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Observations on Some German Contributions to Engineering Design In Memory of Professor Wolfgang Beitz

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Abstract. *This paper, written in memory of Professor Wolfgang Beitz,*[1] *discusses some of the influences of the work undertaken in Germany on systematic engineering design. It highlights differences between the language regions, and gives examples of design research and design education linked to* Konstruktionslehre *– the standard text on systematic engineering design for which Professor Beitz was most widely recognised outside Germany. The paper finishes with a plea for a greater exchange of ideas.*

Keywords: Design education; German research; Systematic engineering design

1. Introduction

Germany has a reputation for the high quality of its engineering products. This is due in part to placing great emphasis on engineering design and according high status to engineering designers.

Professors of Machine Design in Germany normally have considerable industrial experience. This has had a significant influence on German engineering education in general, and on engineering design education in particular. Engineering education in Germany is notable for combining an understanding of engineering fundamentals and basic technology, along with a solid grounding in design methods. The appointment of Professors in Machine Design also stimulated design research. Numerous contributions in this area have been produced, and an early outcome was the development of *systematic approaches to engineering design*. This pioneering work has influenced engineering design in many other countries. The aim of this paper is to concentrate on the influence of some of this work in the English-speaking world, and, in particular, on the contributions of Professor Wolfgang Beitz, who died on 23 November 1998.

Professor Beitz was one of the most prominent and enthusiastic advocates of systematic engineering design in Germany. He achieved an international reputation, and made significant contributions to both design research and design education. His contributions have found their way into the English-speaking world through the translations of *Konstruktionslehre*, VDI 2221, and *Dubbel*.

First an overview of the development of systematic engineering design in Germany is provided, followed by an English perspective on this development. This perspective covers the English editions of *Konstruktionslehre*, the acceptance of systematic engineering design outside Germany, and some examples of design research and design education linked to systematic engineering design.

2. Development of Systematic Engineering Design in Germany

German academics and practitioners have a long tradition of studying the engineering design process, and much research has been undertaken into rationalising the design process and developing supporting methods and tools. It is impossible to mention all the contributions, however a brief overview will help to set the context. When the German approach is referred to, contributions from other continental European countries are included.

Redtenbacher and Reuleaux pioneered some of the earliest ideas on the principles of machine design in the 1850s. The first step-by-step approach was developed

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by Erkens in the 1920s. The concept of systematic design was stimulated in the 1950s and 1960s by Kesselring, Tschochner, Niemann, Matousek and Leyer. They identified the various phases and steps of the design process, and provided specific recommendations and guidelines for tackling them.

One of the early contacts the English-speaking world had with German thinking on systematic design was through the translation of Matousek's book (Matousek 1963). This book provided a clear insight into the valuable work being undertaken in Germany, but this lead was not followed up for several years.

During the 1970s, the aim was to rationalise engineering design and to describe a *generally applicable approach* independent of engineering domain. It is not possible to mention every researcher, but key contributions were made by Hansen, Rodenacker, Roth, Koller, Erhlenspiel and, of course, Pahl and Beitz. Beitz teamed up with Pahl to 'present a comprehensive theory of general engineering design'. One result was their book *Konstruktionslehre* (Pahl and Beitz 1977).

In *Konstruktionslehre* the importance of the decisions taken in the early phases of the design process is emphasised. Of particular importance are the various methods described for tackling product planning, clarification of the task, and conceptual design. Their chapter on Embodiment Design exemplifies the tradition in Germany of linking design methods with machine elements, the essential repertoire of engineering design.

In the early 1980s, questions about the effectiveness of CAD systems were being raised, and it was realised that many design models and methods had not been tested rigorously. These questions prompted design experiments and case studies in which the human activity of designing received much more attention. In Germany, for example, Erhlenspiel, Pahl and Dörner started an important series of experiments to study individual designers working in a laboratory environment.

3. An English Perspective

3.1. The English Editions of *Konstruktionslehre*

The translation of *Konstruktionslehre* was undertaken in the Engineering Department at Cambridge University. During the 1960s and 1970s, a number of key people in the department encouraged and developed the teaching of engineering design, including French, Marples, Reddaway, Glegg and Welbourn. Welbourn was familiar with the German literature on engineering design, and invited Beitz to visit Cambridge. After this visit, it was Welbourn who was responsible for persuading the British Design Council to commission the translation of *Konstruktionslehre*.

In 1978, Wallace joined the Engineering Department at Cambridge and was given the task of continuing to develop the design teaching. To put this teaching on a firmer foundation, he saw the need for a reference book to complement French's book on Conceptual Design (French 1971). *Konstruktionslehre* fulfilled this need by providing a coherent and systematic approach to design supported by many engineering examples. For two years Wallace, who was familiar with German having spent a year working in Munich, worked closely with the translator, Pomerans, on the basic translation. It took a further two years of editing by Wallace to rationalise the terminology, and to ensure consistency throughout. The first English edition was published in 1984 (Pahl and Beitz 1984), and an abridged student edition in 1988. *Konstruktionslehre* has since become one of the most widely referred to books on engineering design in the English language, and is recognised as a standard reference for research, education and practice. In 1994, the authors started work on translating the third German edition, supported by Bauert, a former student of Professor Beitz. The second English edition was published early in 1996 (Pahl and Beitz 1996).

One of the challenges of translating *Konstruktionslehre* was defining the terminology, for example the terms for the main phases of the design process. In German many words represent the English word 'design'. *Konstruktion* was the overall term used in the book, and for the main phases of the design process the terms *Konsipieren*, *Entwerfen* and *Ausarbeiten* were used. The first and last translated easily into Conceptual Design and Detail Design, respectively. It was the middle term that caused difficulties, and many translations were used before the term 'Embodiment Design' was selected. The clue for this was provided by French (1971), who described the middle phase as the 'Embodiment of Schemes'. 'Embodiment Design' has now been fully accepted in the English language, and was used in the first British Standard on engineering design, BS 7000 (BSI 1989).

An extremely difficult concept to translate was *Wirk-*, e.g. *Wirkprinzip*, *Wirkbewegung*, *Wirkfläche*, etc. These concepts, common in the German literature, are not used in English, and refer to the principle, movement, surface, etc., *actively engaged in realising the function being embodied*. There was no exact translation. In the first English edition, it was only necessary to translate the first term as ‘working principle’, as the other terms could be made clear from the context. When editing the English edition of VDI 2221 (VDI 1987), Wallace decided to translate *Wirk-* as ‘active’, e.g. ‘active principle, active movement, etc.’ Eder, when translating the work of Hubka (1984), translated *Wirk-* as ‘action’, e.g. ‘action principle, action movement, etc.’. Neither ‘active’ nor ‘action’ was quite right, and in the second English edition of *Konstruktionslehre*, the translators returned to ‘working’, e.g. ‘working principle, working movement, etc.’. This is still not a completely satisfactory solution, and the latest suggestion is to generate new hybrid terms: ‘wirk-principle, wirk-movement, etc.’.

Before leaving the translation of *Konstruktionslehre*, it is important to mention another book that Beitz was closely involved with – the *Dubbel*. The *Dubbel* is the standard German reference book on the design of machines and machine elements. The first edition of the *Dubbel* was published in 1914, and Beitz was the editor from 1978 until his death in 1998. In 1994 the first English edition (Dubbel 1994) was published. An exciting development is the launch of *Dubbel Interactiv*, an interactive CD ROM version of the *Dubbel* – an indicator of things to come.

3.2. Acceptance of Systematic Engineering Design Outside Germany

In the 1960s and 1970s, interest in engineering design grew, not only in Germany, but around the world. In Germany, much effort went into rationalising the design process, suggesting phased approaches, and developing design methods to support each phase. However, the knowledge was scattered and lacked coherence, and little was exchanged between researchers in various countries due to the language barrier. This, among other reasons, led to a lack of appreciation of the German achievements.

A problem facing systematic approaches, such as *Konstruktionslehre*, is the frequently heard argument that such approaches run counter to the traditional way designers think, which is opportunistic and focuses on elaborating an initial idea. These arguments appear to be based on the view that systematic approaches are actual *descriptions of the design activity*. They are not intended to describe what happens, but to propose new and better ways of working. In that sense, they are not theoretical descriptions; they are *methodologies*.

Probably a more important reason why it took a long time for systematic approaches to become recognised outside Germany is that they differ substantially from those proposed in the UK and the USA, as discussed by Blessing (1994, 1996). The difference between the two approaches is most obvious in the conceptual design phase.

Approaches from the UK and the USA can be characterised as *product-oriented,* i.e. the process of concept generation focuses on the analysis of an initial product idea, which is then transformed into a concrete concept by *step-wise refinement*. The generation of the concept is hardly supported, other than by means of generic idea generation methods. The product-oriented approach is intuitive with respect to the generation of concepts, but discursive with respect to the analysis of solutions.

Most Central European approaches, among which *Konstruktionslehre* is the most widely known, focus on a systematic generation of solutions using various levels of abstraction. The approach can be characterised as *problem-oriented,* i.e. the process of concept generation focuses on analysis of the problem and abstraction, rather than on the analysis and evaluation of an initial product idea. Concept generation is a discursive process. Specific methods are suggested to translate the problem into a concept through a *step-wise concretisation* involving various levels of abstraction, e.g. functions, physical principles and working principles.

This emphasis on systematic methods to support the generation of concepts is the strength of problem-oriented approaches such as *Konstruktionslehre*, as the conceptual design stage is considered to be ‘among the most demanding steps in design work and indeed the whole of engineering’ (Hubka 1984). Unfortunately, some of the methods and concepts proposed to support the transformation from problem into concept are among those that are least understood. This is partly due to the difficulty of translating into English the German terms that are important for dealing with the concept on an abstract level, such as the term *Wirk-* discussed earlier. Many publications elaborating such interesting concepts have not been translated into English.

In most problem-oriented approaches, there is no explicit reference to the product idea resulting from the policy phase, or any other idea that might have come up during the problem definition phase. The process is depicted as a pure abstract-to-concrete process, although the accompanying text emphasises iterations. This has led to many objections, suggesting the approaches are rigid and counter-intuitive. In product-oriented models, it is this initial product idea that is continually elaborated throughout the design process. In this respect, product-oriented approaches are closer to current practice, as suggested by investigations into how designers actually design. This could be one reason why these approaches are generally more accepted outside Germany.

The effectiveness and efficiency of the various approaches are not yet well established, although research in industry (Birkhofer 1979, Hales 1987, Wiendahl 1979) and in the laboratory (Fricke and Pahl 1991, Fricke 1993, Günther 1998) suggests that the potential of approaches, such as that exemplified by *Konstruktionslehre*, is large.

Studies in the UK and the USA (Cooper 1990, Dwyer and Mellor 1991) have identified several success factors in product development. It is clear that the underlying procedures are very similar to those that are typical for a problem-oriented approach. A comparison of approaches suggests that product-oriented approaches are examples of good design practice, whereas problem-oriented approaches propose extensive abstraction to improve ‘good’ design practice (Blessing 1996).

3.3. Some Examples of Design Research Linked to *Konstruktionslehre*

It was mentioned earlier that in the early 1980s, questions were being asked about the applicability and validity of the models and methods that had been proposed during the 1960s and 1970s. Two things needed to be done: (1) to study existing design processes to determine best practice and indicate the need for support tools; and (2) to apply and observe methods and tools in real test cases in order to assess their effectiveness and efficiency. Two research projects involving the authors are discussed briefly.

In 1982 Hales and Wallace started a collaborative research project with British Gas in the UK. The aim of the research was to study the design process in practice, and attempt a preliminary evaluation of a systematic approach to design. The design task to be observed was the design of a Coal Gasifier Test Rig that involved the challenging task of handling flowing coal at high temperature and pressure. The task was seen as both novel and complex.

A systematic approach based on *Konstruktionslehre* was introduced into the design process, and all the design activities were recorded during the 34-month project. The reduced data resulting from this was analysed both quantitatively and qualitatively in terms of the engineering design process (Hales 1987, Wallace and Hales 1987).

The quantitative analysis showed that the design process can be represented by a set of overlapping phases, each consisting of a particular mix of procedural steps and other general design activities. It was found that these general working and managing activities took up 53% of the project time. The results of the project demonstrated the benefits of adopting a systematic approach, but highlighted that the approach must be adapted to match the particular industrial context.

This project has become a benchmark for data gathering in industry, and to this day remains one of the largest studies of its type. It was the success of this research project, and subsequent projects at Cambridge in the 1980s, that provided the foundations for the Engineering Design Centre (EDC) at Cambridge, which was established in January 1991.

A large industrial study with Philips in The Netherlands was undertaken by Blessing, and used as the basis for the development of a computer-based tool to support systematic design. The research involved the detailed observation of the design process of an X-ray system between October 1998 and February 1990, using a variety of research methods. Over 200 people were involved in the design process, which, in total, required tens of thousands of hours of design effort to complete. The project demonstrated the potential of a systematic approach to design, and led to the development of the Process-based Support System (PROSUS) (Blessing 1994).

PROSUS Combines the potential of a systematic approach to design, the advantage of computer processing, and the knowledge and abilities of designers. It is believed that, to improve the effectiveness and efficiency of the design process, computer support should be based on a model of the *process*, rather than a model of the *product.*

The basic building block of PROSUS is the Design Matrix, which represents the design process as a structured set of issues and activities. The Design Matrix combines the advantages of product-oriented approaches in terms of analysis and evaluation, with the advantages of problem-oriented approaches in terms of the steps from problem to concept. The emphasis on the problem-oriented approach is justified by its observed positive impact.

3.4. Some Examples of Design Education Linked to *Konstruktionslehre*

The publication of the English edition of *Konstruktionslehre* had a significant impact on design education in the English-speaking world. Some examples of this impact in the UK and in the USA are described briefly.

The first impact, not surprisingly, was on the design teaching in the Engineering Department at Cambridge University. Around 300 undergraduates are admitted to the department to study engineering each year. A feature of the Cambridge course is that the first two years of study are common for all students. They only specialise in a particular engineering domain in their third and fourth years.

A major revision of the undergraduate engineering course was introduced in 1985, just as the translation of *Konstruktionslehre* was completed. This provided the ideal opportunity to introduce the ideas under-pinning systematic engineering design into the design teaching. The model of systematic design was used to provide an overall structure for all the design teaching in the department, with an introduction to the systematic approach starting in the first year of the course.

In the final year, a new optional course was introduced based on the Embodiment Design chapter in *Konstruktionslehre*. It focused on the principles and guidelines of Embodiment Design, and proved very popular. This course provided the basis for a number of very successful short courses for practising designers organised by the Cambridge Programme for Industry. A further revision of the design teaching was introduced in 1992 (Wallace 1993).

In the early 1980s, the UK government set up a very successful initiative called the Teaching Company Scheme, under which funding was provided for collaborative postgraduate projects. The initial aim of the scheme was to support manufacturing training, but with the enormous growth of interest in design education in the 1980s, this was extended to include design training. The Cambridge Programme, with Baker Perkins Printing Machinery Company, was the first Design Teaching Company, and it was structured around a systematic approach to design (Bassil et al. 1989).

The graduates were presented with their design task on their first day at Baker Perkins. The task was the design of an On-Run Lap Adjuster for a paper-folding machine. They were given managerial responsibility for this task, which was to result in a complex new feature for a high-speed folder. The task was completed within 20 months, by which time the first folder to incorporate this new feature was operating in a customer's premises. The On-Run Lap Adjuster became a standard feature on all Baker Perkins' C2 folders sold outside the USA. Based on the success of the Baker Perkins Programme, further design-based Teaching Company Programmes have been set up throughout the UK. Baker Perkins concluded that the systematic approach adopted had been highly successful.

The systematic ideas in *Konstruktionslehre* also influenced the teaching of design at Massachusetts Institute of Technology (MIT). Seering, from MIT, spent some time at Cambridge in the 1980s as an academic visitor. He witnessed at first hand the impact that systematic engineering design was having on design education and training, and on his return to MIT decided to run a summer session course for participants from industry and academia, with the title *Engineering Design: Creativity and Process Methodology*. He invited Beitz, Pahl and Wallace to help present the course.

In 1992, a book by Ullman was published in the USA entitled *The Mechanical Design Process* (Ullman 1992). This has become one of the most popular books for supporting undergraduate design teaching in the USA. The influences of systematic engineering design can be seen throughout the book. Before writing the book, Ullman visited academic institutions in Germany, and spent some time in the UK. He was familiar with the English edition of *Konstruktionslehre*, and the research undertaken by Hales with British Gas. Many examples from Hales' project on the Coal Gasifier Test Rig are quoted in the book. Ullman acknowledges in his book that one of his key sources was the English edition of *Konstruktionslehre*, which he describes as 'one of the first and most complete efforts at structuring the mechanical design process'.

From these few examples, it is clear that *Konstruktionslehre* has had a significant impact on design education in both the UK and the USA. It is known that this impact has spread to many other countries around the world.

4. Concluding Remarks

Some examples of the German contribution to engineering design in the English-speaking world have been described and discussed. Professor Wolfgang Beitz made a truly significant impact on both engineering design education and design research through his wide range of interests and contributions, and especially through his major publication *Konstruktionslehre*.

Because of language and cultural barriers, there have not been as many exchanges of ideas and results between German-speaking and English-speaking researchers and practitioners as there could have been. This has led to a number of preconceptions and misunderstandings on both sides. Each group has much to learn from the other, and the authors hope that more exchanges will take place in the future.

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