelled process. In this research, the models were usually taken down to the third level from the main diagram.



14.1 The basic concept of IDEF0-method

The comparison of product development theories

Six widely recognised product development processes were chosen as the basis of the research. The chosen processes were:

- systematic approach of Pahl and Beitz (1995)
- generic product process of Ulrich and Eppinger (1995)
- Pugh's (1996) total design
- integrated product design of Andreasen (Andreasen and Hein, 1987)
- Suh's (2001) axiomatic design
- TRIZ (Rantanen, 2002).

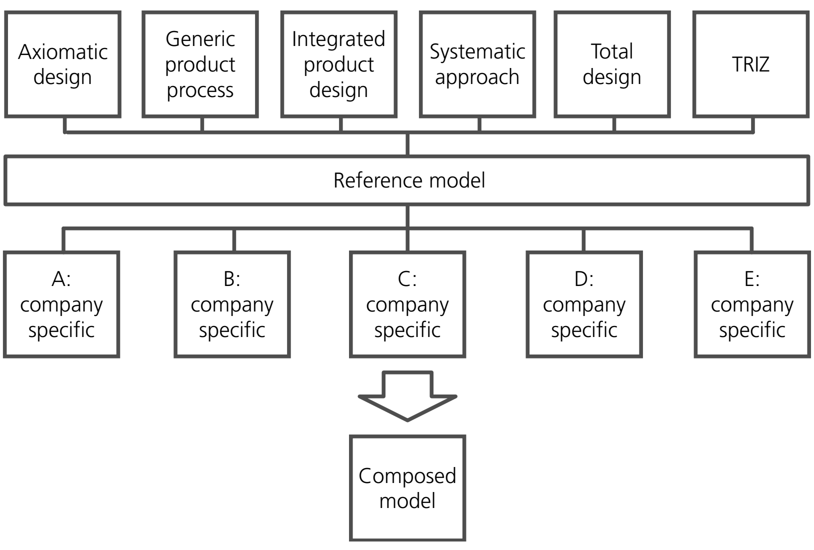
All of the processes were modelled with an IDEF0 flowchart tool in order to make them easily comparable with each other.

The systematic approach model covers the entire design process from task clarification to the detailed design phase. Other models have concentrated on more-or-less narrower parts of the design process. All of the models have some sort of guide for clarifying the task and formulating the problem, but the next step, the generation of solutions, is guided only in the systematic approach, generic product process, TRIZ and axiomatic design. The integrated product design and total design have no implementation tools to guide the generation of solutions.

Generating the model of product development process used in industry

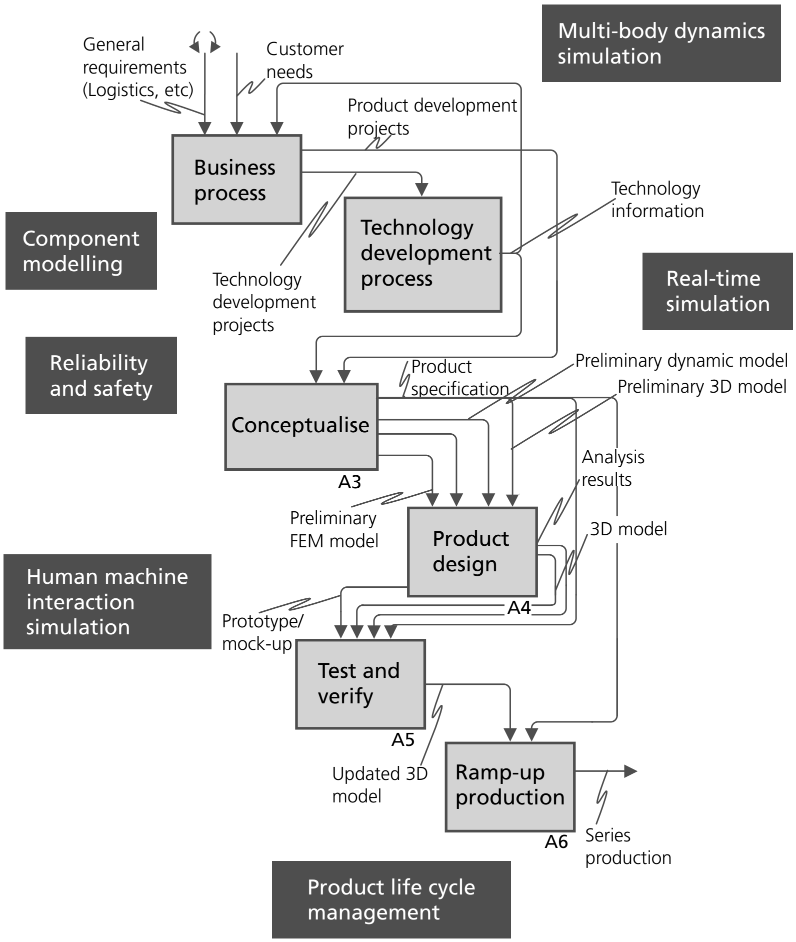
The generic product development process model was composed after interviewing the design project leaders of five globally operating Finnish companies. All of the project leaders involved had participated in large scale product development projects in their company within the last twelve months. The interviews were based on the IDEF0 model mainly derived from the systematic approach of Pahl and Beitz. This model, our reference model, was chosen as the basis of the research because it is widely used in product development education and is therefore quite well known (Figure 14.2).

In collaboration with the design project personnel, the differences between the reference model and their product development processes were identified by modifying design tasks, information flows between tasks and the order of project development task execution. Based on the interviews, a company-specific IDEF0-model of the product development process was created and verified with the personnel of the company in question.



14.2 Method for generic product development process

The common characteristics of these five, *i.e.*, company-specific, differently verified IDEF0-models, were identified and a tentative new simulation-based design process generic model based on Finnish industry was composed (Figure 14.3).

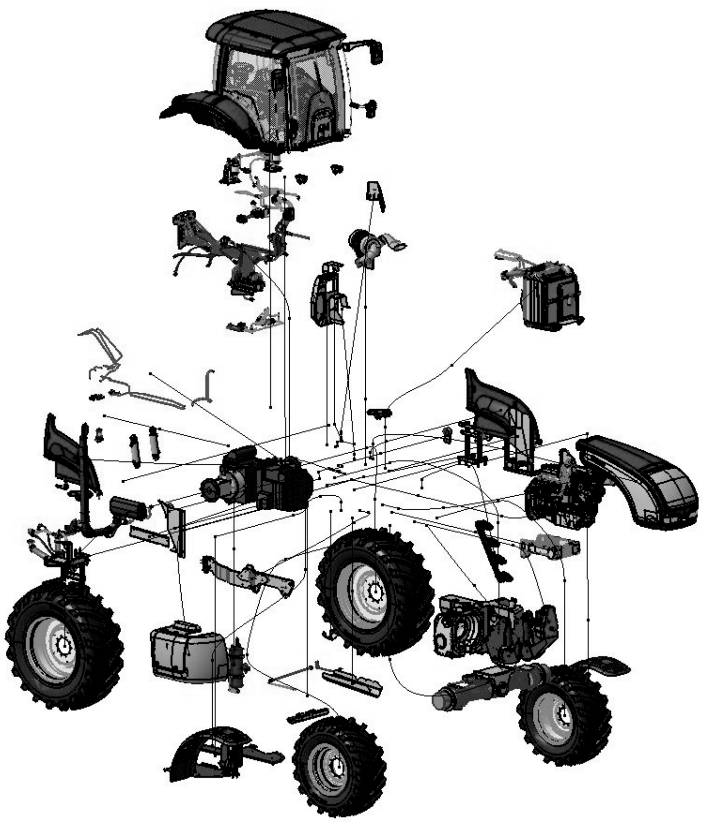


14.3 The tentative simulation-based design process

The product process used in industry is divided into six phases. The first stage is the business process where business cases are investigated and technology development processes or product design processes start. In a technology development process, new technologies and components are researched and the technology information collected in this phase is transferred to the first stage of the product development process, the conceptualisation, or back to the business process as information. In the conceptualisation phase, the preliminary 3D-CAD model of the product is created and the first simulation tests are carried out. In a strongly iterative manner, the concept is finalised and the product design stage begins.

In the product design phase, the preliminary CAD-models are detailed with iterative cycles of simulation and tests and redesigning. After suitable results have been obtained, the simulations are verified by the means of prototype tests. The necessary changes to the product are made and production is ramped up. The verification results are also used to update the simulation tools to make them more accurate.

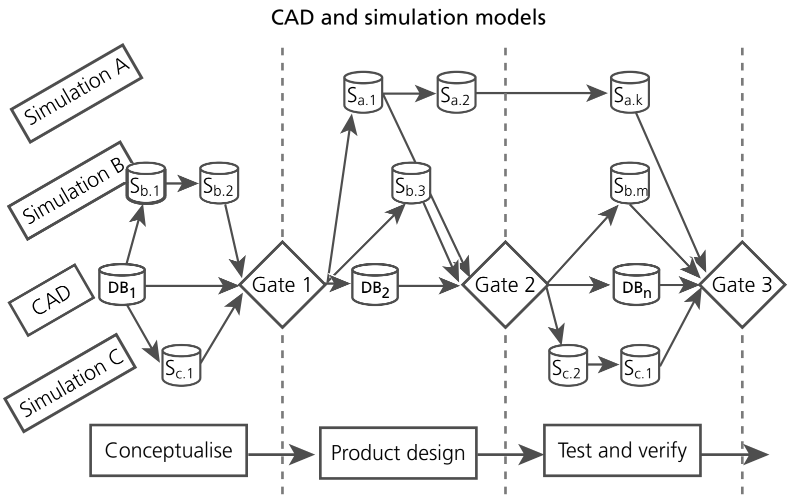
It was noticed that it is not sufficient to just view and share 2D-drawings, especially as in most cases the 2D-drawings are not available in the PDM-system until the design is almost ready for production. In that case, possible



14.4 3D-model of a commercial CAD-system offers good possibilities to make assembly simulations

changes to the designs are much more expensive to make than in the earlier stages of product development. Instead, it is important to share 3D-models, because companies use a 3D-CAD and PDM-based concurrent engineering method in product development (Jämsén, 2004). An example of using a commercial tool for assembly simulation purposes is shown in Figure 14.4. Another example comes from a leading provider of heavy-duty material handling equipment. In a development project, a commercial, advanced CAD-system and its FEM package were used to analyse the structure of the whole machine. Based on analysis and simulation, it was possible to reduce the weight of the machine by 10%.

In a simulation-based design process, the importance of the efficient order of development tasks is crucial. In particular, the 3D-model is used as the starting point in many simulation tools. As the design process proceeds, the product model develops and the different simulation tools produce different simulation models. The PDM-system maintains different versions so that the simulations will always be performed with the right product version. The development of the product model and simulation models at the separate stages of the product process is shown in Figure 14.5.



14.5 CAD and simulation models. Gates show the decision phases of the product process in which the progress of the project is checked and a decision is made on the continuation. The development of the product model is described by DB_1, DB_2, DB_n , and the development of the simulation models conducted from the product model.

Conclusions

The increasing speed of product development processes, as well as the fact that product development responsibility is more and more divided between sub-contractors and partners, increases the importance of well-defined product development process models. The product development process should define all of the necessary breakpoints where the project is evaluated according to defined criteria. A defined glossary is required to avoid misunderstandings between the partners involved in the project.

In this research, it was discovered that IDEF0 modelling of product development processes offers a good visual aid to discuss the stages and milestones of processes. Modelling also offered a good basis to identify actual processes from industry.

Product development processes are influenced by computerised 3D modelling, simulation, analysis and virtual prototyping. The technology development phase and studying the business case have great significance in the product development process used today. Therefore, more powerful tools, such as different simulation tools, especially real-time simulation tools, should be developed to support these phases.

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Chapter 15

Optimisation using the autogenetic design theory

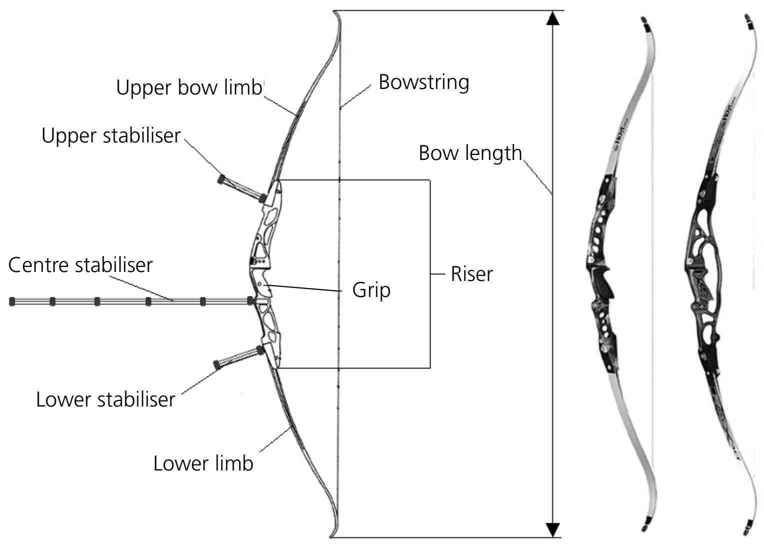
Sándor Vajna, Jürgen Edelmann-Nusser, Steffen Clement, André Jordan
Otto-von-Guericke University Magdeburg

Mario Heller
University of Vienna, Austria

Recurve bows that are used in competitions like the Olympic Games are high technology products. Typical characteristics of the risers of recurve bows are little weight and high stiffness. The aim of this study was to design a riser with a considerably reduced weight at a quite similar stiffness compared to the lightest riser that is used by the archers of the German National Archery Team (actual mass: 1 114g). For this riser the loads that are applied to the riser of a drawn bow were computed and a 3D solid CAD model of this riser with 24 variable parameters was created. The 24 parameters of the model were optimised using evolutionary optimisation according to the criteria of little mass and high stiffness. The best riser out of 1 650 CAD models was selected, manufactured and tested by three archers of the German National Archery Team. The mass of this new riser is 871g, *i.e.* the mass was reduced by 243g or 22%.

Introduction

In the Olympic competitions so-called recurve bows are used. Figure 15.1 shows the essential components of a recurve bow such as limbs, riser and stabilisers. Typical characteristics of a good riser are little weight and high stiffness (Haidn and Weineck, 2001).



15.1 Components of a recurve bow. The limbs are flexible and store the energy. The riser is stiff and made of metal. The stabilisers damp the vibrations after the shot. The limbs are attached to the riser by snapping the limb butts into the limb pockets of the riser.

An important trend in the design of a riser is to reduce weight. For about 20 years most risers have been made of aluminium alloys. The first risers were massive designs and therefore very heavy. Today the risers have lightweight designs as shown in Figure 15.2.

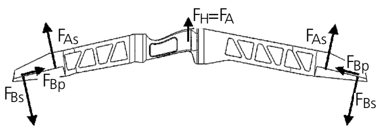
15.2 Three risers of the Hoyt Company (USA) with a lightweight design (side view and front view, respectively). From left to right: the models RADIAN, AVALON, and AXIS. The lightest riser is the RADIAN with a mass of 1 114g. The masses of the AVALON and AXIS are 1 154g and 1 374g, respectively.

The question was whether these designs, especially the design of the RADIAN of the Hoyt Company (see Figure 15.2), are really lightweight designs or whether it is possible to reduce the mass of a riser considerably. Therefore the aim of this study was to design a riser with a quite similar stiffness and a considerably reduced weight compared to the riser RADIAN, the lightest riser that is used by archers of the German National Archery Team.

Methods

The methods consist of the following parts:

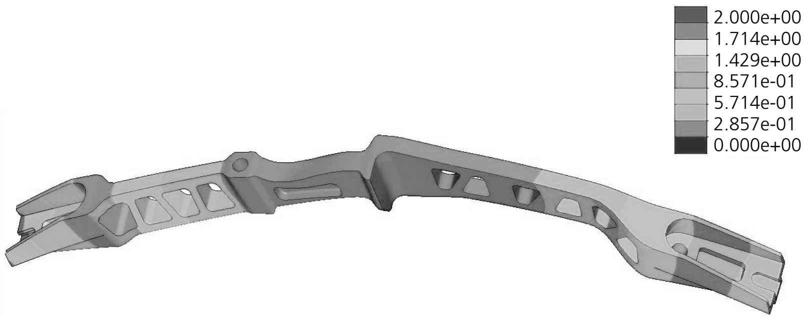
1. An analysis of the loads that are applied to the riser of a drawn bow.
2. A static structural analysis of a riser using the loads of point 1.
3. Design of a parametric CAD model of the riser with 24 variable parameters.
4. Optimisation of the parameters of the CAD model for mass and stiffness using approaches from autogenetic design theory.



15.3 Forces that result in loads on the riser of a drawn bow. At a draw length of 710mm and a draw weight F_H of 200N, the forces in the limb pockets are as follows: F_{Bs} = 1 729N, F_{Bp}= 216N, F_{As}= 1 583N

Load analysis

During aiming, when the bow is drawn, it can be assumed that there is a static balance of forces. For this balance, Figure 15.3 shows the forces or loads that are applied to the riser at the limb pockets and at the grip at a draw weight of 200N and a draw length of 710mm. It should be added that limb pockets are standardised so that limbs and risers of different manufacturers can be combined with each other.



15.4 The CAD model shows the displacements that result from the forces F_{As}, F_{Bs}, F^{Bp} and F_H=F_A at a draw length of 710mm. The colour scale encodes the values of the displacements in mm according to the scale top right. The maximum value of the displacements is 1.85mm. The displacements were computed relative to the point of the load incidence of the force F_H in Figure 15.3.

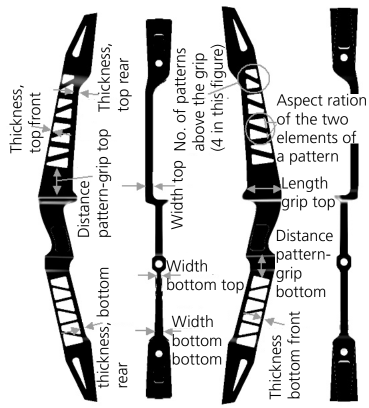
Static structural analysis of the riser RADIAN

Based on a three-dimensional scan of the riser RADIAN a 3D solid CAD model was created. Additionally, the material of this riser was tested in order to get information about its Young's modulus, the yield point and the composition of the aluminium alloy.

After this, the material characteristics and the loads that are applied to the riser were used in the CAD model to compute the stresses and the displacements (Figure 15.4, compare with Figure 15.3). The maximum value of the stresses of the riser RADIAN was 135N/mm^2 and the maximum value of the displacements was 1.85mm. The calculated mass of the CAD model of the RADIAN was 1 048g. This differs from the real mass of the RADIAN of 1 114g because there are three steel bushings to connect the stabilisers to the riser. These steel bushings were not included in the model.

The design of a parametric CAD model of the riser

Based on the scanned model of the riser RADIAN a CAD model with 24 variables (parameters) was designed. Figure 15.5 shows the CAD model and 12 of the 24 parameters. An aluminium alloy (that is mainly used in aircraft industries) was chosen as the material for the optimisation of the riser. The alloy is named AS 28 and is similar to the alloy AlMgSi1. The density of AS 28 is 2.71g/cm^3, its yield point is 403N/mm^2 and its Young's modulus is 72GPa.



15.5 Four side views of the parametric CAD model. 12 parameters of the 24 parameters are exemplarily drawn into the figure. The figure was created using randomised values of the 24 parameters. A pattern consists of two triangular elements; *i.e.* there are four patterns above and three patterns below the grip.

Autogenetic design theory to optimise the parameters of the CAD model for mass and stiffness

Biological evolution means gradual development, permanent adaptation, and optimisation to an aim that thereby changes itself. Evolution is to be understood as a continuous optimisation of a basic solution by observing starting conditions, boundary conditions, and constraints (which may evolve themselves, too). The autogenetic design theory (ADT) is built on analogies to natural evolution to describe and to support product development processes. It provides an evolution-oriented approach for modelling and for supporting the design activity as the substantial activity within product development (Bercsey and Vajna, 1994; Wegner, 1999). The ADT points out that evolutionary operators and driving forces of evolution are important to improve both products and the development process (Clement *et al.*, 2003).

In all phases and at all organisational levels of the evolving new product it is possible to develop new solutions (called individuals) by evolutionary procedures. To develop new solutions the evolutionary procedure (trial and error) dominates in comparison to the deductive approach of conventional design methodology. In accordance with the principles of evolution the best solutions (*i.e.* which fulfil the requirements better) are selected from the preceding solutions (parents) by selection pressure. The selection pressure is formed by the requirements as well as by the driving forces, initial conditions, and boundary conditions of the solution space, which additionally may change during the development process. This so-called autogenetic behaviour is recognisable in the development of any (partial) solution, because each developed solution passes through this self-similar process (Clement *et al.*, 2003). The adaptation is continuous and goal-oriented and therefore can be understood as an optimisation process (Bercsey and Vajna, 1994).

Different research activities show that the genesis of solutions follows in all phases and organisational levels the same procedure (comparable with the TOTE-scheme (Ehrlenspiel, 2001)). The scheme of the genesis of solution is a self-similar procedure. This self-similar procedure exists in all phases of the product development process and the product which is being developed (Wegner, 1999).

The above thesis is also confirmed by the fact that today about 90% of new products emerge from an adaptation design, with the significant hallmark that good properties of preceding solutions are inherited by succeeding. This analogy is attributable to the fact that the human way of thinking is also a product of evolution. Before a completely new product is developed within a given cost frame, attempts are made to adapt existing solutions to the new conditions by modifying them and, thus, reducing cost and development time.

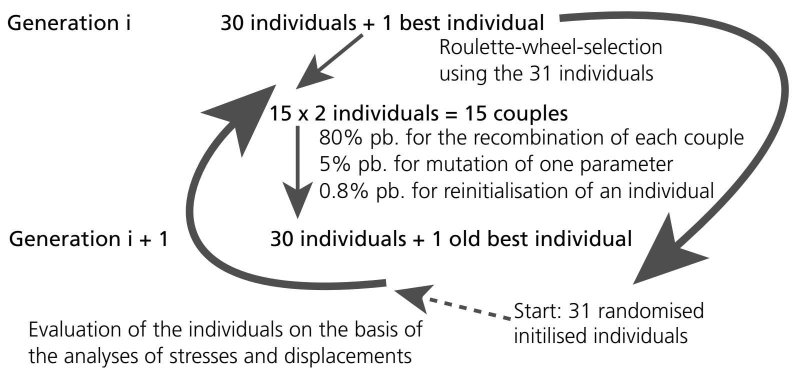
The self-similar processes and the fact that the results of product development cannot be predicted allow the assumption that product development contains elements from Chaos Theory. Chaotic behaviour (for example, Briggs and Peat, 1990) by small changes or failures increases unpredictable system behaviour similar to the product development process. 'Classical' procedure models do not describe (or do this insufficiently) such kind of dynamic reactions to failures.

From the described character of evolution it is to be concluded that evolution is a kind of optimisation (Wegner, 1999). Otherwise, and from the view of product development, designing is an optimisation process with a given aim and contradictory boundary conditions (Pahl and Beitz, 1997). From this it follows that product development can be described from the viewpoint of optimisation by using evolutionary operators. The aim of the optimisation itself may change also because it is based on the respective (and changing) requirements and boundary conditions. This fact clearly induces an evolution.

When performing an optimisation, populations of artificial individuals are created. Each artificial individual is represented by a chromosome. The artificial individuals reproduce themselves in a similar way as biological individuals do and thus create new artificial individuals. To get an optimisation the artificial individuals are evaluated: For each artificial individual its fitness is calculated with respect to the optimisation problem. Generally, a higher fitness of an artificial individual means a higher probability for reproduction. For reproduction, operations such as crossover, mutation and recombination can be used.

In our case the individuals of the population were the risers. Each artificial individual or riser was represented by its chromosome consisting of its 24 individual parameters. The risers reproduced themselves using recombination, mutation and crossover and thus created new risers. The fitness of each riser was defined by its fitness value. To get the fitness value for each riser the stresses and the displacements were computed (see Figure 15.4). This fitness value was dependent on the mass of the riser, the maximal value of the displacements of the riser, and the standard deviation of the stresses of the riser, whereby the mass is the criterion for lightness and the displacement is the criterion for stiffness. On the basis of these stresses and displacements the fitness of each riser or individual was calculated.

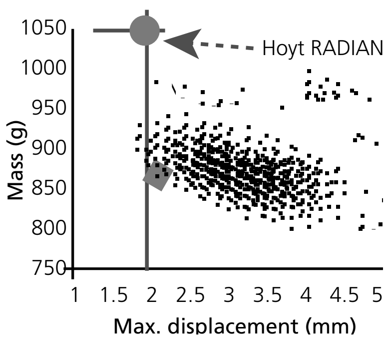
In order to avoid risers with a variance in the stresses that is too large, we used the standard deviation of the stresses when calculating the fitness. We did not use the maximum value of the stresses because the maximal value of the stresses could be assumed to be much lower than the yield point of the material. Hence we assumed that the maximal value of the stresses is not a problem.



15.6 Schematic diagram of the evolutionary optimisation. The algorithm starts down right with 31 individuals that are initialised with randomised values, 'pb' means 'probability'.

Figure 15.6 shows a schematic diagram of the evolutionary optimisation. The algorithm can be explained in the following eight steps:

1. The algorithm starts with 31 individuals that are initialised with randomised values.
2. The 31 individuals are evaluated on the basis of the analyses of stresses and displacements. The fitness value of each individual is calculated. In addition the fittest individual is selected.
3. On the basis of a roulette-wheel-selection, 15 couples (parents) are linked together to be used for reproduction.
4. The 15 parents or couples recombine with a probability of 80% according to the method 'uniform order based cross-over' and create two children each. With a probability of 20%, the couples do not recombine; in this case (no new individuals created) the two children are created as full replications (or clones) of their parents.
5. For each of the 30 children, a mutation of one randomised parameter is done with a probability of 5%. In the case of a mutation the actual value of the parameter is changed to a uniformly distributed value within the range of this parameter.
6. With a probability of 0.8% for each individual of the 30 children, all 24 parameters are reinitialised with randomised values.
7. We now have the next generation of 31 individuals consisting of 30 children and the old best individual (generation i+1 in Figure 15.6). The 31 individuals are each evaluated on the basis of the analyses of their stresses and displacements; the fitness value of each individual is calculated. The new fittest individual is selected.
8. Go back to step 3 and so on.



15.7 Each black rhombus marks the mass and the maximal displacement of one riser out of the 1 650 risers. The circle marks the mass (1 048g) and the maximal displacement (1.85mm) of the riser RADIAN for comparison. The rhombus marks the riser that was selected for manufacturing (mass of CAD model: 869g, displacement: 1.94mm). Not all individuals are included in the figure for there were individuals with a maximal displacement of more than 5mm or a mass of more than 1 050g.

The algorithm stops after a defined number of loops or generations. Alternatively, it may also stop when a certain (prefixed) convergence of the results is detected (which was not applied in our case).

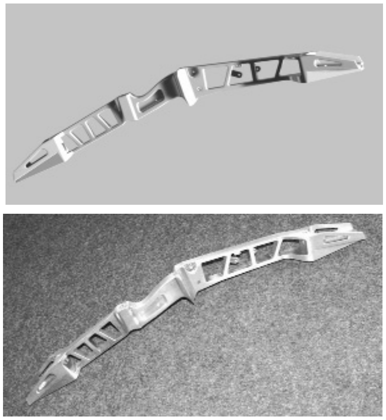
Two runs with different weighting factors and numbers of generations (20/35) were done and one model out of 1 650 models was selected (see Figure 15.7). The selected riser was manufactured with preforged AS 28 using a CNC (computerised numerical control) milling machine.

First tests in practice were done at the Olympic Training Centre in Berlin with three athletes of the German National Archery Team. Two athletes shot nine times each, the third athlete shot 300 times.

Results

Figure 15.7 shows the masses and maximal displacements of the risers that were created in the two runs of the evolutionary optimisation. We see clearly that the mass of the RADIAN is very large compared to the masses of the risers created by the evolutionary optimisation.

The manufactured riser had a total mass of 871g (Figure 15.8), *i.e.*, the mass was reduced by 243g or by 22% at a quite similar stiffness (max. displacement: 1.94mm). The three archers that tested the riser stated that the new riser suits them well and that it is not only very stiff and light but also damps the vibrations after the shot very well.



15.8 Top: CAD model of the selected riser (mass: 869g). Bottom: manufactured riser. Its total real mass including three threaded inserts for the connection of the stabilisers is 871g, Its maximal displacement is 1.94mm and the maximal value of its stresses is 160N/mm^2.

Figure 15.9 shows a completely assembled bow with the new riser and an archer of the German National Archery Team testing the riser.

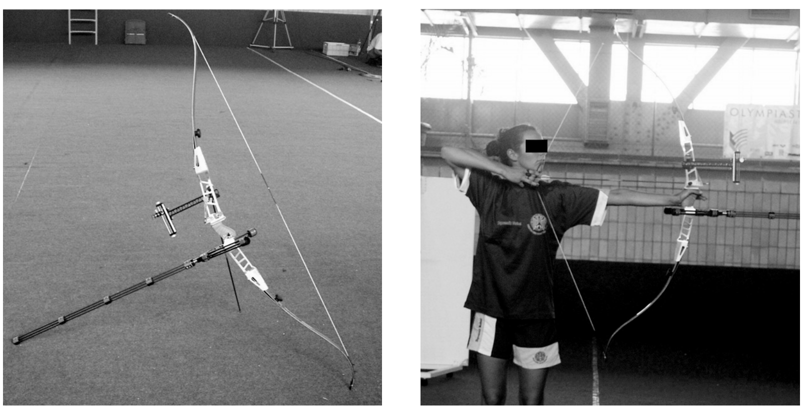
In the shooting tests the three archers were asked to tell their subjective impressions of shooting with the new riser: They all stated that the new riser suits them and that it is not only very stiff and light but also damps the vibrations after the shot very well. The archer who shot 300 times also told that the bow groups very well. In this context, 'to group well' means that, if the archer thinks that an arrow should hit the target next to the hit of another shot, the arrow really hits the target next to the hit of the other shot. *I.e.* the variance in the hits is not a result of some mechanical slackness of the bow but of the variability of the archer's motion control. This archer also asked to use this new riser in the new season.

Discussion

It clearly turned out that the riser RADIAN is in no way optimised for mass or stiffness. Thus, the evolutionary optimisation creates risers with less mass and less maximal displacement as well. So we can assume that, if we had increased the selection pressure in some way to get less displacement, we would have gotten a shift of the scatter plot in Figure 15.7 to the left and to the top. Thus, a lot of risers could have been created with less mass and less maximal displacement compared to the riser RADIAN.

We also see that it is possible to design risers with a mass of less than 800g if we accept maximal displacements up to 4mm. The problem is that we do not really know in which way reduced stiffness influences the shooting of the archers. Though we find high stiffness as a criterion of a good riser in literature (and trainers and archers also think so), there are no empirical studies that support this issue. When we think about the displacement of the flexible limbs, which is 700, 800 or 900mm when the archer draws the bow, we cannot really believe that one, two, or three millimetres of difference in maximal displacement of different risers really influences the shooting. In fact, a much more plausible criterion than stiffness could be the torsion especially of the upper limb pocket. If the torsion is too large, this could result in the fact that, when the shot is released, the arrow is not only accelerated in its axial direction but also in some manner in a direction orthogonal to its axis. As a result, the arrow does not fly straight on to the target but squirms and slides a little bit to the side. This may have a negative influence on both the shot and the score. Therefore the selection of our riser with a maximal displacement of 1.94mm was conservative. Anyway its mass is nearly 250g lower than the mass of the RADIAN.

For further empirical studies with archers we will manufacture a slightly modified riser with the smallest mass of the evolutionary optimisation which is 779g at a maximal displacement of 3.53mm and will compare it to the actual riser with 871g.



15.9 Completely assembled recurve bow and a archer of the German National Archery Team testing the riser

Dedication

This contribution is dedicated to Professor Ken M Wallace for his 60th birthday.

Acknowledgement

This study was supported by the Federal Institute of Sport Science (Bundesinstitut fuer Sportwissenschaft; reference no.: VF 0408/15/40/2003), Bonn, Germany.

15.10 The team. From left to right: Martin Frederick, Chief Coach and German Federal Archery Trainer; Sándor Vajna; Wiebke Nulle, one of the best German archer; Jürgen Edelmann-Nusser; Mario Heller and Joerg Zinner, Head of Olympiastuetzpunkt, Berlin, Germany.

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Authors

Saeema Ahmed
Cambridge Engineering Design Centre, University of Cambridge. Interests include product design, the use of experience and expertise in design, indexing structures for capturing engineering design knowledge and empirical design research methods. Shortly to be joining MEK, Technical University of Denmark, as an Associate Professor of Product Design.

Mogens Myrup Andreasen
Professor and Head of Department of Mechanical Engineering – Engineering Design and Product Development, Technical University of Denmark. Interests include design methodology, product development, methods for synthesis and the creation of a theory foundation for design methodology teaching.

Michael F Ashby
Royal Society Research Professor in the Department of Engineering, University of Cambridge. A Visiting Professor of Design at the Royal College of Art, London, and a Chairman and co-founder of Granta Design Ltd. Interests include mechanisms of plasticity and fracture, powder compaction, mechanisms of wear, methodologies for materials selection, and the modelling of material shaping processes.

Herbert Birkhofer
Professor and Head of the Institute of Product Development and Machine Elements, Darmstadt University of Technology, Germany. Research is focussed on transfer of design methodology into industry, the development of environmentally friendly products (EcoDesign) and empirical design research in collaboration with cognitive psychologists.

Lucienne Blessing
Professor and Head of Department of Mechanical Engineering and Transport Systems – Engineering Design and Methodology, University of Technology, Berlin. Her interests include the introduction of improved methods to help the process of industrial product development.

Rob Bracewell
Cambridge Engineering Design Centre, University of Cambridge. Senior Research Associate and Assistant Director of the Engineering Design Centre. Interests include design research methodology, design rationale capture, design synthesis, knowledge-based engineering and rapid development of usable prototype engineering software tools.

David Cebon
Department of Engineering, University of Cambridge. A Reader in Mechanical Engineering, Managing Director and co-founder of Granta Design Ltd. and the architect of all generations of Granta Design's products. Interests include design and dynamics of heavy commercial vehicles, traffic instrumentation, damage mechanisms of pavement materials and the effects of vehicles on the response and damage of roads and bridges. The use of computers in engineering design and education.

Amaresh Chakrabarti
Centre for Product Design and Manufacturing, Indian Institute of Science. Associate Professor of Design and Director of the Innovation, Design Study and Sustainability Laboratory (IdeasLab). Interests include design synthesis and creativity, design for environment, design collaboration and design research methodology.

John Clarkson
Cambridge Engineering Design Centre, University of Cambridge. Professor of Engineering Design and Director of the Cambridge Engineering Design Centre. Interests include inclusive design, design evaluation, design optimisation and design process improvement.

Steffen Clement
Otto-von-Guericke University

Magdeburg, Germany. Research Assistant of Information Technologies in Mechanical Engineering. Interests include design methodology based on biological evolution (autogenetic design theory), design optimisation based on evolutionary algorithms, computer aided engineering and integrated product development.

Steve Culley
Reader and Head of Design in the Department of Mechanical Engineering at Bath University. He is also a Fellow of the Institution of Mechanical Engineers and non executive Director of Adiuri Systems. Interests include components selection, feedback and decision making, the use of fuzzy logic, the electronic catalogue and component categorisation.

Alex Duffy
Department of Design Manufacture and Engineering Management, University of Strathclyde Director of the Computer Aided Design Centre. Interests include the knowledge early stage design, learning in design, design re-use, performance measurement and design productivity, process optimisation, vague geometric modelling and sketching support.

Jürgen Edelmann-Nusser
Institute of Sport Science, Otto-von-Guericke University Magdeburg. Interests include sports equipment design, biomechanics and computer science in sport.

Crispin Hales
Hales & Gooch Ltd., Chicago, USA and Christchurch, New Zealand. Forensic engineer specialising in engineering design and design process investigations. Interests include managing engineering design, analysing the engineering design process and improving the teaching and practice of engineering design.

Mario Heller
Section of Biomechanics, Kinesiology and Applied Computer Science, University of Vienna, Austria. Research Assistant. Interests include sports equipment, biomechanics, modelling and simulation, neuromuscular activities.

André Jordan
Otto-von-Guericke University Magdeburg, Germany. Assistant of Information Technologies in Mechanical Engineering. Interests include autogenetic design theory, mapping of analogies in product development process, evolutionary product optimisation, and integrated product development.

Sanghee Kim
Cambridge Engineering Design Centre, University of Cambridge. Research Associate. Interests include ontology learning, ontology population, natural language processing and question answering systems

Geoff Kirk
Rolls-Royce plc. Chief Design Engineer, Civil Aerospace. Responsible for design skill, process and professionalism throughout the company. He has led design teams on the detail and conceptual design of the most recent Rolls-Royce Civil Aero Engines, is a member of the Cambridge Engineering Design Centre Steering Committee, and a Visiting Professor at Queen Mary College, London and Nottingham University.

Matthias Kreimeyer
Institute of Product Development, Technical University of Munich. Scientific Assistant. Interests include analysis and optimisation of simultaneous engineering processes, application of CAx-technology in product design, and design integration and simulation in concurrent engineering.

Udo Lindemann
Head of the Institute and Professor of Mechanical Engineering,

Institute of Product Development, Technical University of Munich, Germany. Interests include methods of product development, design thinking, interdisciplinary research, design process improvement, cost engineering and computer support.

Maik Maurer
Institute of Product Development, Technical University of Munich. Scientific Assistant. Interests include product models and structures in product development with particular interests in mass customisation, design structure matrix, graph theory, intelligent strategies and algorithms for product analysis and synthesis.

Chris McMahon
Innovative Manufacturing Research Centre, University of Bath. Reader in Engineering Design and Engineering Director of the Bath IMRC. Interests include information and knowledge management, risk and uncertainty in design and computer-aided design.

David E Newland
Emeritus Professor of Engineering, University of Cambridge. With Ken Wallace and Mike Ashby, one of three founding principal investigators for the EDC; Head of the Engineering Department, 1996-2002. Specialist in mechanical and random vibrations and machinery design.

Gerhard Pahl
Formerly Head of the Institut für Maschinenelemente und Höhere Konstruktionslehre, Technische Universität Darmstadt, now retired and a member of the Institute of Product Development and Machine Elements. Interests include engineering design, systematic approach and design thinking in interdisciplinary research.

Asko Riitahuhta
Product and Production Systems Design laboratory, Institute of Production Engineering, Tampere University of Technology, Finland. Professor of Product Design and Development and Head of Laboratory. Interests include design methodology, product structuring and modularisation, life cycle management of products and services, and radical innovation by design.

Tapio Salonen
VTT Technical Research Center of Finland. Senior Research Scientist. Interests include product data management, PLM, product data standards, STEP and design methodology.

Juha Sääski
VTT Technical Research Center of Finland. Research Scientist. Interests include design methodology, CAx applications and PLM.

Sándor Vajna
Otto-von-Guericke University Magdeburg, Germany. Professor of Information Technologies in Mechanical Engineering, previously 12 years of industrial experience. Interests include integrated product development, design methodology based on biological evolution, dynamic process navigation, CAx applications and PLM (former CIM).

Engineering Design Centre, University of Cambridge, UK

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