COMPARISONS OF SEVERAL DESIGN THEORIES AND METHODS WITH THE LEGACY OF VLADIMIR HUBKA

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PREFACE

This compilation is the result of a recommendation from Yoram Reich, Editor-in-Chief, Research in Engineering Design, who wrote: 'Clearly, this is a basis for a very valuable and useful book for both students and researchers' – having rejected the paper appearing as Section 2 in this compilation.

The author's purpose now is to collect a readily available record of some of the work of Vladimir Hubka, including the contributions made be the author and many others. This follows from one of the Workshops on Applied Engineering Design Science (AEDS) held in Pilsen, Czech Republic, under the general chairmanship of Professor Stanislav Hosnedl, and the auspices of The Design Society. A suggestion offered by Professor Herbert Birkhofer, Technical University of Darmstadt was that 'we should now aim towards convergence of views about the theoretical foundation and practical application of knowledge about engineering design'.

The record offered here consists of a survey of historic developments (see Section 1) leading up to the intended comparison, introduction to a sufficient (but incomplete) outline of the theories developed by Vladimir Hubka and consequently his recommended inclusive systematic/methodical approach to engineering design, and presentation of the comparisons with other approaches as recognized by the author (see Section 2). More comprehensive discussions appear in the latest two books of this development, [Eder and Hosnedl 2008 and 2010]. This separation of theory and method is considered necessary – the theory (a science, even if it is not formulated in mathematical terms) should be as complete as possible to describe the phenomenon (in our case, engineering design, applicable for any engineering product – technical system), the parts of the recommended method can then be voluntarily applied when found useful. That this approach is not necessarily applicable for problems of artistic design is fully acknowledged.

A *science* (from Latin 'scientia' – having knowledge); has the task to produce and verify a body of knowledge, independent of its potential use, to isolate and study (reproducible) phenomena, to abstract and codify from available and observed information. The main aim of *science* is to study what exists, and to try to explain it in a generally agreed way, by *deductive* logic, but also by *induction*, *abduction* and *reduction*, and *innoduction* [Eekels 2000]. This understanding should then be synthesized into a more *holistic* view. Truth usually takes precedence over completeness. Science should thus be as purely *descriptive* as possible, which also implies logical and complete, and as rigorous as possible – but even mathematics is based on a set of unproveable axioms. Neither a reductionistic nor a holistic view alone is sufficient. Equally, both synthesis and application of information must be accompanied by analysis [Eder 2009]. All of these procedures of science require intuitive steps in order to proceed, intuition should be considered as an indispensable ingredient of rationality. This is especially true of those scientific efforts that cannot be verified by controlled experiments, compare [Diamond 2003].

Engineering design itself cannot 'be' a science, engineering design is a process that usually involves the use of scientific knowledge, but it also uses a host of other (unscientific) information, experience, judgement, and other human abilities. Equally, engineering design cannot 'be' an art, yet engineering design may involve the use of artistic judgement and expertise. The word 'be' is inappropriate for the process. Nevertheless, this process of engineering design can be investigated to formulate a set of scientific theories about its fundamentals. This includes the generalized nature of the products of engineering design, the nature of that design process, and about possibilities of supporting it (and its practitioners) with suggested systematic and pragmatic methods, as well as allowing intuition, opportunism, creativity, etc. – again demonstrating the separation between theory and method. These systematic and pragmatic methods cannot guarantee success, they can only make success more likely, and by promoting good record-keeping they can allow retracing and recovery from paths that lead to lack of success – an important aspect of managing the design process. This outlines the legacy of Vladimir Hubka..

Compilations of design methods have been published, e.g. [Jones 1966, 1980 and 1992, Cross 1989 and 1994], they provide listings and descriptions, but generally avoid any theory to substantiate the methods, and avoid suggestions for coordinating two or more methods into suggested sequences – methodologies. Comparisons of methods have also been attempted, e.g. [Jones 1966].

This compilation consists of Section 1, a reprint of [Hubka and Eder 1996, Chapter 3], and Section 2, the rejected paper proposal that was deemed 'not scientific enough', but 'potentially useful'.

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Contents

SECTION 1 – HISTORIC DEVELOPMENT OF KNOWLEDGE TO DESIGN SCIENCE

Hubka, V. and Eder, W.E., **Design Science: Introduction to Needs, Scope and Organization of Engineering Design Knowledge**, London: Springer-Verlag, 1996, Chapter 3, p. 49-66 (headings re-numbered to Section 1), http://deseng.ryerson.ca/DesignScience/

> *He who cannot draw on three thousand years is living from hand to mouth.*
> ***Johann Wolfgang Goethe***

1.1 Sketch of the Development of Ideas about Rationalizing of the Area of Designing

In this sketch we will concentrate:

- with regard to content – only on designing in technology (therefore especially *engineering design*),
- with respect to time – on the period from approximately 1940 to 1995.

We do not wish to discuss *design* in its total breadth. The term *industrial design*, in the sense as it is used in England (with emphasis on ergonomics and esthetics), is only taken into consideration if the properties relating to this characteristic of the technical system are addressed. The similarly sounding term *industrial engineering* comes also only conditionally in our considerations; it is used in North America for engineering-related activities in the preparation and rationalization of manufacture and assembly.

We emphasize that the goal to establish a complete treatment cannot be reached, but we wish to establish some facts which contribute to understanding our new viewpoints.

To expect anything like complete success at stating in a completely rigorous and formal way what the correct procedures are in interpretation would obviously be utopian. This may not, in itself, seem like a terribly important point. After all, complete success at stating the laws of physics may well be a utopian project; certainly complete success at describing the functional organization of a human brain is a utopian project. But physics is possible, even though complete success eludes us, because the laws of physics can be successively approximated; and functional psychology is possible because (we hope) the functional organization of the human brain can be partly described and approximated. Similarly, one might hope that one could obtain partial success in describing the practices and procedures of interpretation.
Hilary Putnam [360]

And similarly, our aim is to establish Design Science in this book. We start by exploring elements of its historic development in this chapter.

1.1.1 Requirements for Efforts Towards Rationalizing

Before the task of rationalizing the work of engineering design can begin, certain *opinions* (prejudices) must be *completely refuted*, namely:

- designing has been said to be an art and only especially talented persons can execute it;
- designing has been said not to be a general (or generalizable) activity, but it is always bound to the particular object to be designed, e.g., *designing machine tools*, but not *designing* generally.

As *premise* for entry to the new direction, two theses must therefore be established:

> **Thesis 1: Designing is a rational (cognitive) activity, which can be decomposed into smaller (design) steps, stages and/or phases** (see Chapter 1);

Thesis 2: The design process (the procedure) is, of course, dependent on the object to be designed, but can be studied and presented in a very general form. The more concrete the object class, the more completely and detailed can the design process be defined.

These two theses *do not imply* that *the design process must be followed linearly (without iterations or recursions)*, nor *exactly* (without deviations or alterations), neither do they imply that *no intuitive steps are allowed*. On the contrary, all methods must be adapted to the subjects and objects. Design methods must be adjusted for the objects to be designed, and for the designers and their environment.

Design education is closely related with the first thesis. Contrary to earlier insights a further important thesis can now be formulated:

Thesis 3: Designing is teachable, conditioned by the existence of the theory (i.e. Design Science), and the right educational methods and media.

This change of opinion (even if it has entered only unconsciously) has opened the gate for improvement efforts concerning the situation in designing. The first evidence of change originates from the period of the Second World War and from the following reconstruction and construction period.

Which were the particular *features of these situations* which have caused the need for improvements? On one hand it was an unusual pressure towards performance in a highly developed industry, especially new and very demanding needs. A further influence was the availability of newly developed means, e.g., computers. On the other hand, a large shortage of means existed, for example shortage of capable people and raw materials, with which one should attain the performances. Time pressure also contributed.

Only rarely did all these conditions occur simultaneously; and so the solutions were found at different times. Up to the year 1967 we could only find some widely scattered and isolated groups or individual experts who proposed certain solution for improvement of design work.

The next period, after about 1967 until today and especially in the seventies, can be labeled as the prime time for the initial development of Design Science. Increasing numbers of research contracts and the founding of Institutes for Design Technology (especially at Technical Universities in Germany) provide for the enlarged capacity to solve the design problems. In addition, the exchange of opinions has been expanded considerably through international conferences (first Prague Conference 1967, the International Conference on Engineering Design – ICED series since 1981), and has increased quality.

The development of Design Science displays characteristic features in the area of individual countries: communication and agreement are understandably more intense on a national level than internationally. Therefore we will develop our sketch of the entire development as partial sketches of selected countries. The selection of representatives is necessarily incomplete, and was made according to originality of the views (so that as many directions as possible are recorded) and also from the importance of the national movement for international development.

1.1.2 Development in the German-Language Area

1.1.2.1 Federal Republic of Germany and Switzerland

In a detailed study, J. Müller [310] (1990) traced the historic development of design methodology in the German language region. Our outline recapitulates both the most important stages of this evolution and the expansion of these themes into Design Science.

In Germany and Switzerland, important personalities such as F. Redtenbacher (1809-1869), F. Reuleaux (1829-1905), C. Bach (1847-1931), A. Riedler (1850-1936) provided the basis for support, and others could build on their suggestions for improvements. Especially F. Reuleaux recognized that a Design Science was necessary (see also Section 1.3).

Independent from the design area, Polya [353,354] (Switzerland) developed general instructions for solving problems in mathematics. Of particular importance was the approach to morphology, which Goethe (1749-1832) had already used. This approach was formulated by Zwicky [465] (Switzerland) for modern science; his attempt to gather and record the whole knowledge of the world in clearly viewable and retrievable form has since then been recognized as impossible.

The pressure of external and internal conditions was especially strong in Germany. Two important works emerged there in the 1940's. The one originates from H. Wögerbauer (1943) [461], who had begun to set up a design methodology. The other work originates from F. Kesselring [245] (1943, Switzerland).

The next wave of rationalizing came after a long interval. The treatments of designing by H. Tschochner [426] (1954), R. Matousek [288] (1957) and A. Leyer [274] (1963-68, Switzerland) contained several new questions, which are not considered as direct contribution to Design Science, but as an important inspiration for some of the characteristics of technical systems, especially design for manufacture.

The period of intensive research commenced only around 1965, with the establishment the first University chair and the Institute for Design Technology at the Technical University of Munich (W.G. Rodenacker [369]). Measured on the pulse of the journal *Konstruktion* (Engineering Design), the peak in the treatment of the design problem was reached in the years 1972-75.

The convinced pioneer of Design Science, F. Kesselring, continued working on this problem. With his book *Kompositionslehre* (Study of Composition) [245] (1954) he not only developed an analysis of design work, but also expressed a warm relationship to his profession. Later he took part in these efforts as committee leader within the Verein Deutscher Ingenieure (VDI – Society of German Engineers) and was decisively involved in originating the VDI-guidelines for the design area (VDI-R 2222, 2225) [23,24,26].

A *bottleneck design* was detected in 1965 (see Beitz [67]), and later a further *bottleneck designers* was described. The VDI participated intensively in the developments and in the unification of existing opinions and ideas.

After 1965 several new Institutes of Design Technology emerged (including aspects of computer-processing) at the Technical and other Universities. Their professors (W. Beitz, K. Ehrlenspiel, R. Koller, G. Pahl, K. Roth, H. Seifert) produced new and original approaches and new publications. Numerous dissertations about designing have been written. The thematically broadest view can be found in the book of Pahl and Beitz [333] *Konstruktionslehre* (Study of Design), which aligns closely with the view of Design Science. Also R. Koller expanded the theme, as he changed the title of his book from *Konstruktionsmethode* (Design Method) [256] to

Konstruktionslehre (Study of Design) [257]. *Designing with Catalogs* by K. Roth [376] contains valuable references to processing the object knowledge in the engineering sciences.

V. Hubka continued the work which he began in the 1960's in Czechoslovakia (see Section 3.1.9 – Czechoslovakia). His book *Theorie der Maschinensysteme* (Theory of Machine Systems) [199] expands the horizon of design knowledge by generalization and recognition of object knowledge. The problem of designing viewed as a process was debated comprehensively in *Theorie der Konstruktionsprozesse* (Theory of Design Processes) [202] and transformed into a general procedural model [204]. He also dealt with design education [203,225]. He started considering Design Science in the essay *Konstruktionswissenschaft* (Design Science) [200].

The characteristics of the socio-technical system, especially the interaction of technology with the social and economic relationships, were explored by Ropohl [374] and scientifically processed to a theory (system theory of technology – general technology).

Slowly a *second generation* of scholars and researchers is emerging, in which the students of the previously mentioned professors appear (for example, H.J. Franke, G.W. Diekhöner, H. Birkhofer, and others), and there are approaches from other specialties, such as Schregenberger [386] (Switzerland) about problem solving in building construction (civil engineering).

Under the leadership of W. Beitz, the VDI-guideline 2221 [21,22] was issued in 1985, which strove for a *universally valid, branch-independent basis of methodical developing and designing*, and expresses the tendency towards unification.

Research also progressed in the area of computer support. Not only was a theoretical basis (a design logic) worked out, but also CAD-systems were developed (e.g., PROREN by J. Seifert [390]).

Design management, planning, representation and other themes were developed parallel and independently.

In 1992, the German edition of *Konstruktionswissenschaft* [229] was published. A new edition of the 1982 English publication *Principles of Engineering Design* (reprinted as [215]) was issued by Heurista under the shortened title of *Engineering Design* [228].

Appraisals of the developments in the discussed areas was undertaken repeatedly, and discussed especially at ICED 81 and 83. This conference series *International Conference on Engineering Design* – ICED, lead by V. Hubka (Switzerland), M.M. Andreasen (Denmark) and W.E. Eder (Canada), has occurred regularly since 1981. The Proceedings [29,125,207,208,209,213,215,221,226,227,230,372] contain more than 1200 contributions of many prominent scientists representing about 50 countries. Several workshops have been held to clarify particular themes, among others in Zürich and Rigi Kaltbad (Switzerland), Pilsen and Prague (Czech Republic), Copenhagen (Denmark), Rome (Italy), and New Orleans and San Luis Obispo (USA). For additional information about these activities, see the preface.

1.1.2.2 The Previous German Democratic Republic (GDR)

During the time period considered here, this part of Germany was practically cut off from the developments in other countries. Here we report on these independent developments.

The first conference of designers in the GDR, in which the *characteristics of design systematics were presented* by F. Hansen, was held in 1954 in Leipzig (with involvement from H. Wögerbauer and W.G. Rodenacker). Many other scholars in the GDR developed their work from that of F. Hansen and his frequently quoted books *Konstruktionssystematik* (Design Systematics) (1965) [186] and *Konstruktionswissenschaft* (Design Science) [187] (1974). These researchers originate both from engineering practice and from the universities (A. Bock, G.

Höhne, J. Müller, W. Heinrich, J. Rugenstein and others). Müller [308,309,310,311] has contributed particularly from the view of a philosopher, and appears with own relevant works, especially *Systematische Heuristik* (Systematic Heuristics, see Section 1.4.6).

Interesting approaches for the methodology of problem solving emerge also in supporting the innovators-movement. This movement aims at renewal of the modes of thought for the purpose of advancing innovation and invention of workers, see also Section 1.4.5. This stems mainly from the Russian ideas (see Section 3.1.8).

Engineering pedagogics has been intensely developed in the GDR for instructional purposes. The strong personality was H. Lohmann from the Technical University Dresden, who expressed the fundamental ideas in his work *Die Technik und ihre Lehre* (Technology and its Study) 1955. A synthesis of the two directions (Hansen and Lohmann) was accomplished by K. Steuer in 1968 in his *Theorie des Konstruierens in der Ingenieurausbildung* (Theory of Designing in Engineering Education).

1.1.3 Great Britain

As was already stated at the Great World Exhibition in 1851, the originator country of the industrial revolution was slowly descending in the worldwide ranking of technical producers. After the second World War one of the recognized defects was that the offered products were technically and visually antiquated. In consequence the discipline of *Industrial Design* was founded at different schools to counteract one of the deficiencies, and has strongly increased in consulting practice. The most important works in this area originate from Ashford [63] and Mayall [291]. Later Mayall confirmed [292] that designing is of great importance, with particular consideration of quality, operational properties, esthetics and ergonomics.

Some early attempts at scientific investigation of the design process originate from England. Based his own design experience, Wallace [439] proposed as model of designing a cyclical series of steps under the mnemonic ATDM – analyze, theorize, delineate, modify.

A consistent series of investigations began around 1960 at the University of Cambridge. Marples [285] followed new paths, by evaluating some design projects in industry through observation, a forerunner of protocol studies. He recognized that design work can be represented by the model of a decision tree. Others have drawn the conclusion that designers can or should use this *family tree* model as instruction for a part of designing (Jones [238,239]) or at least to record the decisions that were made (Eder and Gosling [120], Eder [121,123]). Shortly thereafter, Booker [76] wrote about the use of principles and precedents as guidelines and impulses in developing newly designed systems.

The work of Gosling [174] was directed especially towards electronic systems, however it contains sufficient general insights to a theory of technical systems. Among others, Norris [325] has evaluated and reported about morphology.

The entrance of Great Britain into Design Science occurred through the particularly appropriate analysis of the situation in the design area in the *Feilden Report*. The first *Royal Commission* under the direction of G.B.R. Feilden [149] submitted their report on engineering design, and proposed many innovations, especially for design education and for the respect of the engineer professions in society.

After the period of relative isolation from the continent, some German books were translated (for example, R. Matousek, German 1957, English 1963 [289]; A. Leyer, German 1963-68, English 1974 [275]; G. Pahl and W. Beitz, German 1977, English 1984 [334]; and V. Hubka, German 1980, 1981 and 1984, English 1982 and 1988 [217,219,220]).

Archer [51] published an approach to a systematic method of designing. Also further works by Archer [52,53,54,55] suggest interesting ideas for design methodology. Another attempt, which developed the earlier work of Gosling [174] for mechanical engineering, came from Eder and Gosling [120]. Checkland [88] contributed to system thinking.

An important conference was organized in Birmingham (Gregory [175]), which presented the state of the art in design methodology in Great Britain – without international participation. This conference is important for our survey, primarily for the number and breadth of important contributions (among others from G.H. Broadbent, C.H. Buck, C.T. Corney, A.L. Davies, W.E. Eder, J. Farradane, S.A. Gregory, R.J. McCrory, P. McMullen, E. Matchett, W.H. Mayall, A.M. Penney, I.M. Ross, B. Shackel, A.F. Stobart, B.T. Turner and R.D. Watts) and also that Gregory already defined very well the scope of Design Science as goal of design research [176], see section 2.1.1. In addition, for the first time attention was paid to definitions (Eder [121,122]).

A series of important books marks the further development: Cross [96], Ellinger [143] (from his own experience of designing), French [159,160] (conceptualizing, and evaluating using approximate and appropriate mathematical relationships), Glegg [168,169,170] (philosophy of design), Morrison [306] (decision theory), Pitts [349].

Also some contributions are dedicated to creativity: DeBono [102,103,104] published his volumes about *lateral thinking* for stimulating creativity.

The journal *Design Studies* (Butterworths, now Butterworth-Heinemann) with emphasis on Design Science and design in other fields was founded 1979 under the editorial supervision of the Design Research Society (DRS).

French [161] discussed analogies between artificial (human) constructions and natural formations and living thing. He shows that the natural structures are a good approximation to the theoretically optimal, and how artificial formations can be conceptually optimized. A similar project was pursued by Maunder [290], however with particular relation to movement and mechanisms.

The *Journal of Engineering Design* (Carfax), founded 1990, aims at bridging between design research and industrial application.

Important conferences were held and the Proceedings published in book form, among others directed by Booker [77,78], Cross [95], DeSimone [108], Gregory [175,177], IMechE [17], Jones and Thornley [237], Langdon [270], Loughborough University [19] and Pitts [350].

Not only design methodology, but also other areas of Design Science are practiced, for example, the management of design (B.T. Turner), information systems for the designer (G. Pitts), managing the design process (Hollins and Pugh [194], Leech [272], Wearne [447]) among others.

Newer works on engineering design include those by Cross [98], and Pugh [359].

A peculiarity of the development in Great Britain is the *institutionalization* of the efforts towards improvement. Already 1944, the *Council for Industrial Design* was founded, with emphasis on appearance and human operability (ergonomics) of products. In 1981 it was renamed *The Design Council*, to give more emphasis to engineering. Also in 1981 an *Engineering Council* was founded with the task of improving the situation, particularly with regard on the splintered nature of the engineer organizations, consisting among others of *The Institution of Mechanical Engineers* (IMechE) and *The Institution of Engineering Designers* (IED), each of which have also provided their positive contributions.

An occasional series of reports was demanded and prepared for government offices, but also by other interested organizations. The most important were Corfield [92], Department of Trade and Industry [10], Feilden [149], Fellowship of Engineering [5], Finniston [156], Lickley

[276], Mellor [296] and Moulton [307]. In the late 1980's the government has encouraged the causes of design for the purpose of reconstructing the industry. Some centers for research and dissemination of knowledge about design and design management have emerged, and have seized this initiative, e.g., the group around Glasgow and Strathclyde (Engineering Design Research Centre), and the Universities of Cambridge, Lancaster and Newcastle, with City University (Engineering Design Centre). Various publications originated from this institutionalizing, e.g., from Abbott [31,32], the teaching aids [3,4,185,358] from the organization SEED (Sharing Experiences in Engineering Design, see also Kimber [247]).

1.1.4 France

The French literature related to scientific designing is quite varied. Already in the seventies the *Méthodologie de la construction mécanique* appears from J. Chabal, R. De Preester and R. Ducel (1973). Methodical approaches are also available in all later books with the theme of design study (for example A. Chevalier, P. Poignon). Likewise the processing of technical knowledge (for example *Technologie de construction mécanique* from M. Norbert *et al*, 1969) shows a very systematic approach which in form come close to the design catalogs (compare the works of Roth [376] and Koller [257]).

The particular interest in these books is that they were published only as textbooks and all authors are without exception professors at technical intermediate schools (technical colleges). No attempt was undertaken to our knowledge to expand this bare alignment on teaching, or to present the available experiences in an international discussion and to compare them with the systems in other countries.

1.1.5 Italy

The research and teaching in the area of design knowledge have been taken up in Italy at two universities: in Rome (U. Pighini) and in Milan (G. Biggioggero, E. Rovida), where the problems of representation and modeling has been assigned much research capacity.

1.1.6 Scandinavia

In the industrially highly developed Scandinavia the solutions the problems of design began in the sixties under pressure of the market.

In Sweden, individual approaches and guidelines as part of the Sveriges Mekaförbund have been prepared (e.g., Ko7 – quality of design, 1958). Also in design instruction (teaching) we report about progressive courses (F. Olsson: Compendium, TU Lund, 1966).

In Denmark, in the Laboratory for Design under leadership of V.A. Jeppesen, a progressive design teaching system was set up. It was carried by M. Myrup Andreasen, and realized several new approaches especially to the themes of *design for assembly* and *integrated product development* [47,48,49,50] in a series of books and lectures. Andreasen was already named as one of the leading persons of the ICED-conferences. His cooperation with E. Tjalve [423,424] has enriched the theme of *representing-modeling* with new ideas.

Also in Norway and Finland interesting design themes were initiated at the universities.

1.1.7 USA and Canada

Attempts to outline the development of design knowledge together with efforts for improvement, as we have done for other political areas, is not appropriate for the USA and Canada. An early blossoming of design thought occurred almost simultaneously with the trends in Great Britain. The *Design Methods Group* (DMG) that was founded in California in those years still exists, but after a short burst of high general activity it seems to have lost its influence, perhaps because of its emphasis on architectural design, and was overtaken by other events. The impulses for these events lie in other directions, and so we must describe certain partial areas as sources for the present knowledge potential. As in the earlier development stages, the knowledge of these sources is accepted into the area of designing and serves often rather unconsciously as inspiration.

Efforts in this vast geographic region seem to have been patchy. Specific areas of design were addressed, and many different schools of thought grew up around regional centers. There seems to have been little in the way of collecting, coordinating and synthesizing into a more general abstraction.

1.1.7.1 Bases for Design Knowledge

– Problem Solving

The work about problem solving methods for mathematics by Polya [353,354] was taken up and developed by Wickelgren [455]. Newell and Simon [318,397,398] treated problem solving thinking. Problem solving was generalized by Wales [437,438]. Relationships to computer techniques were established by Starfield *et al* [408]. A more direct relationship to design was not produced, but the application is recognized by the originators of this direction as important.

– Systems Theory

Systems theory and systems thinking were developed in the USA since the 1950's, for instance represented by Bertalanffy [69] and Hall [183]. Further progress and concretizations can be recorded by Churchman [90], and Klir [250,251,252], both in system theory, and in their application to analysis and problem solving. The goals of system theory were disclosed through an announcement in the journal *Philosophy of Science* (Vol. 22, 1955, p. 331):

1. to explore the isomorphy of the concepts, laws and models in different areas and to support useful transfers from one area to another;
2. to encourage the development of suitable (or sufficient) theoretical models in areas, where they are missing;
3. to avoid the duplication of theoretical efforts in different areas;
4. to advance the uniformity of science through improvement of communication between specialists.

– Decision and Management Bases

A structure of human decisions as one of the important steps of designing was developed by Miller [300]. Nadler [314,316] has developed a method of planning from the point of view of company organization, which he considers also suitable for designing.

From company management, the works of Ackoff [33,34,35], Argyris [57,58], Drucker [117,118] and Schön [385] should be mentioned. Combinations between system thinking and management occur in Ackoff [36] and Churchman [90].

Starr [409] defined design as an almost pure decision process. His work is broadly laid out in the mathematical processes, which cohere with decision theory. This line was later extended and popularized by Suh [415], unfortunately under the claim of a design method.

In order to make engineering design accountable for its actions and decisions, two trends have been derived from legal actions regarding product liability [400,401,402,403]. One is towards improved definitions and knowledge about human factors (ergonomics and capabilities) for engineering application [65,100,138,379,399,460]. The second led to methods and procedures for independently validating, verifying, checking, reviewing and auditing the intermediate and/or final results of design work [382].

Concern for *satisfying the customers* has led to introduction of various management techniques with links to designing, e.g., TQM, QFD, Taguchi experimentation

– Error Events, Error and Failure Elimination

One of the many reactions to error events came from Warfield [442,443]. His thesis is that appropriate efforts of political and operational supervision are needed, to keep error events within acceptable boundaries. This can occur only by using suitable methodical measures on the part of the management. A systematic method of design management is proposed and called *generic design*.

Abstracting from historic reports of failures that occurred, mainly in civil and structural engineering, Petroski proposed a model for how development of systems over time takes place [343,344,345,346]. He pointed out several paradigmatic failure causes and tried to relate these to available knowledge and social conditions.

– Knowledge about Creativity

Advancement of creativity *per se* was the goal of works by Jewkes [235], von Fange [434,435], Weisburg [449] and Whiting [452]. Gordon [173] proposed and developed the system *synectics* as a formal problem processing method for a group of participants, and this method is considered especially useful for organizational problems. Osborne [330] developed *brainstorming* as a further group method to enhance creativity. A partial support for these methods through research in psychology followed only five years later through the work of Guilford [178].

Another problem of creativity, namely how one can free the human brain of prejudiced and fixed ideas, is clarified by Adams [37], presumably as a basis on which creativity can be enhanced. Similar explanations in reference to intuition and its advancement stem from Goldberg [171]. In a further development, Nadler and Hibino [317] proposed a philosophic system for renewal of management approaches, especially regarding products.

1.1.7.2 Design Knowledge

Examining the USA literature regarding engineering design shows two typical characteristics for the improvement efforts. Firstly the number of works peaks clearly in the period 1960-1970, secondly the absolute majority of the works deals with or is based on creativity.

Psychological insights were incorporated consciously and unconsciously in the instructions for designing, especially for advancement of creativity, as with Adams [37], Crawford [93], Dixon [111], Gordon [173], Nadler [317], Osborne [330], Schön [385], von Fange [434,435], Whiting [451] and others. Already the first important book in the engineering area, authored by D.S. Pearson, meshes into these themes and carries the title *Creativeness for Engineers* (1959). Also the much used book of H.B. Buhl *Creative Engineering Design* (1960 [86]) and many others, including the *Prentice-Hall Series in Engineering Design*, belong to this class.

To explain engineering design and general engineering for students is the main purpose for Krick [261,262,263], whereby creativity is emphasized and the description of the design processes occurs almost only as a secondary matter.

Further introductions of similar kind were published by Gibson [167], Middendorf [298], and Vidosic [433]. Assemblies of projects were compiled by Spotts [405] and Vidosic [432], as exercises for design. Wilson [457] shows the development of a product from an idea up to a working model.

In this sense, but with more relevance to designing, works of Harrisberger [188] and Woodson [459] are noted. Likewise a large number of these works which deal with *design instruction* (*Introduction to Engineering Design*), emphasize creativity or invention (I.E. Edel 1967; J.R. Dixon [111] 1966 and partly also J.P. Vidosic [433] 1969).

Another direction is opened by the works of M. Asimow [64] (*Introduction to Design*, 1962), R.J. McCrory [293] (*The Design Method - A Scientific Approach to Valid Design*, 1964), and G.N. Sandor [380] (*The Seven Stages of Engineering Design*, 1964). In this more discursive direction are also the books about *design instruction* by E. Pare *et al* [336], T.T. Woodson (1966), R.E. Parr (1970), I.R. Wilson (1970) and others. Alger [41] places large value on the creative processes, but also describes some mathematical methods, especially for evaluating the proposed solutions. Roe *et al* (Canada) [370] have tried to develop a rational model of designing. Also in Canada, Love [282] opened a consulting office and developed courses for systematic design, based mainly on methods and approaches known in the English language region.

In the following years, treatments of *Engineering Design* are relatively rare. In contrast, more general works about methods (therefore with extended validity and directed towards management) accumulate, as for example from G. Nadler [314,315,316]. The object field of the methods approaches the one in Great Britain.

A new situation came about in the USA during the eighties. The need for new knowledge about and for designing with computers developed more rapidly in the computer area than in design practice.

The scene in the USA was subjected to a rapid development and a quantity of research money was made available through the NSF (National Science Foundation) Initiative on Design Theory and Methodology. The appeal [15] was answered by a report published by Rabins [361]. The recipients of research money have held an annual seminar, and the papers usually published as proceedings volumes (e.g., Newsome [321]).

Following ICED 87 Boston, a conference series was started in 1989 under the title of *ASME Design Theory and Methodology Conference*, and has been run annually since then (e.g., Rinderle [367]). Although this conference is directly sponsored by the ASME (American Society of Mechanical Engineers), its scope has included other engineering disciplines, architecture, and even clothing manufacture.

A newly founded journal, *Research in Engineering Design* (Springer-Verlag, New York), aims at dissemination of research results, with particular emphasis on observation and protocol methods, and on progress in the computer application.

The theme of observations and protocols has received much attention in recent times in the

USA. For instance, Ullman [429] has belatedly discovered the importance of the sketching for conceptualization through observation and protocol research. A similar quest as Tjalve [423,424] about the importance of sketching, but from the point of view of psychology, is treated by McKim [294].

From his own observations of the processes of designing of chemical industry plant, Westerberg [450,451] set up a theory of the design process. Some of these approaches are similar to the Theory of Technical Systems [214,219] (see Section 7.1) .

Further significant works, especially related to embodiment, layout and detail design, have been published by Ertas [145] and Ullman [430]. Dym [119] produced a noteworthy attempt at synthesis of the existing (mainly North American) views, with particular emphasis on the use of computers in design.

– Artificial Intelligence and Computer Applications

If design problems should be supported by applications of computer systems, the predominant approaches are developed from artificial intelligence (AI), especially the method of knowledge-based systems (expert systems). The latter are suitable on one hand for diagnosis, on the other hand they are being developed within design research as advisers for evaluation, to coordinate the activities of design groups (*design teams*) and their management, and for other activities. Examples of such program attempts originate from Eisenberger [142], Papalambros [335], Rinderle [366], Subramanian [414], Talukdar (and collaborators) [418,419,420] and Westerberg [450,451].

A more general application of CAD, coupled with AI within the design processes (see Section 7.5), is the goal for the IFIP (International Federation for Information Processing), especially through conference series of different study groups, e.g., Yoshikawa and Warman [464]. From this work, and applying the theories of Yoshikawa [425,462,463] (see Japan, Section 3.1.11), new approaches for CAD-programming in object-oriented languages are undertaken (e.g., Warman [444]), which is better adjusted to the stages of layout, drafting and detailing (*embodiment design*) for the known modes of operation of designers.

Newer developments include the use of *genetic algorithms* within computer-assisted design processes [87], and of *fuzzy set theory*, *ambiguity*, *nonspecificity*, and *strife* [253].

1.1.8 Russia – Previous USSR

The first known work in scientific design originates from P.I. Orlov: *Basis of Designing* [329]. The subtitle *technical knowledge and methodology* points to the methodical aspect. Otherwise the references to methodical designing in the literature are fairly scarce. It appears however, that the application of the computer increases the pressure towards the investigation of the design processes and objects, and has brought new points of view and results (compare Klimov, Lebedeva in WDK 10 [213]).

Completely different is the situation in the area of the support of innovators and inventors. One direction consists of general references, e.g., I.N. Sereda, who works at the Peoples University for Technical Creation in Riga, and whose book *Worker - Inventor* [392] belongs among the very widespread books in the USSR. Another direction is represented by Altschuller: *Inventions - (Not) A Problem* [42] (see also Section 1.4.5).

Based on a detailed investigation of patent submissions, Altschuller has found [42,43] that the majority of the inventions were prepared using a small number of known methods. He proposed five kinds of problems and their solution.

The methods that may be utilized were summarized in a system recommended for inventing, an invention algorithm (for example ARIZ 59, improved as ARIZ 61 and ARIZ 80), to indicate to inventors the question about the way to a solution (invention). This is a system of organized methods and planned activities which are based on logical rules and instructions. The algorithm has been computerized by the Invention Machine Laboratory, Minsk, Republic of Belarus [427], and exported to subsidiary companies in Germany, the USA and other places. In some respect this algorithm is similar to systematic heuristics after Müller [212] (see Section 1.5.4).

Two further study groups under the direction of Odrin [326,327,328] and Powilejko [356,357] are interesting here. They have developed innovative design methods as expansions of morphological analysis (as reported by Arciszewski [56]).

Another widespread research direction in the USSR aims at organizational-economic questions of development. J.S. Sapiro belongs to this circle. His book *Organization and Effectiveness of Technical Development* (1980) [381] treats this problem.

As in other areas, the situation in Design Science in the previous USSR is fairly unknown, because the available literature does not necessarily reflect the status of knowledge.

1.1.9 Previous Czechoslovakia

In Czechoslovakia in the sixties, efforts for design improvement proceeded in three directions: first the invention method of K. Backovsky (1963) in continuation from W. Ostwald (1932) (the prior timing is noteworthy), second the movement of innovators and inventors who looked for a solution methodology (compare Sections 3.1.8 – USSR and 3.1.2.2 – GDR), and finally some designers in engineering practice who were trying to improve their work and have formulated relevant measures (V. Hubka, J. Smilauer, S. Vit). This phenomenon of the participation of designers from engineering practice in design research is singular in the history of Design Science.

These three directions were combined (at least partially) in the years 1962 and its members formed the Design Committee of the Scientific-Technical Society of Czechoslovakia. A series of conferences and seminars was organized by this committee, and cared for the transmission of knowledge, especially in design methodology. The conference in Prague 1967 is particularly important for the development in the world, because there a first international exchange of opinions occurred: Great Britain, the Federal Republic of Germany, the GDR, Switzerland, Poland and Czechoslovakia were represented by delegates.

In the following years attention was dedicated to the working means (tools, equipment, information sources, etc.) of engineering designers, including computer applications.

The particular development of Design Science shown in this book started with preparatory work in Prague, as Hubka reported in [198]. This work was transferred to Denmark as a consequence of circumstances, and later to Switzerland (see Section 3.1.2.1). The basis is a comprehensive Theory of Technical Systems, and its development through works by Hubka [199,214], Andreasen [46], and Hubka and Eder [219,228,229]. Derived from this work is a theory of design processes [202], a procedural model with instructions for implementation of the design process [204,217], and a set of case examples to illustrate the use of the procedural model for conceptualizing [220].

1.1.10 Poland

The very intense research in the whole area of Design Science in Poland today is based on the work of J. Dietrych. Already in the year 1967 he enriched the Prague conference around a new, holistic view of design. As professor at the Technical University of Glivice, he extended the study of machine elements to design in general. His efforts are directed especially towards the practical work of the designer. Dietrych [210] has produced a comprehensive theory based on a series of definitions for key-words and *termini technici*.

Beside that a very general direction of designing and project work has been developed. Building on the work of Kotarbinski [258,259], a group in Warsaw has tried to set up a science of sciences. From this, Gasparski [164] has developed an explanation and philosophy for design, which is known as Praxiology, and is also connected with the name A. Sielecki. Goralski [172] has taken the concepts of morphology into this work direction.

1.1.11 Japan

An attempt to apply formal logic with some axioms was undertaken by Yoshikawa [425,462,463] (see also Section 3.1.7) with the goal to generate a complete algorithm of designing on digital computers (especially for CAD-application). Kaoru Hongo presented thoughts about design education as part of the ICED-conferences.

1.1.12 Other International Developments

Apart from the ICED conference series, several other efforts at international cooperation should be acknowledged. A series of conferences and seminars on applications of computers to architectural design have taken place, starting around 1986, mainly under the leadership of J. Gerö (Australia). The methods and validity of protocol studies of designers in action have come under scrutiny in a recent seminar.

A significant book on engineering design was published by Lewis and Samuel [273], emphasizing methods in the context of detail design of machine elements.

1.1.13 Summary

Figure 1.1 presents an attempt to survey the development. The names of the most important design scholars as authors of books form a chronological series in four columns. This provides a comparison of the development tendencies in four geographical areas.

1.2 Description of the Development of Design Knowledge

1.2.1 Elements of the Development

The sketch of development of design knowledge has shown clearly the different rates and stages of progress. To the question about elements of these processes, only some can be hypothesized at present: the degree of industrial development, the levels of education, the organization and extent of research, the culture and tradition in the individual areas, the size of the area (country). The connections and interactions of these and other elements would show an even more complicated picture.

Survey of the 'Evolution' of Contributions to Design Science

Legend:

T ... Translation
C ... Conference Proceedings
R ... Report
G ... Guideline
J ... Journal

G ... Germany (united)
F ... France
CZ ... Czech Republic
PL ... Poland
DK ... Denmark

S ... Sweden
AU ... Australia
J ... Japan
SU ... USSR (previous)

69 ... refers also to later contributions — some authors appear several times (with abbreviation of book title)

	USA, CDN	D, CH	GB	Other countries
		1850 Redtenbacher		
		1853 Reuleaux		
		1919 Riedler		1929 Kotarbinski
1940				(PL)
		43 Kesselring		
		43 Wögerbauer		
45	45 Polya			
	47 Miller			
	48 Zwicky	48 Konstruktion (J)		
1950				
		52 Bischof–Hansen	52 Wallace	
	53 Bross			
	54 Crawford	54 Tschochner		
	54 von Fange			
55		55 Lohmann		
		57 Matousek		
		57 Brandenburger		
	58 Jewkes			58 Richtl. Ko7 (S)
	58 Whiting			
	59 Pearson			
1960	60 Simon		60 Marples	
	60 Buhl			
	61 Gordon			61 Sereda (SU)
	62 Ackoff		62 Gosling	62 Goranski (SU)
	62 Asimov			
	62 Hall			
	63 Starr	63 Leyer	63 Feilden (R)	63 Altschuller (SU)
	63 Norris		63 Matousek (T)	63 Hubka (CZ)
	63 Pare		63 Jones (C)	63 Smilauer (CZ)
	63 Osborne			63 Backovsky (CZ)
	64 Alger	64 VDI–R 2225 (G)	64 Archer	
	64 Drucker			
	64 McCrory			
	64 Sandor			
65	65 Krick	65 Engpass–Konstr.	65 Eder/Gosling	
		65 Lehrstuhl München		
		65 Hansen (KoSyst)		
	66 Woodson		66 Gregory (C)	66 Olsson (S)
	66 Harrisberger			
	66 Dixon			
	67 Tech–Innov (C)	67 Müller (OpVerf)	67 Mayall	67 Dietrych (PL)
	67 Miller	67 Hansen (C)		67 Prag (C–CZ)
	67 Nadler			
	67 Roe			
	68 Bertalanffy	68 Steuer	68 DeSimone (C)	
	68 Gibson		68 Ellinger	
			68 Morrison	
	69 Churchman		69 Ashford	69 Norbert (F)
	69 Klir		69 Clegg	
	69 Middendorf			
	69 Vidosic			
1970	70 Parr	70 Rodenacker	70 Jones	70 Geminard (F)
	70 Wilson			
			71 French	71 Vidal (F)
			72 Gregory (C)	72 Powilejko (SU)
			72 Cross (C)	

Figure 1.1 Historical Developments in the Literature [229]

Legend:

T ... Translation
C ... Conference Proceedings
R ... Report
G ... Guideline
J ... Journal

G ... Germany (united)
F ... France
CZ ... Czech Republic
PL ... Poland
DK ... Denmark

S ... Sweden
AU ... Australia
J ... Japan
SU ... USSR (previous)

69 ... refers also to later contributions -- some authors appear several times (with abbreviation of book title)

	USA, CDN	D, CH	GB	Other countries
	73 Love	73 VDI-R 2222 (G)	73 Pitts	73 Odrin (SU)
	73 Holloway	73 Schw.M.Mkt. (J)	73 de Bono	73 Chabal (F)
	73 Miles			
	74 Wickelgren	74 Hubka (TMS)	74 Leyer (T)	
	74 Newell	74 Hansen (KoWiss)	74 Pitts (C)	74 Svensson (AU)
75				
	76 Warfield	76 Hubka (TKoP)	76 Moulton (R)	
		76 Franke		
		76 Steinwachs		
		76 Koller		
		77 Pahl/Beitz		77 Orlov (SU)
	78 Argyris			78 Yoshikawa (J)
		79 Ropohl	79 Loughborough (C)	79 Tjalve (DK)
			79 Corfield (R)	
			79 Design Studies (J)	
1980	80 Adams		80 Finniston (R)	80 Andreasen (DK)
	80 McKim			80 Sapiro (SR)
				81 ICED 81 Roma
		82 Roth	82 Hubka/Eder (WDK1)	
		82 Schregenberger		
	83 Goldberg		83 Lickley (R)	83 ICED 83
	83 Schön			Kopenhagen
			84 Cross	84 Gasparski (PL)
			84 Langdon (C)	
			84 Pahl/Beitz (T)	
85	85 NSF	85 Ehrlenspiel		
		85 ICED 85 Hamburg		
		85 VDI-R 2221 (G)		
	86 Wales	86 Seifert		
	86 Rabins (B)			
	87 ICED 87 Boston			
	88 Hubka/Eder (TTS)		88 Trade & Ind. (R)	88 Lewis/Samuel (AU)
			88 Hubka/Andr./Eder	88 ICED 88 Budapest
	89 Newsome (C)		89 ICED 89	89 Andreasen/Hein
	89 Westerberg		Harrogate	
	89 Suh			
1990	90 Res.E.Design (J)	90 Müller (AMeth)	90 J. Eng. Design (J)	90 ICED 90 Dubrovnik
	90 Starfield			
		91 ICED 91 Zürich	91 J. Des. & Prod.(J)	
		91 Hubka/Eder (KoW)	91 Pugh	
	92 Ullman	92 Hubka/Eder (ED)		
		93 Pahl/Beitz (3rd)		93 ICED 93 The
	94 Dym		94 Cross	Hague
95		95 Roth (2nd)	95 Redford	95 ICED 95 Prague
		95 Hubka/Eder (DSci)		
		(current volume)		

Figure 1.1 Historical Developments in the Literature [229] (cont.)

- The level of industrialization plays a large role, because first a need for rationalizing the design process must be recognized, so that solutions can be looked for. This happened certainly in the most of the described cases. This thesis is confirmed by the situation in other countries, e.g., in China, and India. There the research problems have been taken over as a task in some universities, but despite strong interest, the results remain currently of low significance, because the problems in those countries are not urgent. This thesis of the degree of industrializing appears to be problematic for the USA or Japan. It is surprising how sparsely and under which unfavorable circumstances the research projects for design knowledge began to work and – this counts especially for the USA – how weak the interest in the already existing knowledge was. A preliminary explanation to this could be (as an additional sub-thesis) that the degree of industrializing is changed through the economic power of the area. In areas, where this economic power is apparently strong, a persistence and inertia exists, which decreases research for the purpose of improvement of the modes of operation. To some extent, the prevailing cultural outlook and linguistic factors interact with economic power.
- The dependence of the intensity of improvement efforts on the degree of education has not been recorded in our historic sketch, because it would be necessary to expand the investigation to individual typical persons. It is, however, clear that university graduate engineers are more open for these questions than graduates of the lower engineering schools or industrially trained designers. It may be that university engineers are less represented in the design process, and they especially process the more abstract conceptual and analytic tasks in which the newer researches in design knowledge could be useful. In comparison, the graduates of the engineering technical colleges (e.g., two-year colleges) and trained designers dedicate themselves predominantly to the more concrete tasks, where results from the older existing engineering sciences appear more important. In comparison with the universities much less pressure exists for teaching personnel in the lower engineering schools to participate in research. These facts agree with the number of Institutes for Design Methodology (titles vary from place to place) at universities, if one compares them with similar institutes at the engineering technical colleges.
- Design research began mostly at university institutes – and is promoted there – either as part of the general research tasks or in funded research projects. Most scholars of the first generation (sixties and seventies) have chosen the range of problems from their own experience in design, having in part recognized the defects. A minority (especially in the USA, and more recently in the UK, Holland and other places) only discovered the research possibility with the availability of research money, and mostly without own design experience in industry. Motivation to research and to engineering design consequently appears as a relevant (human) element, and its influence can be seen also in different functions and successes. A unique way to the solution has been shown in this respect by one group of designers from engineering practice in Czechoslovakia, as reported above.
- Generally considered, only relatively little research money has been invested in this problem until recently. The more theoretical and reflective tasks can be accomplished with less support. Relatively much of the available research money has flowed into the more concrete tasks, especially those of computer application.
- The cultural traditions also present a decisive element. The understanding about goals and means in the countries of the European continent is different from that in Great Britain or the USA. Concerning the situation in Japan, much more can be learned from the culture

tradition here than from other points of view.

- The size of the country (and with it also the financial power) appears not to play as large a role as one would at first suppose. The results in Germany or in the Scandinavian countries towards Design Science is incomparable in this regard with those in the USA, the Soviet Union or Italy. In comparison, the output of results from computer tasks from the USA far outweigh any others.

Our considerations must remain in the hypothetical stage, because we do not intend to further explore these questions in any scientific way.

1.2.2 Development on Individual Planes

To obtain a more precise picture of the situation (a snap shot for a certain time), we would have to bring together on a time axis the current status and development, which runs on several planes, i.e. one would have to observe minimally the following partial areas:

- the development (and/or the situation) in research;
- the development (and/or the situation) in engineering design practice;
- the development (and/or the situation) in design education.

We have not done this systematically in our sketch, because the available material does not suffice for us to dare to make a founded statement. The biggest part of the information in our description affect the results of research, insofar as no other statements accompany a certain information.

1.2.3 Progress

To the sketch of the development in individual countries one can add also a description of the course of development:

- In the beginning in an organization or in an area, the rather isolated encounters have gradually changed with the time into a broader international movement, and the single problems have fused to a total problem of Design Science. Still the impression of fragmentation can emerge from individual work areas.

1.3 The Present State of Design Knowledge

In broad brush terms the state of design knowledge can be described (end of 1994) as follows:

- Much knowledge has been accumulated, mainly however as *islands of knowledge*, because too little synthesis was pursued. Many elements of design knowledge have striven for and approached the goal of the totality. Relationships between these elements have been inadequately explored. In the drive towards unification, only insignificant successes have been reached.
- Within the design knowledge the available knowledge has not been prepared evenly.
  The individual areas were – and are – not evenly explored, which is, of course, a disadvantage, since the interrelationships do not emerge in the system of the knowledge. For that reason one must often return to make additional corrections to the existing conventional knowledge.
  Most frequently care was taken of the methodology of designing, because in the beginning it was a white spot on the map of general and design knowledge. There the achievements have been substantial. Some part problems crystallized either into partial tasks or even to

principles for design methodology, for example:

- ○ Task to obtain a clear and actionable description of design procedures (the results of which can then be demanded by management);
- ○ Task to obtain a finest possible structuring of the process with clear separation of individual activities, especially the ones with special character, for example:
  - – searching for and finding solutions;
  - – evaluating;
  - – information activities;
  - – representing, etc.;
- ○ Principle of working out as many alternatives as possible and their optimization in the earliest tasks of the design process;
- ○ Task of adjustment of the general procedure to different elements, for example:
  - – for work in groups (team work);
  - – for the application of computers, etc.;

- The quality of knowledge is not uniform, and extends from experience knowledge up to precise statements.
- Because of linguistic and conceptual barriers (especially between cultural and language regions), understanding and agreement is difficult and has not reached a satisfactory level.
- The way into engineering practice has not yet been found.

These efforts are in large part little known or acknowledged, or their importance is underestimated. Symptoms for this are the typically human outlooks, in English usage occasionally summarized as NIH (*not invented here*, thus allegedly not useful) and NIMBY (*not in my back yard*, because even the thought appears often too dangerous).

1.4 References to Section 1

Reference numbers have been retained from the original book, see beginning of this section, page 5.

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SECTION 2 – COMPARISONS OF SEVERAL DESIGN THEORIES AND METHODS WITH THE LEGACY OF VLADIMIR HUBKA

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Abstract

Aspects of design engineering are explored with respect to products and design procedures. Design engineering is compared to the more artistic forms of designing to highlight the constraints from the engineering sciences and opportunities from several more abstract models of technical systems available for design engineering.

A basis is presented for the development of an engineering design science, as proposed by Hubka and colleagues, represented by a theory of technical systems and a coordinated theory of design processes. A recommended systematic engineering design method is derived from this theory of technical systems, via the theory of design processes, including a model of problem solving, that demonstrate where creativity can usefully be applied within a systematic approach. Verification of this method is outlined by referencing several published case examples.

On this basis, several pragmatic and theory-based methods and design approaches from design practice and research are selected, discussed and related to Hubka's legacy. Many of these are shown to be useful extensions and/or clarifications that fit into parts of Hubka's proposed theories and methods. This paper thus aims to advance a convergence of engineering design research.

2.1. Introduction

Investigations of design engineering, as distinct from general artistic designing, started from the early 1950's, almost simultaneously in Germany and England, with various attempts from other regions. A few of the results are by Wallace [1952], Kesselring [1954] and Matousek [1957], the last of these was translated into English, mainly combining engineering design practice (object information) with the engineering sciences. Gregory [1966] organized a conference mainly devoted to design engineering. Rodenacker [1969] refined the approach to combine practice and engineering science information. Leyer [1974] (translation) denied the utility of any methodical design procedure. Verein deutscher Ingenieure (VDI) [1969, 1977, 1982] started to offer guidelined for engineering practice. A significant advance was achieved by Pahl and Beitz in 1984 [Pahl *et al* 2007], emphasizing a practice-based design methodology for conceptualizing, embodying and detailing design. This was incorporated into [VDI 1975]. Contributions from Koller [1979, 1985] augmented the Pahl/Beitz approach. Roth [1995] in 1982 developed a set of design catalogs to assist engineering designers in selecting and combining suitable constructional principles. VDI continued its guidelines [1980, 1987] to assist design engineering, and [VDI 2004] to guide development of mechatronics products. Meanwhile, the English-speaking regions gave greater emphasis to creativity as a separate concept. The book "Design Science" [Hubka and Eder 1996] contains a discussion of developments in other parts of the world, including the English-language regions.

Vladimir Hubka (1924 -2006) was singular in this development, he started [Hubka 1967] to formulate a theory of designed engineering products (technical systems), showing at an abstract level what all such technical tangible products (and their purposes) have in common. He and colleagues continued this development into a comprehensive theory of technical systems, a science about engineerng design, and a derived engineering design methodology [Hubka 1974, 1976, 1982, 1984, Hubka and Eder 1988, 1992a, 1992b, 1996, Eder and Hosnedl 2008, 2010], with many related considerations.

Creativity in design engineering, depends to some extent on the experience and mental capabilities of the design practitioner [Eder 2009a]. We can distinguish between long-term memory and working (short-term) – the latter restricted to 7"2 'thought chunks' or less [Cowan 2001, Miller 1956a, 1956b, 1956c, 1960, 1970]. If mental capacity is exceeded, something is lost and the outcome may be failure [Nevala 2005]. Externalizing thoughts in (verbal, graphical and/or symbolic) sketches, and mentally interacting with them, overcomes some of this limitation.

Müller [1990] states that engineering designers work at typically three levels of action operation:

(1) *normal or routine*, within their competence and comfort zone for the design problem at hand, preferred and carried out by an individual working below his/her highest level of expertise;

(2) *risk*, around the limit of their competence, tends to demand team activity, when some systematic and/or methodical tools can help; and

(3) *safety or rational*, a problem appears much less routine, engineering designers need advice how they can proceed to overcome the barriers, a systematic and methodical approach is probably essential, from which a designer can select the appropriate parts.

Methods need to be learned in a neutral, non-threatening environment *before they are applied* to a serious problem, attempting to learn a method 'on the job' is a recipe for failure. Systematic and methodical approaches do not guarantee success, and intuitive and opportunistic actions are encouraged, especially if justified *post hoc* within the systematic methods..

2.2. Outline of Design Engineering

Products can serve several classes of customers, including consumers (durables and consumables), industrial users (tools, machinery, processing plant), society and its governance (infrastructure, communications, energy supply), and others. An informal classification of many sorts of products has been published [Eder and Hosnedl 2008 (Ch. I.7), 2010 (Ch. 3)].

Where engineering products are manufactured or processed, both the product, its operational (usage) process (if applicable), and its manufacturing process needs to be established in advance of its existence – 'design engineering'. With substantial engineering content, the product is either a transformation system, TrfS, a technical process, TrfP, or a technical system, TS, where the TrfP and the TS are constituents of the TrfS. Each needs to satisfy preferably all requirements for operational use, manufacture, distribution, customer satisfaction, upgrading, repair/maintenance, disposal, and a range of other processes.

Engineering designers often need to manually prepare to solve their design problem without computer assistance. Computers cannot design independently, they are tools, partly automated, that can assist designing [Hubka and Andreasen 1983], help to solve problems, improve TrfP(s) and/or TS(s), optimize quality, and improve and perfect the parameters of the design process – '(s)' signifies the 'subject', the product of interest that should be or has been designed.

2.3. Design Engineering Compared to Artistic/Industrial Designing

Design engineering and the more artistic forms of designing, industrial design, have much in common, with partly overlapping duties, but substantial differences, see figure 2.1 – the descriptions show a contrast of extremes, rather than all aspects of designing.

Objectives, Design Conditions	Design Engineering	Artistic–Architectural–Industrial Design
The object to be designed, or the existing (designed) object	Transformation Process and/or Technical System; primary: functioning, performing a task	Tangible Product; primary: appearance, functionality
Representation and analysis of the object as designed, and its 'captured design intent'	Preparing for TS(s) manufacture, assembly, distribution, etc., AI, CAD/CAM/CIM	Rendering for presentation and display, product range decisions
Design process (for the object), methodology, generating the 'design intent'	Theories of designing, Engineering Design Science, formal design methodologies	Intuitive, collaborative, interactive designing
Properties of the object as output of designing	Mediating and Elemental Design properties, to establish observable properties	Observable properties to achieve customer satisfaction
Design phenomenology	Empirical, experimental and implementation studies	Protocol studies
Responsibilities	Professional, ethics, reliability, safety, public, legal liability, enterprise, stakeholders	Organization, stakeholders (Architecture adds organizational and contract responsibility)
Location	Design/Drawing Office	Studio

Fig. 2.1 Scope of Sorts of Designing [Eder and Hosnedl 2008, 2010]

If a product is intended to be visually attractive and user-friendly, its form (especially its observable shape) is important – a task for *industrial designers*, architects and similar professionals. Industrial design [Flursheim 1983, Julier 2000, Tjalve 1979, Tjalve, Andreasen and Schmidt 1979], in the English interpretation, tends to be primary for consumer products and durables, emphasizes the *artistic elements*, appearance, ergonomics, marketing, customer appeal, satisfaction, and other observable properties of a product. This includes color, line, shape, form, pattern, texture, proportion, juxtaposition, emotional reactions [Green and Jordan 2002], etc. The task given to or chosen by industrial designers is usually specified only in rough terms. The mainly *intuitive* design process emphasises 'creativity' and judgment, is used in a studio setting in architecture, typographic design, fine art, etc. Industrial designers can introduce new fashion trends in their products.

For *industrial designers*, 'conceptualizing' for future tangible products consists of preliminary sketches of observable possibilities – a direct entry into hardware (the constructional structure) and its representation. The sketches are progressively refined, and eventually *'rendered'* (drawn and colored, and/or modeled by computer or in tangible materials) into visually assessable presentation material, full artistic views of the proposed artifact, to provide a 'final' presentation, for management approval. Considerations of engineering may take place. Industrial designers usually work '*outside inwards*', defining the observable envelope, thus constraining the internal constituents and actions.

If a tangible product should work and fulfill a purpose by helping to perform a process (e.g. mechanical or chemical), its *functioning and operation* are important – a task for engineering designers. Anticipating and analyzing this functioning is a role of the engineering sciences. *Engineering* intends to create what does not yet exist, that is likely to work. Engineering needs designers to be aware of a wide range of existing information and its complex interactions, and to consider and accommodate all relevant influences of scientific, technical, economic, societal, political and other areas to achieve a successful and optimal product. The outcome of design engineering is a set of manufacturing instructions (detail and assembly drawings to scale, including tolerances and raw material specifications – these may be computer-resident) for each constructional part, including instructions for assembly, adjustment, testing, use, etc. In addition, documented analytical verification of anticipated performance in all life-cycle phases must be delivered, preferably be a qualified professional engineer.

Design engineering is more constrained because

(a) a design specification is usually prescribed by a customer or a marketing department, and is often the basis of a legally binding contract,
(b) the relevant engineering sciences must be applied,
(c) societal norms and regulations (including laws) must be satisfied, and
(d) risks and hazards must be controlled, the existing information must be respected.

Design engineering has available a theory of technical systems [Hubka and Eder 1988] and its associated engineering design science [Hubka and Eder 1996], which suggests several abstract models and representations of structures for transformation processes and technical systems that can be used as tools for establishing requirements, and for verbal/graphical and cognitive-conceptual modelling of novel or redesigned products (mathematical modelling is well established in the engineering sciences). This allows the engineering designers to generate a wider range of solution proposals at various levels of abstraction from which to select – one of the hallmarks of creativity.

Engineering designers tend to be primary for technical systems and their operational processes, as well as their manufacturing processes. These designers tend to solve the problems of making something work, including usability, manufacturability, economics, and life-cycle related properties. They work from critical zones for capability of functioning, e.g. form-giving zones ('windows' according to Nevala [2005]), from '*inside outwards*', defining the internal operational means first, constraining the outside. Novelty may be a consideration, but primary considerations are usually reliability (risk control), operational safety, and achievability of functioning.

Is a car an engineering product? The steering mechanism, the suspension, the motor and drive train, the instruments, and a whole range of other items internal to the car are certainly engineering products, to which industrial-artistic designers can have little input. Mostly these items are not observable for the driver, passenger or by-stander, and some are OEM/COTS parts (engineering products) manufactured by other organizations, e.g. starter motors, alternators, computers, etc. Even the interior of doors and other body parts (structural members, stiffeners, etc.) are much more engineering than artistic. The exterior of the body parts (including the passenger compartment side) is certainly more industrial-artistic, for instance the arrangement and appearance of the dashboard. Even the arrangement and division of individual body panels are engineered for manufacturability – an engineering responsibility. In fact, a car is definitely an engineering product – without the engineering you only have an essentially decorative monument. Without the industrial design, the appearance and appeal of the car may be unsatisfactory, reference the 1940's 'U.S. Army General Purpose Vehicle (GP)', the original Jeep. Is this is a reason why the industrial designer often gets named, but the engineering designers are not ever mentioned, and credit for the engineering items is often given to 'science'? In contrast, an electrical power transformer (500 MVA, 110 kV) hardly needs industrial design.

This comparison of artistic vs. engineering designers is, of course, extreme and exaggerated, the truth is somewhere in between, but it is based on the author's personal experience in industry and life – 10 years in industry (1951-1961) 'on the drawing board' for electrical power transformers and switchgear, and other non-consumer engineering products.

2.4. Basis for Engineering Design Science

The approach used here, initiated by Dr. Vladimir Hubka around 1965 [Hubka 1967] and under continuous development since then [Eder and Hosnedl 2008,2010], consists of formulating a comprehensive theory of technical systems (engineering products), existing and to be designed, and using this theory to derive a recommended (but voluntary) systematic method of designing. This is confirmed by Klaus [1965,1969] in cybernetics: *'both theory and method emerge from the phenomenon of the subject'.* A close relationship should exist between a *subject* (its nature as a concept or object), a basic *theory* (formal or informal, recorded or in a human mind), and a recommended *method* – the triad 'subject – theory – method', see figure 2.2. The theory should describe and provide a foundation for explaining and predicting 'the behavior of the concept or (natural or artificial, process or tangible) object', as subject. The theory should be as complete and logically consistent as possible, and refer to actual and existing phenomena. The recommended method either for using or for designing the subject can then be derived, to be applied when needed, and consider available experience. Clearly theory should be separated from method.

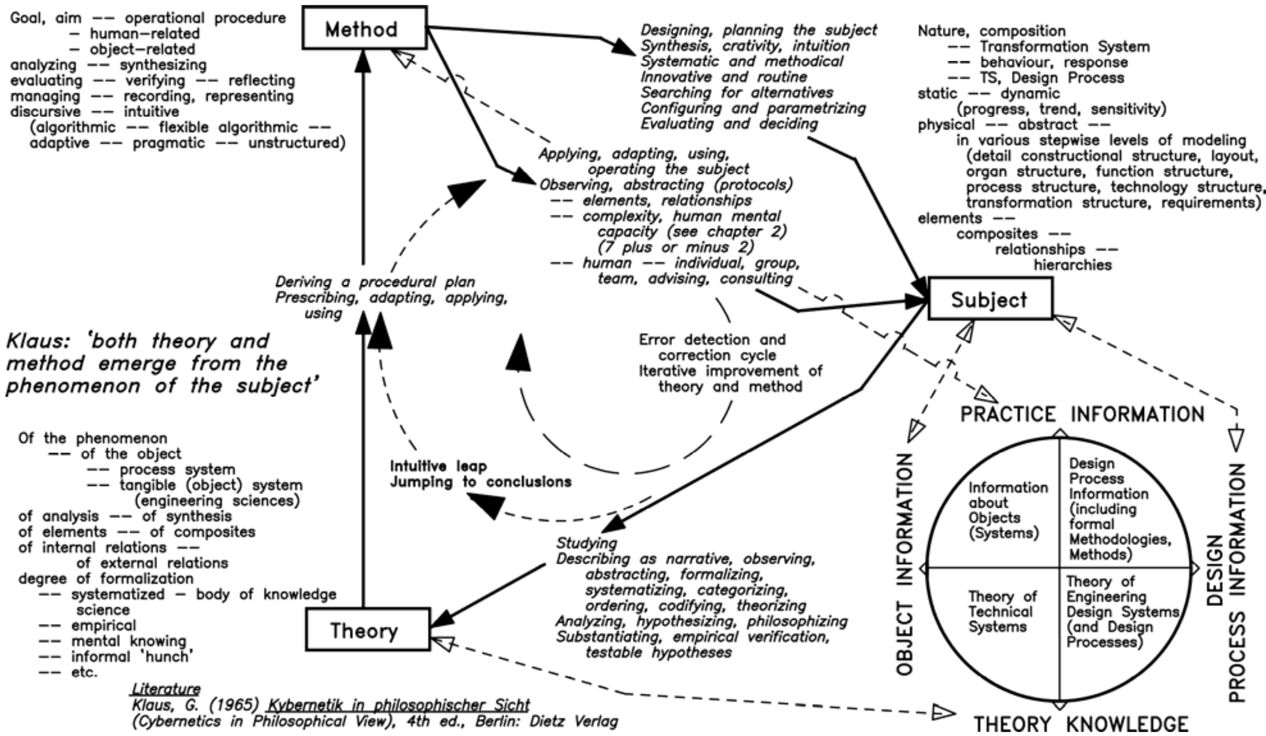


Fig. 2.2 Relationships among Theory, Subject and Method [Eder and Hosnedl 2008,2010]

The explicit theory of technical systems (TTS) describes what all existing technical systems (engineering artifacts) have in common, and what distinguishes transformation systems from other products – later expanded to 'engineering design science'. This was not intended to imply that design engineering *is* a science, the word 'is' is misplaced, the activity and process of designing involves a combination of the processes of science, art, experience, heuristics, creativity, and several other factors, as well as the information available for these activities. Nevertheless, both the activity and process of designing, and the product can be investigated with the tools of scientific endeavor, and described in formal and generalized terms.

The knowledge and information about design engineering can be 'mapped' onto two orthogonal axes, as shown in figure 2.3. The north-south axis ranges from 'practice information' to 'theory knowledge'. The west-east axis ranges from 'information about existing transformation systems' to ' information about designing of products, and about the design process itself'. This points to the importance of (a) information about technical and other objects, existing and to be designed, and (b) information about design processes, including the mental activities and the methods, information, and computer applications that may be useful for designing.

Strict separation (especially in the map of EDS, figure 2.3) was found necessary between (a) the existing TrfS, especially the TrfP and TS, in the 'as is' state, either fully designed, or fully implemented and manufactured, the 'west' hemisphere, and (b) the TrfS, including the TrfP and the TS, during the design process, especially the 'as should be' state, and the recommended systematic design process, the 'east' hemisphere.

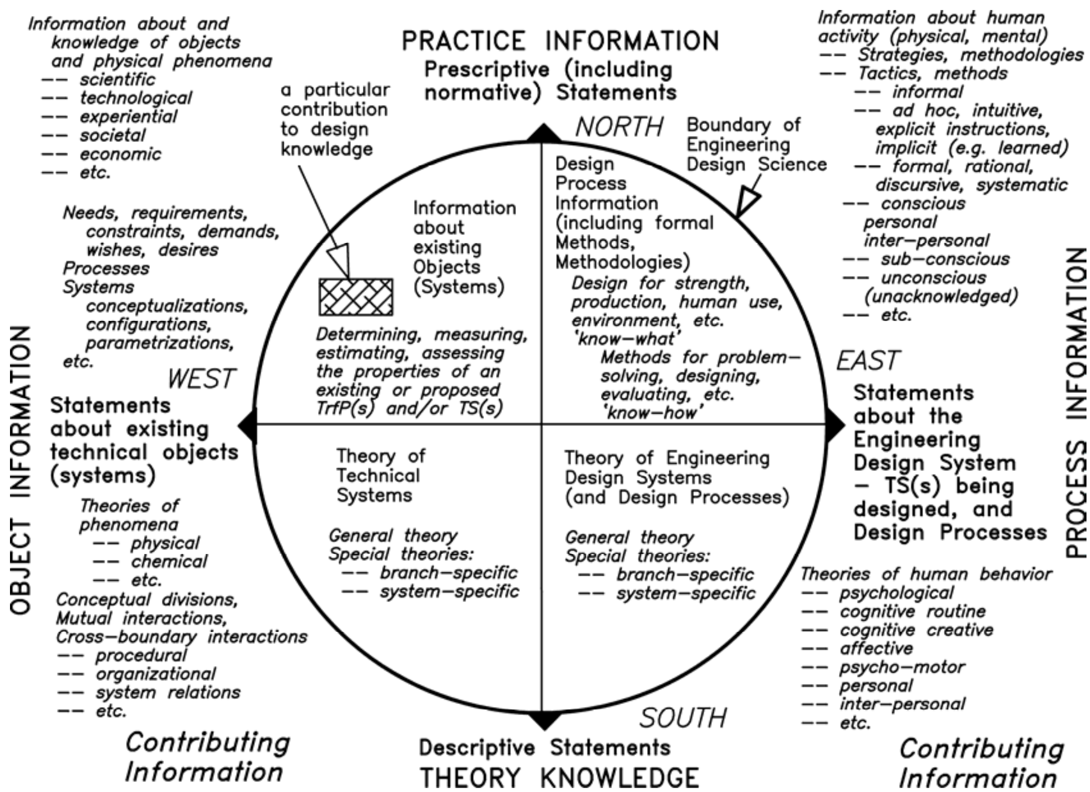


Fig. 2.3 Model (Map) of Engineering Design Science [Hubka and Schregenberger 1987, 1988, 1989, Schregenberger 1986, Stegmüller 1973, Hubka and Eder 1992b, 1996]

2.4.1. Technical Subject – Theory of Technical Systems

The basis of this theory is an axiomatically ('a statement regarded as obviously true' , 'a necessary and self-evident proposition, requiring no proof') complete abstract model for all (artificial, man-made) transformation systems, figure 2.4.

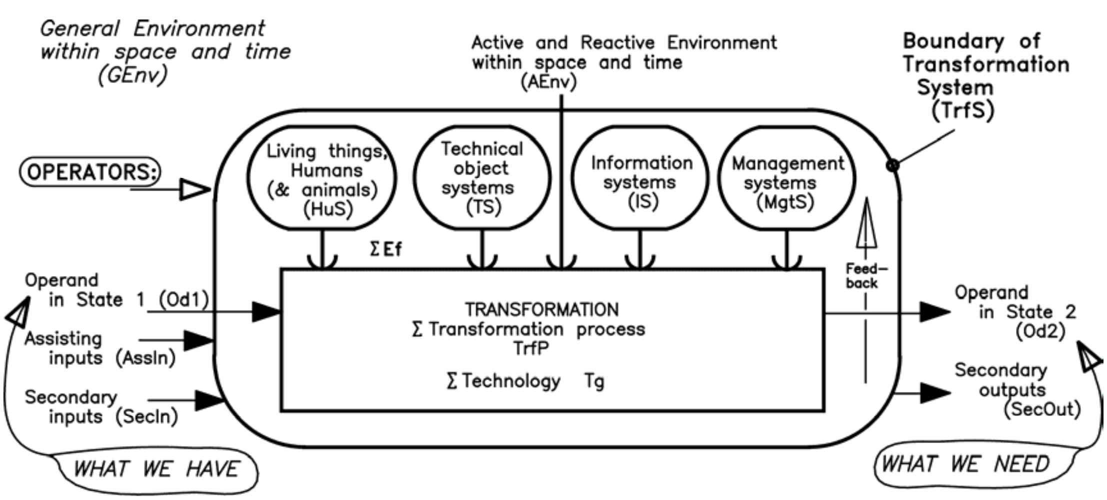


Fig. 2.4 General Model of a Transformation System [Eder and Hosnedl 2008, 2010]

The model of the *transformation system* in figure 2.4 declares:

- **An *operand* (materials, energy, information, and/or living things – M, E, I, L) in state Od1 is transformed into state Od2, using the active and reactive *effects* (in the form of materials energy and/or information – M, E, I) exerted continuously, intermittently or instantaneously by the *operators* (human systems, technical systems, active and reactive environment, information systems, and management systems, as outputs from their internal and cross-boundary processes, acting separately and/or jointly), by applying a suitable technology Tg (which mediates the exchange of M, E, I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.**

The operators can be active or reactive in their interaction with each other and in their technology-interaction with the operand. A hand power tool is reactive to its human operator, but active towards the operand. An automotive automatic transmission is mainly active. Maier and Fadel [2009] proposed 'affordances' as requirements and TS-properties that allow a user to do something with a technical system – they are all included in the requirements for TrfP and TS, see section 4.2, mainly as observable properties, especially where the TS is an operand or a reactive operator in the considered transformation system (TrfS). For instance, a step-ladder, an example used by Maier and Fadel [2009], is almost purely reactive to its loading – its transformation process operations could be established as: (1) remove TS from storage, (2) transport TS to usage site, (3) open and secure TS, (4) position TS, (5) permit human operator to climb up and down TS and to manipulate other items, (6) disable and close TS, (7) transport TS to storage site, (8) store TS. Maier's DAU (design team, artefact, user) model shows that these factors, plus other factors of the active and reactive environment, can influence each other, but does not specify in what way the influences can be exerted or used for designing. A research study shows a time sequence for DAU-internal interactions [Maier *et al* 2010] during a student design project for industry.

The operators of a TrfS can in most cases be regarded as full transformation systems in their own right. For instance, the management system (MgtS) performs its management process, driven by human managers, management technical systems, a management environment, a management information system, and an upper-level management system.

The general environment (regional, national and global) covers physical, chemical, societal, economic, cultural, political, ideological, geographic and all other influences indirectly acting on or reacting to the transformation system.

Various manifestations of the operand, input, output and effect can be defined:

M *material*: gas, liquid, solid; or in special cases a combination of these.

L *living things*: only applicable for an operand, includes humans, animals and plants.

E *energy*: needs a state (static, 'across') variable, and a flow (dynamic, 'through') variable, and can only be transmitted and/or transformed if both are non-zero.

State variable: force, torque (moment), pressure, voltage, temperature; Newton's law that 'action and reaction are equal and opposite' is valid for force, torque and pressure.

Flow variable: velocity, angular velocity, volume or mass flow rate, electric current, entropy.

Energy transfer and its dynamic behavior can be modeled by a sequencing of four-pole elements [Weber 2005b, 2005c]. One variable, state OR flow, can be *active*, it determines the behavior of the system, and can be calculated forward through the sequencing of four-pole elements. The other variable, flow OR state respectively, must be *reactive*, and can only be determined by calculating backwards through the sequencing of four-pole elements. Both the static and the flow variable need to be considered in establishing the necessary sizes.

I *information*: analog, digital; recorded, tacit/internalized/mental; etc.

These classes (M,E,I) always occur in combination, they are *interdependent*, but one of them will usually be *dominant* relative to the others.

The transformation process, TrfP, that is the main purpose of the transformation system, TrfS, has a structure of operations and their arrangement or sequencing. The transformation process, TrfP, can take place if (and only if): (a) all operators of the transformation system, TrfS, are in a state of being *operational*, they (especially the TS) should be able to operate or be operated, if appropriate inputs are delivered to the operator; (b) an operand in state Od1 is available; and (c) both are brought together in a suitable way, with an appropriate technology. The transformation operations can be represented as a flow chart. Each (group of) operation(s) needs a technology (Tg), which applies the useful output of each relevant operator to cause a deliberate change in the operand (Od) of that operation.

Primary classes of properties for an existing transformation process, TrfP, are shown in figure 2.5.

Actual properties of an existing TrfP can be completely arranged into the classes shown in this table.

	Class	Description
TrfP— OBSERVABLE PROPERTIES	TrfP—Pr1	Operand in state Od1, Od2, and in each intermediate state
	TrfP—Pr2	Assisting and secondary inputs
	TrfP—Pr3	Secondary outputs
	TrfP—Pr4	Technology for each transformation or operation
	TrfP—Pr5	Active and reactive effects received from the operators by means of the applied technology
TrfP— MEDIATING PROPERTIES	TrfP—Pr6	TrfP—Intrinsic design properties —— experience information, etc.
	TrfP—Pr7	TrfP—General design properties —— engineering sciences, etc.
	TrfP—Pr8	TrfP—Elemental design properties —— Types of transformation or operation performed on the operand, and their relationships

Fig. 2.5 Primary Classes of Properties for Existing Transformation Processes [Eder and Hosnedl 2010]

The operator that is deliberately designed to deliver the desired effects is the technical system, TS(s), that exists and operates within its TS-boundary, '(s)' designates that TS as the subject of designing. Various operational and supporting structures can be observed in a TS(s), the ones most suited to design processes are the TS-function structure (structure of TS-internal and cross-boundary functions), the TS-organ structure, and the TS-constructional structure, see figure 2.6. TS-internal and cross-boundary functions describe the capabilities of the TS(s). TS-organs realize these functions in operational pairings of action locations on adjacent (contacting) constructional parts, organs are responsible for the mode and capability of action. The constructional structure consists of constructional parts and their arrangement. During designing, the constructional structure may be manifested as a preliminary or sketch layout, a dimensional or definitive layout, or a set of detail and assembly drawings (or computer-file equivalents), parts lists, and instructions of various kinds.

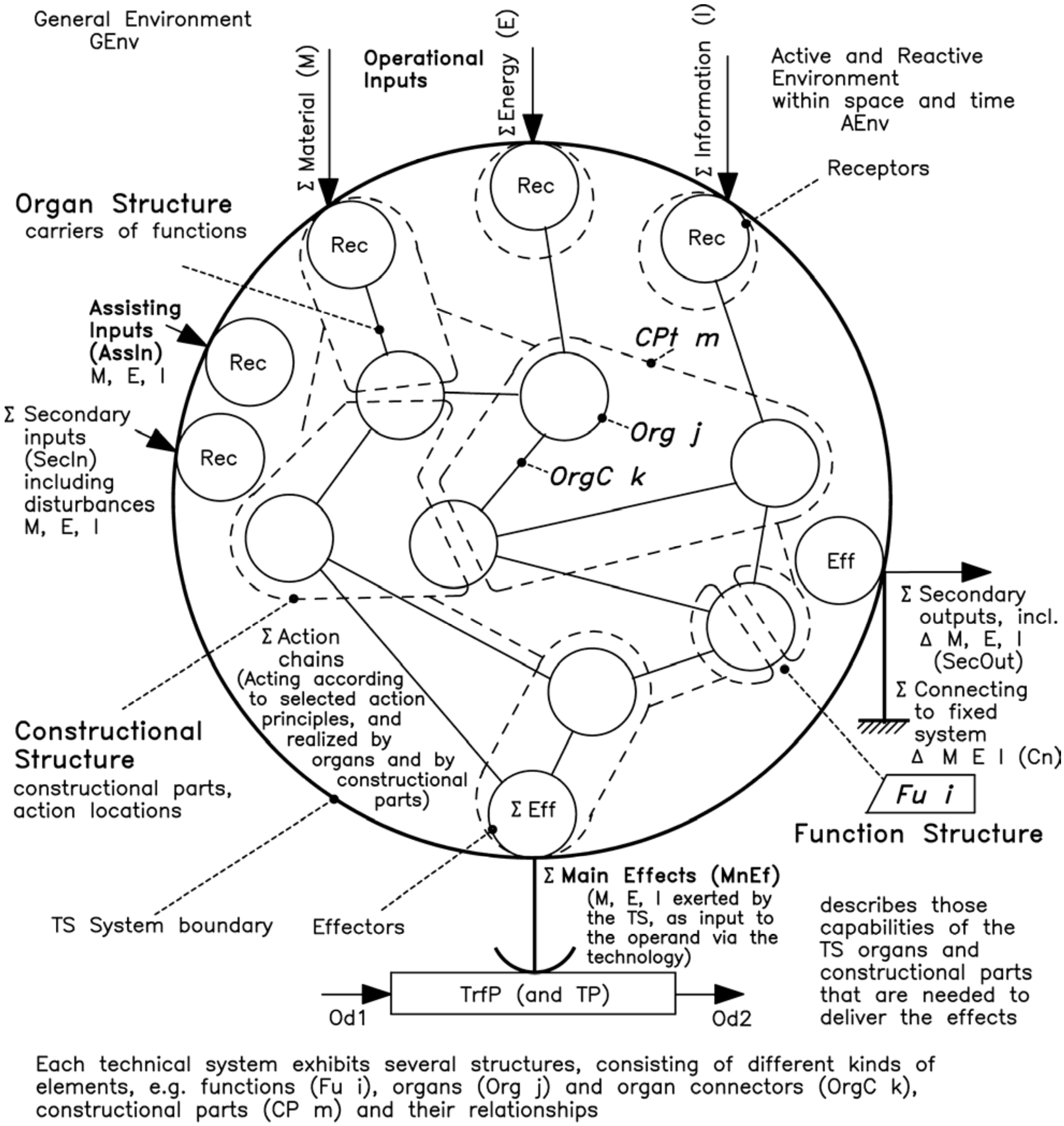


Fig. 2.6 Model of a Technical System – Structures [Eder and Hosnedl 2008, 2010]

Closely following the ‘function’ definitions provided by Pahl *et al* [2007], Hirtz *et al* [2002] have attempted a reconciliation of several proposals for a complete list of ‘functions’. As distinct from previous proposals, in their ‘functional basis’ they separate ‘flows’ from ‘functions’. In terms of Hubka’s theories, the Hirtz *et al* ‘flows’ are either transformation operations, or operator effects exerted via technologies on the operand. The Hirtz *et al* ‘functions’ are equivalent to the TS-internal and cross-boundary functions.

The models in figures 2.4-2.9 encompass all possible modes of action of technical products. Each *mode of action* (way of operating) is based on an *action principle*, usually supported by an engineering science – mechanical, hydraulic, pneumatic, electrical, electronic/analog, electronic/digital, building, chemical, optical, nuclear, biomedical, software, or other discipline or engineering branch, singly or in a hybrid combination, in a static and/or dynamic mode – 'high-tech' products are mostly hybrids of mechanical, computer, and other disciplines. Mechatronics and nanotechnology are the result of automation and miniaturization.

Technical systems (TS) exist in typically four levels of complexity: (I) constructional parts which can usually not be sub-divided without destroying them; (II) groups, sub-assemblies and modules capable of some TS-internal and cross-boundary functions; (III) machines, apparatus, devices, equipment capable of performing a complete function; and (IV) plant, complex machine unit that fulfills several functions. Each of these hierarchical levels may be sub-divided into several to many intermediate levels. A partial TS is also a TS in its own right, only the perceived or assumed TS-boundary is redefined to restrict the 'window' of observation [Nevala 2005], especially during designing.

A generalized life cycle of technical systems, consisting of typically seven (classes of) transformation systems, figure 2.7, and is axiomatically complete.

Primary classes of properties of existing technical systems are shown in figure 2.8, and have been demonstrated to be complete [Eder and Hosnedl 2008 (figure 6.8, part 2, p. 311)]. They are separated into TS-observable (previously 'external'), TS-mediating (previously 'internal'), and TS-elemental design properties. TS-observable are the properties that anyone can see, assess and/or measure for the chosen boundaries of the TS. TS-mediating are the properties that are not observable, they are hidden by the chosen boundaries of the TS, and include those related to the engineering experiential information and to the engineering sciences. TS-elemental design properties are those that are under the direct control of engineering designers during the design process, and include the TS-structures (function, organ and constructional), their elements and relationships, and for the elements the classes of arrangement, form, size, materials, anticipated manufacturing methods, deviations (tolerances), surface quality, etc. Any one property can appear in one or more classes, and the classification can change according to the situation, e.g. a change of the assumed TS-boundary and 'window' of attention [Nevala 2005]. The first draft of this model was published in [Hubka 1974].

For any one defined view of the TS-boundary, the TrfP is external to the TS – the operand cannot be part of the TS (within the assumed boundaries). The TS can be operational and can operate (or be operated) without an operand (see also the 'duty cycle' below). This led to a confusion in concepts between (a) the view of something being external or internal to the TS boundaries, and (b) the original designation by Hubka of the classes of 'external', 'internal' and 'elemental' properties [Hubka 1974, 1984, Hubka and Eder 1988, 1996] – causing a recent change in naming to 'observable', 'mediating' and 'elemental' properties [Eder 2009b].

The *state* of a TS is given by a suitable aggregate of the manifestations and/or values of all measurable and assessable properties and at a given point in time. The *states* of TS-properties exist and change among the different states of existence for each TS, e.g. various life-cycle phases of a TS(s), and under various operating states, the 'duty cycle' of an operational TS: (a) at rest, no operation; (b) during start-up; (c) during normal operation – idling, full-power and part-load, overload, etc., for self-acting operation (automatic), or running and ready to be operated by another operator, e.g. human or another TS; (d) during shut-down, ending an operational state and returning to 'at rest' conditions; (e) in fault conditions – (e1) internal faults – overload, safe trip-out, breakage or equivalent, and (e2) external faults – damage, wrecking, etc.; (f) during maintenance, repair, testing, etc.; (g) at 'life ended'; (h) any other states. The TS(s) can thus be operational, and even operating, in the absence of the operand of the TrfP.

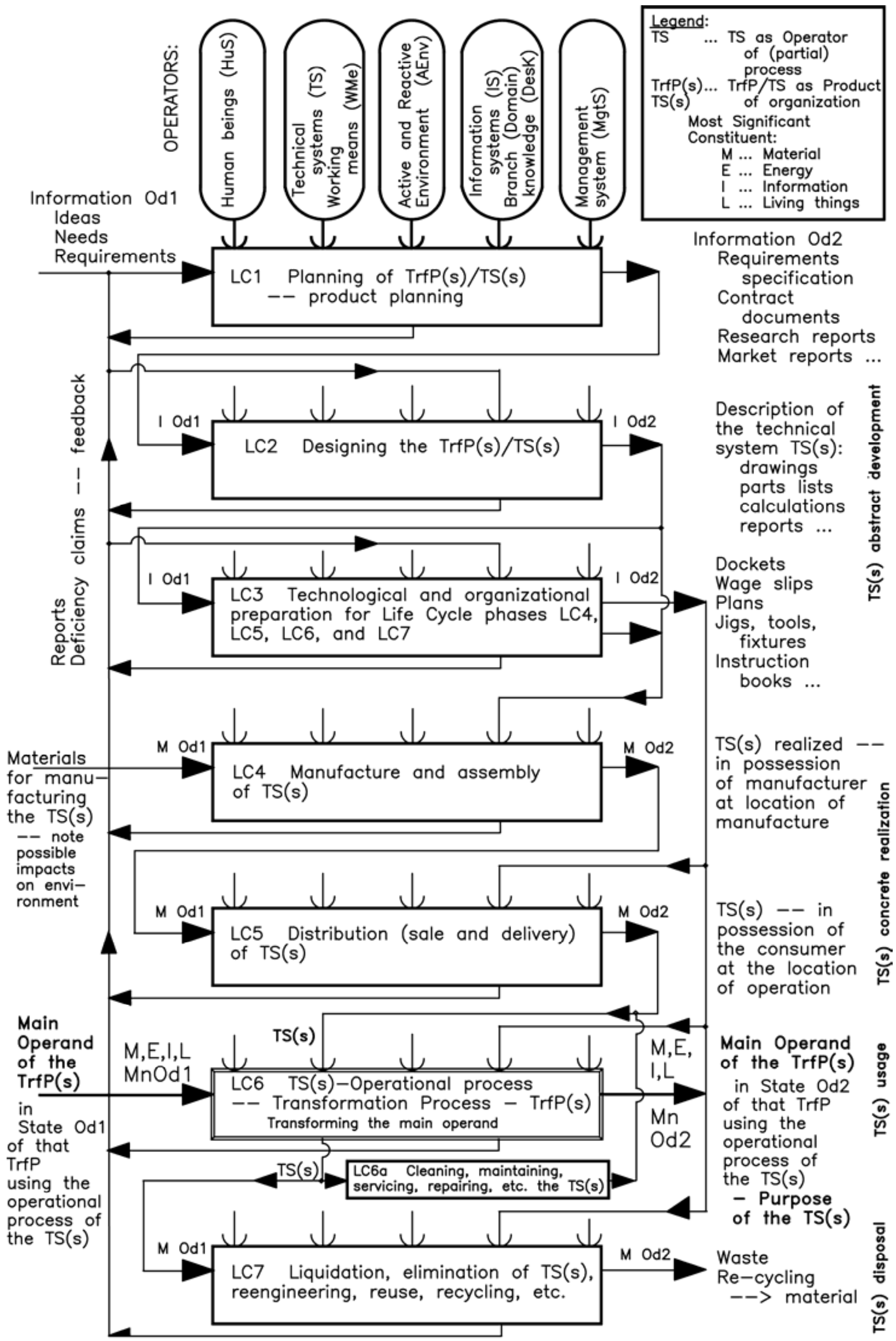


Fig. 2.7 General Model of the Life Cycle of Technical Systems [Eder and Hosnedl 2008, 2010]

Advanta-geous, Suitable for:		Symbol	Class of Properties	Typical Questions about the Class	Groups or Examples of Property Class -- Emergent Properties of TS(s)
TS-Observable Properties	Particular Phases -- Processes of TS(s)-Life Cycle	FuPr EfPr (Pr1A) – LC6	Functions Properties Effect Properties (TS(s)-Purpose Properties (Pr1) for TS-Operational Process TrfP(s))	What does the TS(s) do? What capability does the TS(s) have?	Main function Assisting functions: auxiliary function propelling function regulating/controlling fu. connecting function
		FuDtPr (Pr1B) – LC6	Functionally Determined Properties	What conditions are characteristic of the function?	Power, Speed, Size Functional dimensions Load capacity
		OppPr (Pr1C) – LC6	Operational Properties	How suitable is the TS(s) for its operational process TrfP(s)?	Operational safety Reliability, Life Energy consumption Space occupation Maintainability Adjustability Modularization
		MfgPr (Pr2) – LC4	Manufacturing and other Origination Properties	How suitable is the TS(s) for manufacture?	Manufacturability Assemblability Manufacturing quality
		DiPr (Pr3) – LC5	Distribution Properties	How suitable is the TS(s) for transport, storage, packaging, etc.?	Transportability Storage suitability Packaging suitability
		LiqPr (Pr4) – LC7	Liquidation Properties	How easy is the TS(s) to liquidate, dispose of, recycle, re-use?	Re-cycling
	Particular Operators of Each Phase -- Process of TS(s)-Life Cycle	HuFPr (Pr5)	Human System Factors related TS(s)-Properties	How is the TS(s) operated, what influence does the TS(s) have (directly or indirectly) on human beings (esthetic, emotions, senses, comfort, danger, endurance, etc.)?	Operator safety Way of operating Secondary outputs Requirements for human attention Form, color, surface
		TSFPr (Pr6)	Technical Systems Factors related TS(s)-Properties	What TS were used for the TS(s)-life cycle process? What other TS cooperated?	Manufacturing equipment, office machinery, etc.
		EnvFPr (Pr7)	Environment Factors related TS(s)-Properties	Do harmful outputs exist? What cultural and societal effects occur? What laws (etc.) were followed?	Cultural norms, societal expectations, pollution, ecological loads, etc. Danger of wastes
		ISFPr (Pr8)	Information System Factors, 'Know-how' related TS(s)-Properties	What information and know-how was available? Are instructions sufficient? What laws, codes of practice, standards exist?	Library, publications, standards, patent clearance, legal requirements
		MgtFPr (Pr9)	Management, Economics, Societal, Goals, Organization, Personnel related TS(s)-Properties	What organizational, planning, management influence exist? How economic is the working and manufacturing process? When was the TS(s) delivered? Manufacturing quantity?	Management procedure, Operating and Manufacturing costs, effectiveness Manufacturer recommended price Delivery capability, time Quantity production
TS-Mediating and Design Properties	Causes of all Observable Properties of TS(s)	IntDesPr (Pr10)	Intrinsic Design Properties	What technological principles, action sites, etc. are employed?	Legend: TS ... TS as Operator of (partial) process TS(s) ... TS(s) as Product of organization
		GDesPr (Pr11)	General Design Properties	Which engineering sciences, etc. are applicable?	
		DesPr	Design Properties	With what means are the observable properties (classes Pr1--Pr9) realized?	Structures (Fu, Org, C) Relationships/Elements Form, Shape, Geometry (size) Materials Type of manufacturing Surface quality State of assembly etc.
		ElDesPr (Pr12)	Elemental Design Properties	What structures, arrangements, elements/parts are used?	

Fig. 2.8 Primary Classes of Properties of Technical Systems [Eder and Hosnedl 2008, 2010]

The *behavior* of a TS(s), the sequencing of states through which the TS(s) passes in response to its inputs, the sequencing of changes in manifestations and/or values of TS-properties, is the result of performing its TS-internal and cross-boundary actions or reactions. Each such action results from a *mode of action* (way of operating) based on an *action principle*, see section 4. Action principles are mostly described by the engineering sciences, and they exhibit relationships and interactions.

Technical systems evolve over time, by developments of some of their properties to a more advanced state. The currently 'best' manifestation of a particular sort of TS is called the state of the art.

2.4.2. Designing as Subject – Theory of Design Processes

Once the logic of the transformation system (TrfS), figure 2.4, and of the structures of TS, figure 2.6, is understood, a theory-based prescription for a systematic approach to design engineering of novel systems can be derived. A summary of the important stages, taken from [Eder and Hosnedl 2010 (figure 11.1, p. 219-221)], and using the structures of TrfP and TS as guide, shows:

- *task defining*:

(P1) establish a design specification for the required system, a list of requirements;

(P2) establish a plan and time-line for design engineering;

- *conceptualizing*:

(P3a) from the desirable and required output (operand in state Od2), establish a suitable transformation process TrfP(s),

(P3.1.1) if needed, establish the appropriate input (operand in state Od1);

(P3.1.2) decide which of the operations in the TrfP(s) will be performed by technical systems, TS, alone or in mutual cooperation with other operators; and which TS(s) (or parts of them) need to be designed;

(P3.1.3) establish a technology (structure, with alternatives) for that transformation operation, and therefore the effects (as outputs) needed from the technical system;

(P3b) establish what the technical system needs to be able to do (its internal and cross-boundary functions, with alternatives);

(P4) establish what organs (function-carriers in principle and their structure, with alternatives) can perform each of these functions – usually with the help of a morphological matrix – and to combine them in various ways, e.g. topological arrangements. These organs can be found mainly in prior art, especially the machine elements, in a revised arrangement as proposed by Weber [Weber and Vajna 1997, Eder 2004, 2005];

- *embodying/laying out and detailing*:

(P5a) establish what constructional parts and their arrangement are needed, in sketch-outline, in rough layout, with alternatives;

(P5b) establish what constructional parts are needed, in dimensional-definitive layout, with alternatives;

(P6) establish what constructional parts are needed, in detail and assembly drawings, with alternatives.

Adaptation for redesign problems (probably about 95% of all design engineering tasks) proceeds through stages (P1) and (P2) above, then analyzes from (P6) or (P5b) to (P4), and/or to (P3b) to 'reverse-engineer' these structures, then modify them according to the new requirements, and use the stages in the usual order to complete the redesign.

At each stage it is possible (advisable) to search for candidate alternative solutions as indicated, and to select the most promising for further processing, whilst keeping full records of the (temporarily) rejected solution proposals. This is an essential aid to creativity made available by the outlined systematic approach together with the model of problem solving, section 4.3 of this paper. Other design-related pragmatic or 'industry best practice' methods, viewpoints, and theories can often be used in conjunction with this outlined method Eder and Hosnedl 2008, 2010].

Innovations are most likely in stage (P4) – this is the stage usually requiring a high level of creativity and/or use of a systematic and methodical approach (and see section 4.3 below). The transition from a TS-function structure to a TS-organ structure encourages a search for different candidate modes of action of the TS. This is seen in recent changes in the automotive industry (e.g. from mechanical control to digital-electronic control, from liquid fuel carburation to spray injection, from liquid fuel propulsion to hybrid to battery-electric). These hardly influence the observable properties of the product, they are often purely internal engineering changes that improve TS-behavior, its performance.

CAD – computer-aided design – can effectively be used in stages (P5a), (P5b) and (P6) – in earlier stages the representations are often too abstract for computer processing (including semantics and implications), but mathematical analysis and simulation in earlier stages are often useful – CAE, computer-aided engineering.

The apparent linearity of this procedure is only a broad approximation [Müller 1990], parts of the TrfP(s) and/or TS(s) will inevitably be at different stages of concretization, and of different difficulty (routine to safety [Müller 1990]), and will force iterative and recursive working – repeating a part of the design process with enhanced information to improve the solution proposals, and breaking the larger problem into smaller ones to recursively solve and re-combine. In the process, the perceived or assumed TS-boundary is frequently redefined to restrict and focus the designer's 'window' of observation [Nevala 2005].

For engineering design, *properties* of existing 'as is' TrfP, figure 2.5, and TS, figure 2.8, and *requirements* for 'as should be' TrfS need to be differentiated. Properties of existing 'as is' systems include only those life-cycle phases in which a tangible TS exists – TrfP(s) in life cycle phase LC6, figure 2.7, and of TS in phases LC4-LC7. The list of requirements, the design specification, design stage (P1) for a novel or re-designed 'as should be' TS(s), should also include the (financial, organizational, operating and other) requirements for the designing and manufacturing organization (LC1-LC3), and possibly for the using organization (LC6), for the TrfP, and for the TS, see figure 2.9. The resulting primary and secondary classes of requirements provide a good basis for setting up a design specification for any problem of design engineering.

It is, of course, true that engineering designers need and use intuition, based on their own internalized knowing and experience, which serves well for routine problems [Eder 2009a]. At that stage, they have already internalized their personal methodology, and usually cannot explain it, they even deny it. When the problem gets difficult, the engineering designer must be able to fall back to a formalized systematic approach to help in overcoming the difficulties – which is where Hubka's work, and many other design theories and methodologies, apply. Such a systematic engineering design process is not regarded as compulsory, it is intended as a guideline from which the engineering designer can choose the parts, models and procedures which he/she can find useful in that design situation.

Properties of a TS(s) to be designed must preferably fulfill all requirements that arise from each process in the TS life-cycle, and from the operators of each of these processes, in an optimal way.

Class	Symbol	Description	*With respect to:*
Rq1	OrgRq	Organization requirements	LC1 – LC3
Rq1A		of human operators of LC1 – LC3	
Rq1B		of TS operators of LC1 – LC3	
Rq1C		of environment operators of LC1 – LC3	
Rq1D		of information operators of LC1 – LC3	
Rq1E		of management operators of LC1 – LC3	
Rq2	TrfRq	Requirements of the Transformation	LC6
Rq2A		of operand in state Od1, Od2 and intermediate	
Rq2B		of assisting and secondary inputs	
Rq2C		of secondary outputs	
Rq2D		of technology Tg for each operation	
Rq2E		of active and reactive effects exerted by operators that cause the TrfP(s)	
Rq3	EfRq	Effects requirements of the TS	LC6
Rq3A	FuRq	Function requirements – behavior	
Rq3B	FuDtRq	Functionally determined requirements – parameters, requirements conditional on the TS(s) operating	
Rq3C	OppRq	Operational requirements	LC6a
Rq4	MfgRq	Manufacturing requirements, planning and preparation – realization requirements, manufacture, assembly, adjustment, packaging, etc.	LC4
Rq5	DiRq	Distribution requirements, maintenance and service organization, warranty, consulting	LC5
Rq6	LiqRq	Liquidation requirements	LC7
Rq7	HuFRq	Human factors requirements – ergonomics, esthetics, psychology and emotions, cultural acceptability	
Rq7A		In product planning, LC1	
Rq7B		In design engineering, LC2	
Rq7C		In organizational preparation, LC3	
Rq7D		In manufacturing, LC4	
Rq7E		In distribution, LC5	
Rq7F		In TS(s) operation, LC6	
Rq7G		In liquidation, LC7	
Rq8	TSFRq	Requirements of factors of other TS (in their operational process)	
Rq8A		In product planning, LC1	
Rq8B		In design engineering, LC2	
Rq8C		In organizational preparation, LC3	
Rq8D		In manufacturing, LC4	
Rq8E		In distribution, LC5	
Rq8F		In TS(s) operation, LC6	
Rq8G		In liquidation, LC7	
Rq9	EnvFRq	Environment factors requirements, LC1 – LC7	
Rq9A		Social, cultural, geographic, political and other societal factors	
Rq9B		Materials, energy and information – TrfP/TS inputs – effects of/on environment – TS–material – effects of and on environment – TrfP/TS secondary outputs and TS disposal	
Rq10	ISFRq	Information system factors requirements, LC1 – LC7 –– including law and societal conformity, cultural, political, and economic considerations, information availability, etc.	
Rq10A		Scientific information	
Rq10B		Technological information	
Rq10C		Societal information	
Rq10D		Legal information	
Rq10E		Cultural information	
Rq10F		Other information	
Rq11	MgtFRq	Management factors requirements	
Rq11A		Management planning – product range, LC1	
Rq11B		Management of design process, LC2	
Rq11C		Design documentation – design report, version control, LC2	
Rq11D		Situation – management climate, personnel relationships, etc., LC2	

TrfP–OBSERVABLE REQUIREMENTS (Rq2 – Rq2E): *Purpose of TS(s) Operational Process – the TrfP(s), LC6*

TS–OBSERVABLE REQUIREMENTS (Rq3 – Rq11D)

Rq1 – Rq6: ***Particular phases of the TS(s) life-cycle***

Rq7 – Rq11: ***Factors of particular operators of each TS(s) life-cycle phase***

Part 1 of 2

Fig. 2.9 Primary and Secondary Classes of Requirements for Transformation Systems [Eder and Hosnedl 2010]

	Class	Symbol	Description	With respect to:
TS-OBSERVABLE REQUIREMENTS		MgtFRq		Factors of particular operators of each TS(s) life-cycle phase (cont.)
	Rq11E	(cont.)	Quality system — quality of design, quality control, quality assurance	
	Rq11F		Information requirements — licensing, intellectual property, etc.	
	Rq11G		Economic requirements — costs, pricing, returns, financing, etc.	
	Rq11H		Time requirements — delivery, planning, process durations, repair, maintenance, etc.	
	Rq11J		Tangible resources — availability, accessibility, etc.	
	Rq11K		Organization — goals, personnel, etc.	
	Rq11L		Supply chain requirements — availability, delivery time, reputation, reliability, etc.	
	Rq11M		Other management aspects	
TrfP- and TS-MEDIATING REQUIREMENTS	Rq12	*Subsidiary cause of all TrfP(s) and TS(s) observable properties*	Intrinsic engineering design requirements Transformation principle Technological principle Mode of action Technologies Action sites Mode of adjustment etc.	Designing
	Rq13		General engineering design requirements Application of engineering sciences: strength, stiffness, wear, corrosion, hardness, etc., physical. mechanical, thermal, chemical, electrical, optical, technological, biological, etc. requirements	
TrfP- and TS-DESIGN REQUIREMENTS		DesRq	Engineering design requirements for TrfP(s) and TS(s)	
	Rq14	*Primary cause of all TrfP(s) and TS(s) observable properties*	Elemental engineering design requirements TrfP–Structure –– operations structure TS–Structures –– function, organ, constructional structures TrfP– and TS–Elements –– arrangement, relationships TS–Elements –– Level of abstraction of modeling Form (incl. shape) Size (drawing dimensions) Materials (physical, mechanical, electrical, chemical, optical, thermal, technological, etc. properties Type of manufacturing Size deviation (tolerance, limits) Surface quality (roughness, chemical) etc.	

Relationships:

With respect to a transformation process within the transformation system, designing is not useful unless the purpose of the TrfP(s) and the TS(s) is fulfilled.

Design engineering delivers the quality of the TS(s) as designed.

Manufacturing gives the quality of conformance, quality control, quality assurance for manufactured and purchased parts.

Management should be concerned with Life cycle assessment and engineering.

Quality management system –– ISO 9000:2005

Part 2 of 2

Fig. 2.9 Primary and Secondary Classes of Requirements for Transformation Systems [Eder and Hosnedl 2010]

2.4.3. Problem Solving – Sub-Process of Designing

Superimposed on the systematic approach to design engineering is a sub-process of problem solving, frequently applied in every design stage. Don Woods [1994] (McMaster University, Hamilton, Ontario) recognizes about 90 models of problem solving. In design science, the problem solving process appears as in figure 2.10. Obviously, operation Op-H3.2 'Search for solutions' is the step in which creativity is applicable, in addition to experience-based search. Noteworthy are the three auxiliary processes: Op-H3.5 'Prepare information', Op-H3.6 'Verify, check, reflect', and Op-H3.7 'Represent' – these have not been specifically stated in any other model of problem solving known to the author.

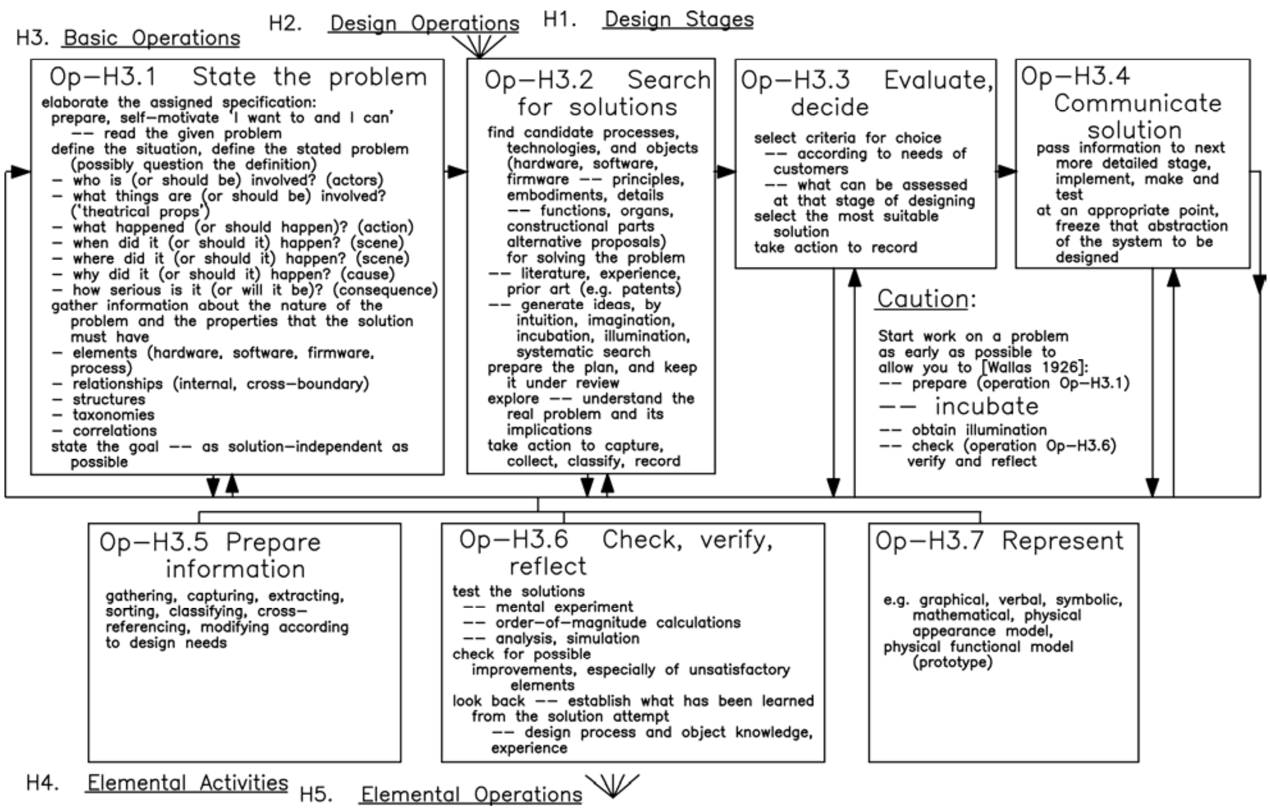


Fig. 2.10 Basic Operations – Problem Solving in the Design Process [Gregory 1966, Koen 2003, Schön 1983, 1987, Wales et al 1986a, 1986b, Wallas 1926, Hubka and Eder 1996, Eder and Hosnedl 2008, 2010]

Only in engineering design science [Hubka and Eder 1992, 1996, Eder and Hosnedl 2008, 2010] is this problem solving a formalized sub-process of the overall design process. In comparison (for instance) Pahl *et al* [2007] include 'evaluation' and 'decision' in their main design process and do not acknowledge a separate sub-process of problem solving.

Operation Op-H3.3 has received special consideration, it is probably the most discussed operation of problem solving. Many different methods have been proposed, see Reich [2010], each with strengths and weaknesses.

Iterative working is related to TrfP/TS properties, requirements, and both heuristic and analytical use of the mediating properties, the engineering sciences, and the problem solving cycle [Eder 2009b, Weber 2005b, 2008], see figure 2.11. Observable and mediating properties of future 'existing' TrfP(s)/TS(s) can be analytically determined from the established elemental design properties, giving a reproducable result. The inversion of this procedure, synthesis, is indeterminate, each required observable property is influenced by many different elemental design properties that therefore need to be iteratively established to approach the desired state of the observable property. Analysis is in essence a one-to-one transformation, convergence to one solution. Synthesis goes far beyond a reversal of analysis, it is almost always a transformation that deals with alternative means and arrangements, involving divergence as well as convergence, a one-to-many (or few-to-many) transformation. Synthesizing, as part of Op-H3.2 'Search for Solutions', is the more difficult kind of action [Eder 2009b]. Figure 2.11 constitutes proof that iterative procedure is a theoretical necessity in EDS, and a practical necessity in design engineering.

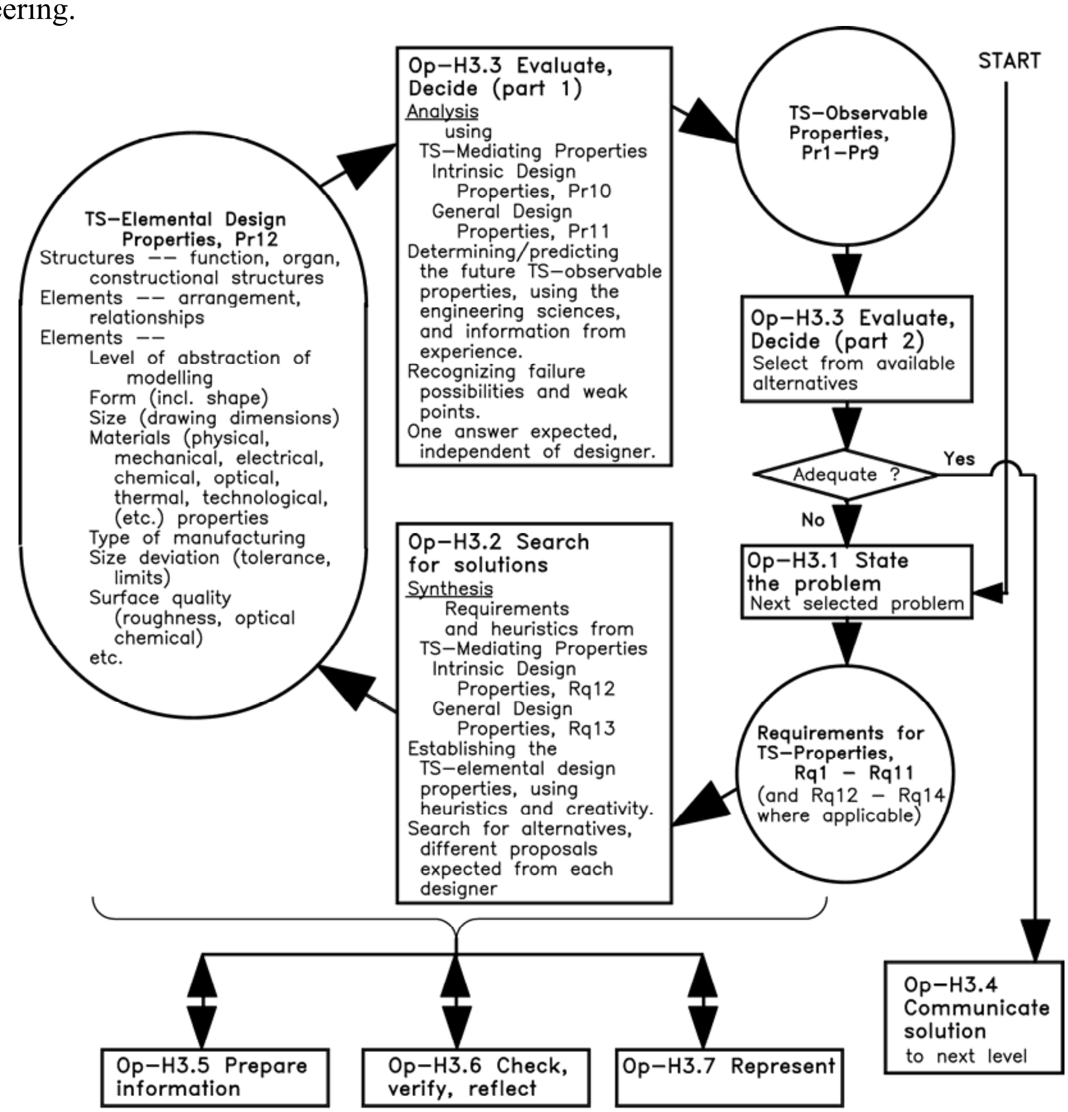


Fig. 2.11 Main Relationships Between Problem Solving, and Mediating. Elemental Design and Observable Properties (adapted from [Weber 2008a, Eder and Hosnedl 2010])

The Hubka methodology has been demonstrated on several case examples. Care should be exercised when reading these case examples, they were not intended to show a plausible optimal resulting proposed TS(s), and some of these cases are doubtful in that respect. The cases have nevertheless proved valuable (a) to validate, check for correctness, illustrate and document the theories, procedures, methods and models that can be used within systematic design engineering, and to show up deficiencies which were corrected in the theories, models and methods – especially relating to the different abstract structures of TS, or of properties; (b) to provide teaching examples of the recommended systematic procedure, especially for the conceptualizing phases of the design process, to demonstrate to students and other interested people that the systematic method can be made to work. The initials in brackets after the case title indicate the originator – (VH) = Vladimir Hubka, (MMA) = Mogens Myrup Andreasen, (WEE) = W. Ernst Eder, and (SH) = Stanislav Hosnedl.

The first case study, systematic according to the state of the theory and method at that time, appeared in [Hubka 1976] – a machine vice (VH). Hubka and Eder [1992a] included the second case study – a welding positioner (VH). The next three case examples, also systematic, were published in 1981 in German – a riveting fixture (VH), a milling jig (VH), and a powder-coating machine (MMA) – the first two were systematic, the third took an industrial-artistic design approach. Another set was published in 1983 in German – a P-V-T-experiment (WEE), a hand winding machine for tapes (VH), and a tea brewing machine (MMA) – again, the third took an industrial-artistic design approach. An English edition of case studies was finally published in [Hubka, Andreasen and Eder 1988], after several revisions requested by the publisher, and included the existing six case studies, plus two new items – a wave-powered bilge pump for small boats (MMA), and an oil drain valve (VH) – and again the bilge pump only loosely followed the systematic method.

Three further case studies were published in [Eder and Hosnedl 2008] – the tea machine revised to current systematic procedures showing enhanced engineering information (WEE); re-design of a water valve (WEE – first demonstration of systematic re-design); and an electro-static smoke gas dust precipitator, with rapper for dust removal (WEE) [Eder 2009c]. The most recent book in this sequence [Eder and Hosnedl 2010] contains three new case studies, a portable frame for static trapeze display demonstrations (WEE) [Eder 2010a] which was actually built and used, re-design of an automotive oil pump (WEE – second demonstration of re-design) [Eder 2010b], and a hospital intensive care bed (SH) – the latter shows cooperation between industrial design and design engineering [Hosnedl, Srp and Dvorak 2008]. Four more cases have now been prepared, two for the International Conference DESIGN 2012 [Eder 2012a,2012b], and two for the Canadian Engineering Education Association 3rd Annual Conference [Eder 2012c, 2012d], three of them designed and manufactured for the Caravan Stage Barge [2010] which has been in operation since 1995,.

2.5. Further Considerations

Hubka's separation of TrfP, Tg and TS encourages a consistent view of all engineering design problems at any level of complexity, especially in stages (P1), (P3a) and its sub-stages, and (P3b). It also shows that a TS-internal or cross-boundary function of a higher TS can be used as the TrfP for the next lower hierarchical level or sub-level of complexity of TS [Eder and Hosnedl 2006], as demonstrated in the electrostatic smoke gas filter and rapper [Eder and Hosnedl 2008, Eder 2009c], and the hospital intensive care bed and level compensation [Eder and Hosnedl

2010]. This confirms that designers can use the same form of systematic and/or intuitive design process can then be used for all hierarchical levels of decomposition or complexity, especially for recursive sub-division of the problem for solving and re-integrating. This process is reversible. The 'function decomposition' proposed in [Pahl *et al* 2007] has thus been proceduralized (operationalized) within EDS.

Human intuition and feel for design [Hubka 1975], experience, creativity, opportunism, and other such characteristics are vital parts of the engineering design process, but a systematic process is more likely to produce an optimal engineering solution, and allow better management of designing. An 'intuitive' response, is more or less to be expected at all levels of expertise, as the relevant theory and method becomes well enough internalized to run routinely, i.e. as an improvement of the mind-internalized theory, and formal examination becomes more difficult. Practicing of formalized methods and systematic approaches (following instructions) leads to their sub-conscious use, then a denial of use due to unacknowledged familiarity. This adaptability is now known as experience-dependent neuroplasty [Brown and Fenske 2010] – it is the reason for experts to generally claim that the use of methods is detrimental to creativity, but all experts use methods. Even complete denial of using methods indicates use of that method. The situations in which the engineering designers need to use formal systematic and methodical approaches have been more fully articulated [Eder 2009a].

The systematic design approaches need to be learned preferably in a non-threatening environment before the designer needs to apply them to a real problem. This learning happens most likely in safety operation – and engineering students are generally novices – even their academic staff are often novices at design engineering.

Hazelrigg [2005] pronounced that 'design is decision making'. This view is not useful for our purposes. It makes no distinction between 'design' as a noun and 'design' as a verb. It subsumes all steps and operations of the engineering design process into Hubka's problem solving operation OpH3.3, and thus discourages any separable theoretical explanation and derivable method for design engineering.

2.6. Comparisons

Comparison of Hubka's work with some other design approaches and theories has been attempted [Eder and Weber 2006, Weber 2009]. None of these approaches or theories show the comprehensive scope of Hubka's proposals, most are only based on unarticulated and incomplete theories, and most can be used in some appropriate situations within Hubka's full systematic method [Hubka and Eder 1992, 1996, Eder and Hosnedl 2008, 2010].

The headings for the following discussions are somewhat arbitrary, they are intended as convenient labels, one way of characterizing the different approaches, theories and methods of design engineering, to give a reasonable structure to this paper. Section 7 considers derivations from TTS and the derived design methodology. Section 8 considers some approaches with insufficiently articulated theory. Section 9 offers comments on some set-theoretic approaches. Section 10 views soma applications of artificial intelligence (AI). Section 11 looks at some knowledge-based approaches. Section 12 considers some approaches mainly limited to constructional structures, the most concrete design phase (P5a), (P5b) and (P6).

Pahl *et al* [2007] and The German Society for Engineers, VDI [1975, 1977, 1992, 1987], show a procedural model of design engineering, a methodology, based on pragmatic considerations (they are essentially identical). In this model, a 'total function' for a technical/transformation system is defined, and this 'total function' is then 'decomposed' to establish the TS-internal and cross-boundary functions. All the steps in this model are included in the procedural model of Engineering Design Science (EDS) [Hubka and Eder 1992b,1996, Eder and Hosnedl 2008,2010]. Conversely, the EDS theory and derived methodology contains several additions which includes the transformation process, TrfP, and the technology, Tg, as defined by Hubka, see figure 2.4.

In contrast to the Pahl/Beitz/VDI model, Hubka's legacy [Eder 2011] prefers a complete separation of TrfP and TS, which consequently allows and encourages a search for alternative solution proposals at several additional levels of abstraction (TrfP- and TS-structures), operational states and 'duty cycles' of the TrfP(s) and of the TS(s).

Pahl *et al* [2007] recognize a function structure, but subsume the structures of technologies (Tg) and transformation process (TrfP) into this composite function structure. They only recognize the application of the engineering sciences and schematic concept sketches within the Hubka TS-organ structure. Their strength lies in a fuller and more comprehensive treatment of the TS-constructional structure. In contrast, their underlying theory of technical systems, treatment of the phases of conceptualizing, properties and requirements, life cycle and others remain somewhat rudimentary, and they subsume the processes of problem solving into their main quasi-linear methodology. Strengths of the Hubka approach is the specific separation of the comprehensive theory from its application as methodology of designing, and separation of problem solving from the development of the transformation process and its driving technical system.

Evidence exists for the efficacy of the Pahl and Beitz and VDI design methodologies, see [Birkhofer 2011].

2.7. Theory of Technical Systems and Procedural Model of Design Engineering

During Vladimir Hubka's residency at the Technical University of Denmark, Kongens Lyngby, Denmark (1968 onwards), and for several years afterwards, Andreasen [1980,2011] worked closely together with Hubka, and adopted many of his ideas – including the idea of three significant structures of technical systems (TS), i.e. function structure (FuStr), organ structure (OrgStr), and constructional structure (CStr). The CStr was previously also called 'component' or 'anatomical' structure. On this basis, Andreasen [1980,2011] proposed a 'domain theory' – each TS-structure has a 'domain' on orthogonal axes of 'abstract to concrete' and 'incomplete to complete'. Designing aims towards concrete and complete description of a TS(s) in all its structures. This 'domain theory' is therefore a small graphical extension of a part of Hubka's Theory of Technical Systems, but contrary to figure 2.1 intermixes theory (of technical systems) and method (of designing) in its formulation. In later years, Andreasen [2011] denied the utility of 'functions', and lumped TS-functions, technologies, and transformation operations into a category he termed 'actions' – thus he reverted essentially to the Pahl *et al* [2007] model, and applied it mainly to non-engineering products [McAloone and Bey 2008], opportunities for finding alternative solution candidates at the additional abstract levels disappeared.

A development by Andreasen [Robotham 2002] of a 'function-means tree' is a reflection of the scheme of 'goals-means' [Hubka 1974 (fig. 5.13, p. 78)]. It has been adopted into EDS as the sequencing of steps for any *evoked* functions recognized during the design process as needed additions to the established TS-function structure, i.e. to find more detailed means to realize some TS-functions. The form of presentation shown in [Robotham 2002] does not fully follow Hubka's theories, and reverts to the Pahl *et al* [2007] model.

The 'chromosome model' by Mortensen [1999] graphically shows the relationship among the TS-structures, as shown in a text passage in [Hubka 1974 (fig. 5.4, p. 60-61)], which states that 'each TS carries all of its structures, and the elements and relationships of each structure is related in a complex way with the elements and relationships in all other structures'. Consequently, the *partial* design theories of 'domains', 'goals-means' and 'chromosome' are graphic clarifications, and are a sub-set of TTS and/or EDS.

Albers *et al* [2003,2004,2009] proposed the 'contact and channel model' (C&CM). A 'Contact' is defined as a 'working surface pair' on two contacting components, identical to Hubka's 'organ' [Hubka 1974,1976,1984, Hubka and Eder 1988,1992b,1996, Eder and Hosnedl 2008,2010]. Each working surface is also identical to a 'Wirkstelle' (an action location) on a constructional part (see already in first edition of [Pahl *et al* 2007]). A 'Channel' is defined as a 'support structure', identical to a 'constructional part' [Hubka 1974,1976,1984, Hubka and Eder 1988,1992b,1996, Eder and Hosnedl 2008,2010]. C&CM is thus also a sub-set of TTS [Hubka and Eder 1988], a fact not directly acknowledged by Albers in his publications. Hubka's 'organ' (and Albers' 'contact') and 'constructional part' (or 'channel') may apply to any technical system using any principle of operation, including active or reactive hybrid and high-tech devices, operating in a static and/or dynamic mode, and using a mode of action based on mechanical, hydraulic, pneumatic, chemical, electrical, electronic/analog, electronic/digital, nuclear, biomedical, and other modes of action, singly or in any combination.

VDI published a guideline for mechatronic systems, VDI [2004], which includes a 'V-model' of design development, figure 2.12. By implication, the procedural models of VDI [1975, 1977, 1992, 1987] are included in the 'domain-specific design'. Blanchard [2004] shows a similar model with respect to software systems. Similarity to the Procedural Model of Design Engineering [Hubka and Eder 1992a,1992b,1996, Eder and Hosnedl 2008,2010] is claimed:

- the 'domain-specific design' is represented by separate functions in the TS-function structure, which may specify TS-internal and cross-boundary functions that can be realized by mechanical, electrical, chemical, software, or any other mode of action or system,
- 'integration' can and should take place in any of the relevant structures (TrfP, TgStr, FuStr, OrgStr, CStr), but is especially necessary in the constructional structure because cooperation among the specialists is especially necessary here, and
- the cycle of 'substantiate, verify, improve' at the end of each design stage in the EDS Procedural Model [Hubka and Eder 1992a,1992b,1996, Eder and Hosnedl 2008,2010] leads to a feedback to any previous stage, not just to the horizontally referenced level, although this level may be the most likely target.

2.8. Methods with Insufficiently Articulated Theories

TRIZ and its equivalents stems from an extensive investigation by Altschuller [1973,1987], who searched several thousand patents to discover parameters and principles for technical systems. He proposed a method to assist designing, presented as a 'Theory of the Solution of Inventive Problems' (TIPS) – yet a coherent theory was not formalized or articulated in words and/or diagrams. His proposed method can help to develop clever solutions to problems that show a contradiction, where improving one parameter would adversely influence another parameter. 39

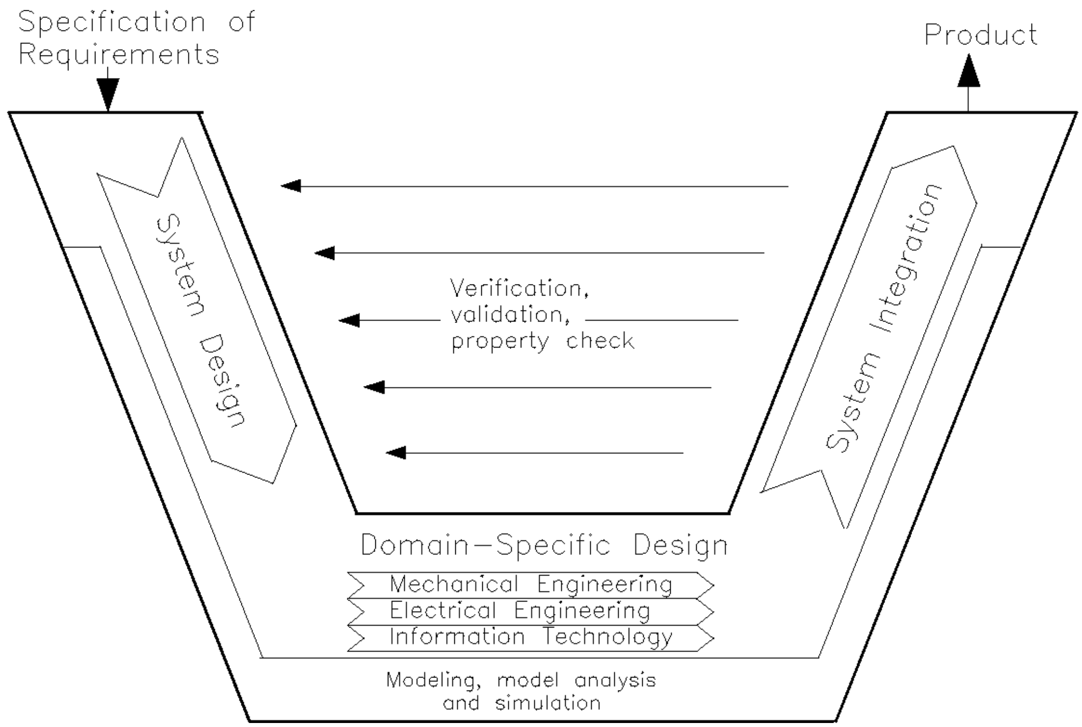


Fig. 2.12. 'V'-Model of Design Development [VDI 2004, Blanchard 2004]

'general parameters' (equivalent to some of the TS-properties) were defined (originally named from the Russian language), and 40 'principles' for finding design solutions were found, but neither include the electronic, digital-electronic and mechatronic principles. The 'parameters' and 'principles' have more recently been put into English-language terms. Coherent theories do not exist for object-related information, nor for design processes, and the two lists of 'parameters' and 'principles' are not complete, and have not been amended by more recent developments. Application is expected mainly in stages (P3b) and (P4) of the Hubka methodology.

Axiomatic Design was proposed by Suh [1989], with little advice about performing the design process to establish candidate solutions, he declares this as simply 'creative'. Suh defines design as a mapping of FRs (functional requirements) to proposed solutions, DPs (design parameters) in the physical space. He acknowledges further mappings from the customer space to the functional space, and from the physical space to the process domain of manufacturing. The 'functional requirements' thus concatenate the design specification, TrfP with the Tg and TS, stages (P1), (P3), (P4) and (P5). Each of the FRs and DPs is assumed by Suh to behave in a *linear* fashion – but most engineering systems are by nature non-linear in their behavior. If the numbers of FRs and DPs can be made equal (resulting in a 1:1 mapping of FRs to DPs), a square matrix of FRs vs. DPs can be formulated, which can be inverted – implying that synthesis is a direct inversion of analysis, but this is necessarily a special case, see section 4.3 of this paper.

The axioms (not easily acceptable as 'obviously true' , or 'requiring no proof') proposed by Suh, and the procedures are intended for *evaluation* of the 'proposed designs' (noun), part of problem solving operation Op-H3.3. Making decisions about the 'best' of the available candidates according to mathematically solvable criteria can then be performed by linear algebra, i.e. matrix methods. The axioms are now being used as to assist designing, but the difficulties introduced here are (a) proposing a set of guidelines for design procedure, and (b) actually achieving the assumed linear and orthogonal (independent) behavior in the proposed constructional structure.

- Axiom 1: The Independence Axiom – Maintain the independence of FRs – all functional requirements are preferably assumed orthogonal to each other (and therefore linear in their behavior), interactions are to be avoided.
- Axiom 2: The Information Axiom – Minimize the information content.
- Eight ‘Corollaries’ and 16 ‘Theorems’ complete the listing.

When comparing typically 2 to 5 alternative solution proposals, this normally leads to formulating a few (an equal number of) extremely complex FRs, compared to the usually 50-plus statements in a typical design specification, and probably leads to simplistic choices [Starr 1963, Morrison 1968]. These axioms have been incorporated as design principles, ‘working principles’ or ‘guidelines’ in [Eder and Hosnedl 2008 (ch.8, p. 381)] and [Eder and Hosnedl 2010 (ch. 14, p.331)].

The mapping of FRs to DPs by Suh, with no search for alternatives, may be compared with the multiple ‘mappings’ recommended in [Hubka and Eder 1992a,1992b,1996, Eder and Hosnedl 2008,2010], in which alternative solutions can be developed: design specification – transformation process TrfP – technologies TgStr – TS-function structure FuStr – TS-organ structure OrgStr – TS-constructional structure CStr, the latter in preliminary layout, definitive (dimensional) layout, and detail. These mappings are represented in the stages in Hubka’s Procedural Model of design engineering (the methodology), see section 4.2 in this paper, and form a positive procedural recommendation for any design situation.

2.9. Set Theoretic Models

The General Design Theory, GDT, was proposed by Yoshikawa [1981a,1981b,1981c,1983], and has been developed by Tomiyama and others. The declared aim was to fully automate the design process by digital computer. At present, it is therefore only applicable to stages (P4) onwards, where a physical representation of the future TS is available. GDT is based on a mathematical set-theoretic and deterministic world view in which the ‘ideal knowledge’ includes everything that is now known, and everything that will be known in future. This can conditionally be accepted, if in a computer implementation any future discoveries can be entered as they are discovered, and any fully obsolete knowledge can be deleted. GDT only considers a technical system once it exists, with a one-to-one mapping of entities onto their representations (‘concepts’) – defining requirements, and conceptualizing are not considered as a part of the design process. Under these conditions, synthesis is a direct matrix inversion of analysis, and the full ‘design intent’ should be available for capture by computer processing. There is no envisaged possibility of searching for or recording alternative solutions at any level, all possible solutions are already available for selection. In essence, only the final constructional structure is considered, and only those properties that have a measure and value can be included – ‘appearance of the TS’ as a TS-property seems to be denied. The point of overlap between GDT and TTS may be the definition of classes of TS-properties. Aims of GDT include construction of a computer system and its formulation for computer-aided design leading to absolute optimization of the product. Some useful computer implementations have been achieved, with good results, but not full automation of engineering design.

Tomiyama [1995,1998] has extended GDT to include his own cognitive protocol research results on a design project, see also [Yoshioka and Tomiyama 1999], to produce a ‘grounded theory of synthesis'. The resulting 'cognitive design process model' shows distinct similarity to the over 80 problem solving processes published to date. It does acknowledge the differentiation proposed in EDS [Hubka and Eder 1992b,1996, Eder and Hosnedl 2008,2010] between object information and design process information (called 'action level'). EDS shows a synthesis of many of these problem solving processes in figure 2.10 – as a sub-process that takes place many times in each step or stage of the overall design process.

Tomiyama's [1998] report shows that six categories of design knowledge were identified, relating to: entities (presumably constructional parts), functions (unspecified whether TrfP operations or TS-internal and cross-boundary functions), attributes (presumably properties), topological relationships, connection methods, and manufacturing methods. Eight types of primitive transitions between them were identified: (1) from functions to entities, (2) from entities to functions, (3) from attributes (properties) to entities, (4) from entities to attributes, (5) from attributes to attributes (via entity), (6) from topologies to relationships, (7) from entities to manufacturing methods, and (8) from manufacturing methods to attributes.

The accompanying figure (numbered 7 in that paper) shows a transition between 'topological relationships' and 'connection method' that does not appear in the listing of the eight transitions – and (6) 'from topologies to relationships' seems to have been compressed into one concept. There are no transitions (a) between 'manufacturing method' and 'connection method', and (b) between the cluster of 'entities, functions, attributes' and the cluster of 'topological relationships' – the absence of these is counter-intuitive.

An implementation of Tomiyama's [1998] 'cognitive design process model' in a CAD program seems to have been achieved, to reproduce the process as a 'design simulator' – it succeeded in playing back the design process obtained by the protocol experiments, but could not actually design, i.e. produce any alternative solution proposals. The human capacity for novel and associative thinking seems still to be largely ignored. Other conclusions in this paper render Tomiyama's concepts somewhat doubtful.

Grabowski, Rude and Grein [1998] organized a Workshop on Universal Design Theory (UDT), with contributions from many eminent persons. There seems to have been no attempt at this stage to compare or coordinate the opinions, or to attempt to find a common terminology. His own contribution [Grabowski *et al* 1998] attempts to reconcile the general German methodology (e.g. VDI Guidelines) with computer application – but it is well known that the sub-process of 'conceptualizing', Hubka's stages (P3a), (P3b) and (P4), is largely a process performed as an interaction by human designers between their mental and graphical representations, including with very abstract models that are at present not amenable to computer processing, especially in their semantics.

Lossack [2002], under supervision from Grabowski, proposed a Universal Design Theory (UDT) based on a methodological framework consisting of 'theory', 'applications' and 'validation' to characterize a 'design working space' in preparation for computer processing. At present, it is therefore also only applicable to stages (P4) onwards, where a physical representation of the future TS is available. 'Theory' is divided into 'solution patterns' of design knowledge, and a 'formal framework' containing design guidelines, design principles, and axioms. 'Applications' are claimed from mechanical engineering, chemistry, materials science, computer science, biology, pharmacology, and architecture. 'Validation' should be by empirical research, utilization and transfer. The design process is described using the methods and 'layered model' of VDI [1992,1977] coupled with a generic problem solving cycle developed by Rutz [1995] (but see the comments about problem solving and figure 2.10). The resulting connections among the 'requirements', 'function', 'physical principle' and 'embodiment' layers looks strangely like the chromosome model of Mortensen [1999], but with a better formalization of the relationships. Lossack [2002b] expanded UDT by attempting to define a Domain Independent Design Theory (DIDT).

Grabowski, Lossack and Bruch [2004] reported an attempt to use UDT to create a computer program for 'requirements development', equivalent to Hubka's stage (P1). The non-deterministic process of developing a list of requirements was divided into elemental steps, and described by its states, and the appropriate state transitions. This process should result in a progressively more detailed requirements network. Developing the 'requirements' allows selection of constructional parts for the product. A software prototype was produced. It seems that the authors in part did not separate 'requirements' (normally pre-specified) [Eder 2008b] from TS-internal and cross-boundary functions.

2.10. AI Applications

Operation Op-H3.2 of problem solving, figure 2.10, has recently received a good partial fomalization in the unified C-K theory of design reasoning [Hatchuel and Weil 2003, Hatchuel, LeMasson and Weil 2006]. It also confirms the need to encourage interaction of a human mind with graphical representations on paper or other suitable medium [Wallace 1952] in an attempt to partially overcome the limitations of human short-term memory [Cowan 2001, Miller 1956a, 1956b, 1956c, 1960, 1970].

Hatchuel's proposal tries to avoid the restrictions of GDT and UDT. Their survey of existing theories does not include the works of Hubka and associates, and of many others. There seems to be no differentiation between information (including knowledge and data) that is internalized in mental structures of humans (mainly in C), and information that is available in recorded form (much of K). According to C-K, design, undefined whether used as noun or verb, should be defined independent of any domain or professional tradition – which seems to deny any differences between design engineering and the more artistic design disciplines, see figure 2.1 and comments in the introduction to this paper.

'K' is defined as a knowledge space, containing propositions that have a logical status for the designer – logical status defines the degree of confidence that a designer assigns to a proposition. 'C' is defined as a concept space, in which the propositions have no logical status. Apparently, the only operations (called 'operators' in C-K) that can be performed are K–>C, C–>K, C–>C and K–>K. These propositions have been verified by set-theoretic considerations [Reich *et al* 2010]. By definition, 'design' is a process of generating other concepts or transforming them into knowledge. How, with what models and methods, this is to be done is not defined. Hatchuel claims that 'the metaphors of "exploration" and "search" are confusing for design'. Yet especially in design engineering we generally explore and search for possible solutions from existing precedents [Booker 1962], from tacit/internalized knowing, from the literature, and many other locations. The model of problem solving, figure 2.10, as sub-process of an engineering design process (see [Eder and Hosnedl 2008 (figure I.21, p. 64)], and [Eder and Hosnedl 2010 (figure 8.4, p. 160)], specifically contains an operation of Op-H3.2 'search for solutions'. The C-K theory is obviously a good partial formalization of this problem-solving operation. Without disputing the claimed rigor of the C-K theory, it seems that this formulation has some similarity with the much earlier insights about interaction of cognitive processes (mental constructs in a human mind) and external representations (verbal, graphical, 3-D solid, etc.) produced by a human. This was formulated by Wallace [1952] in his overall model ATDM – Analyze, Theorize, Delineate, Modify. Theorizing takes place in a human mind (Hatchuel's

C?), delineating transfers some of the thoughts onto a mind-external medium (Hatchuel's K?), and modifying starts a new ADTM cycle. This interaction of thought with graphical representation is a normal procedure for almost any human activity, especially necessary in view of the limitations of human short-term memory – 7"1 chunks of information or less [Cowan 2001, Miller 1856a,1956b,1956c,1960,1970].

Even with recent advances in formulation [Hatchuel and Weil 2009], the C-K theory seems to be reasonably valid for industrial/artistic 'designs' and designing, but is insufficient as description and/or guideline for design engineering, in contrast to Hubka's theories and methods that are directly applicable to design engineering, and may be useful for other design disciplines. Hubka's [1992a] statement that problem solving can be viewed as a paradigm for the whole design process accords in part with the C-K theory, but his development goes far beyond.

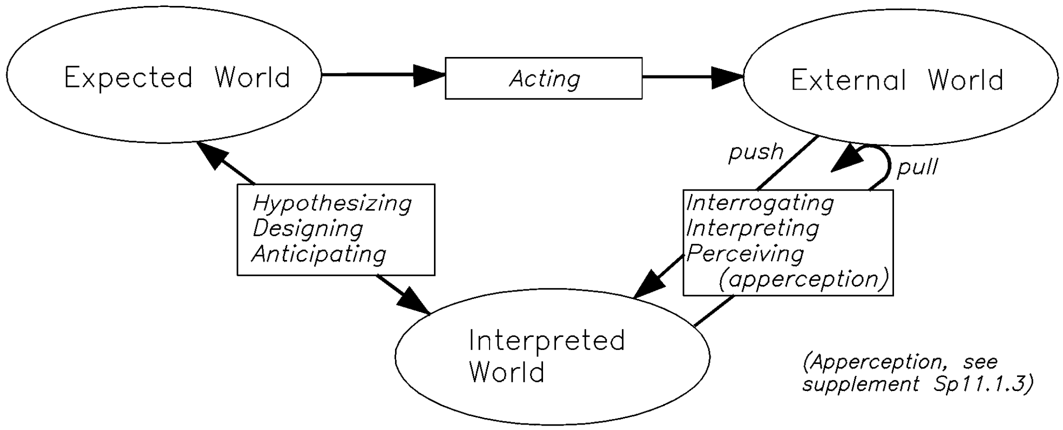
Noteworthy among other extant theories of design is a model of situatedness in designing [Gero 1998, 2004, Gero and Kannengiesser 2004], see figure 2.13, showing a relationship among an external world ('as is'), an interpreted world ('as observed'), and an expected world ('as designed'). A second model includes relationships among 'function', 'behavior' and 'structure'. In this second model, Gero seems not to differentiate transformation processes, TrfP, from TS-internal and cross-boundary functions, all are subsumed into his 'function'. He seems to recognize only one form of structure – probably the constructional structure – due to his emphasis on computer processing. His main aim is computerization and possible automation of design processes, applicable at present mainly to the constructional structure, Hubka's stages (P4) onwards. Gero's list of 'transformations' (of the design process) show some similarity to problem-solving, as illustrated in figure 2.10 of this paper. An advantage gained by the Hubka approach described in this paper is the availability of searching for solutions at several other structures, enhancing the possibilities of applying creativity.

Following from Gero's proposal of situatedness, see figure 2.13, Kazakçi [2005] finds a need to add spaces of the internal and external world to the Hatchuel C-K Theory. The 'interpreted world' of Gero is replaced by Hatchuel's C-K spaces.

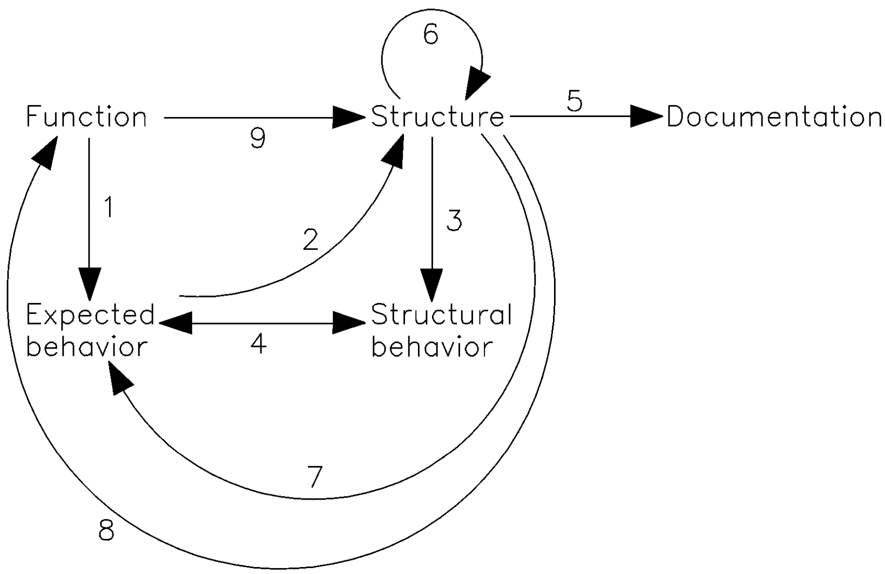
2.11. 'Knowledge' Base

Smithers [1999], using concepts of artificial intelligence (AI), proposed to define a structure of knowledge at various levels to enable design, as a Knowledge Level Theory of Design (KLDE), independent of implementation. He defines 'knowledge' (in an e-mail to Prof. Christian Weber) as a 'capacity to act rationally with respect to some class of objects' – without differentiating whether this knowledge exists in tangible records or in the mind of a human. He defines 'information' as the communication of data between (knowledgable) agents – but much information is available in verbal and pictorial-graphical forms, with or without numerical values [Constant 1980, Vincenti 1990], and may be printed on unresponsive paper. According to Smithers, 'data' with values is only obtained by measurement, mathematical derivation, or computation – but apparently not by estimation or assessment by humans. Knowledge has three 'roles' and four 'type relations', from which he defines 18 types of knowledge used, and 13 types created in designing – there seems to be no way to establish that these classifications are complete. Smithers [1999], in his introduction, states: 'So far, all of this engineering activity has been carried out in the absence of any usable theory or theories of design process' – he quotes

A Situatedness in Designing



B Function – Behavior – Structure (F-B-S)



Legend of transformations:
1 ... Expected behavior from function by finality
2 ... Structure form expected behavior by finality
3 ... Structural behavior from structure by causality
4 ... Structural behavior compared to expected behavior
5 ... Documentation from structure by causality (representation)
6 ... Structure self-referred
7 ... Expected behavior from structure by analysis
8 ... Function from structure by analysis
9 ... Structure from function

Literature:
Gerö, J.S. and Kannengiesser, U. (2003) 'The Situated Function-Behaviour-Structure Framework', Design Studies, Vol. 25, No. 4, p. 373-391
Gerö, J.S. (2004) 'Situated Design Computing: Introduction and Implications', in Proc. International Design Conference – Design 2004, Dubrovnik, May 18 – 21, 2004, pp. 27-36, on CD-ROM

Fig. 2.13 Situatedness in Designing, and Relationship 'Function – Behavior – Structure' [Gero 1998, 2004, Gero and Kannengiesser 2004]

Hubka and Eder [1992b], but not Hubka and Eder [1996]. It seems that for Smithers everything must be transformed into a computational realization – human mental activity and interaction with hand-produced representations is not considered.

Braha [2006] describes a rule-based approach to automating a design task. The paper sets out several arbitrary 'facts' that seem to be descriptions of usage for a car, a set of 44 'structural attributes' that represent an incomplete collection of items, and a set of 30 'functional attributes' that are equally incomplete. 38 'if-then' rules are laid out to relate the functional and structural attributes. The reported algorithm can then provide a 'consistent solution' to the problem, using a Boolean satisfiability encoding. No specific car is recognizable in the reported 'solution', in fact the car now needs to be designed for external appearance and for internal (technical) operation and operability (mechanical, electrical, computer-control, road behavior, driver actions, etc.) to this set of attributes before any parts of it can be manufactured. The reported algorithm is probably useful for pure configuration products, for which each constructional part (sub-system) has been fully designed, manufactured, and tested, ready for final configuration and assembly.

Kuate *et al* [2006] present a scheme derived from a protocol study, see figure 2.14, which confirms the 'windows' view of Nevala [2005]. When a designer 'dives into detail', he/she also recalls relevant general and professional information, e.g. mental descriptions and models of the surrounding constructional structure. Nevertheless, the designer comprehends the total problem through a restricted 'window' [Nevala 2005], as a design zone, including a form-giving zone as viewed by an engineering designer during his/her design process [Hubka and Eder 1992a,1992b,1996, Eder and Hosnedl 2008,2010], especially in stages (P4) and (P5). The boundaries of that window are determined by the immediate design task, the personal knowing, and the organizational position of the individual, and these change from incident to incident – the design situation.

A more comprehensive scheme was proposed by Eekels [1994, Roozenburg and Eekels 1995], see figure 2.15. This is part of a 'Logic of Design', derived from a combination of design engineering and industrial design. This 'logic' seem to equate 'function' with both 'transformation process operation' and 'TS-internal and cross-boundary function'. The partial representation of the 'cosmonomy' consists of a set of hypothetical statements such as 'if A, then B', under the assumption that reality is likely to behave that way, as a strictly logical 'causal model'. A discussion of the 'logic' aspects shows the formalization of deduction, induction, reduction/abduction, or innoduction [Eder and Hosnedl 2008,2010, Eekels 2000], all of which are needed for science and for design, and none of which exclude intuition and routine work from experience. The 'logic of design' represents a more abstract level of science, probably between the 'general design science' and the Engineering Design Science in figure 2.16.

2.12. Constructional Structure

Property-Driven Development/Design (PDD) [Weber 2005b,2005c,2008a,2008b, Weber et al 2004] distinguishes 'characteristics' and 'properties'. His 'characteristics' are almost coincident with Hubka's definition of TS-internal properties (now renamed 'TS-mediating' [Eder and Hosnedl 2008,2010, Eder 2008b]) and TS-elemental design properties. His 'properties' are almost coincident with TS-observable properties. Physical and/or digital/virtual analysis consists of determining and/or predicting a product's observable properties and behavior from the existing or established elemental design and mediating properties. Synthesis and product development consists of establishing and assigning the product's mediating and elemental design properties

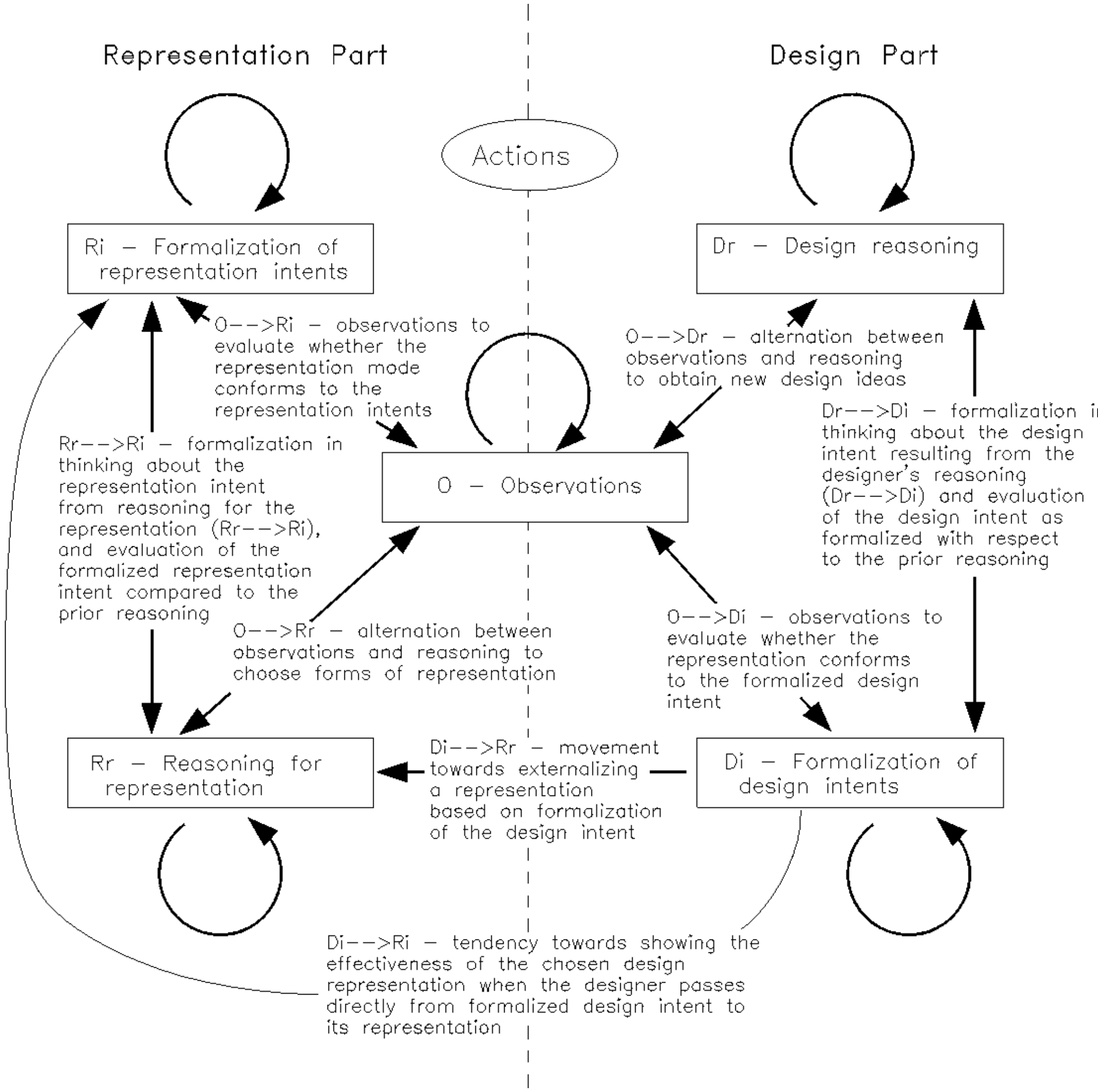


Fig. 2.14. Design Activities Model [Kuate et al 2006]

from the requirements for observable properties – almost coincidental with Hubka's stage (P4). Modeling products and product development processes may be performed by a 'Characteristics-Properties Modeling' (CPM) procedure. The mediating and elemental design properties show a complex relationship to the observable properties. In analysis, these relationships are known and can be determined, the elemental and mediating properties (causally) determine the observable properties. In synthesis, 'inverting the relationships' can and often does result in ambiguities, because each mediating and/or elemental property established from a required observable property may influence in turn several to many other observable properties in unanticipated ways. These are conflicts which must be resolved by iterative progress. External conditions are seen as properties of neighboring systems – 'Design *for* X' (DfX) is the process of considering these external conditions when designing a product. 'Design *of* X' (DoX) is a process of simultaneous engineering of the external conditions, e.g. the manufacturing system, as reflected in figure 2.11.

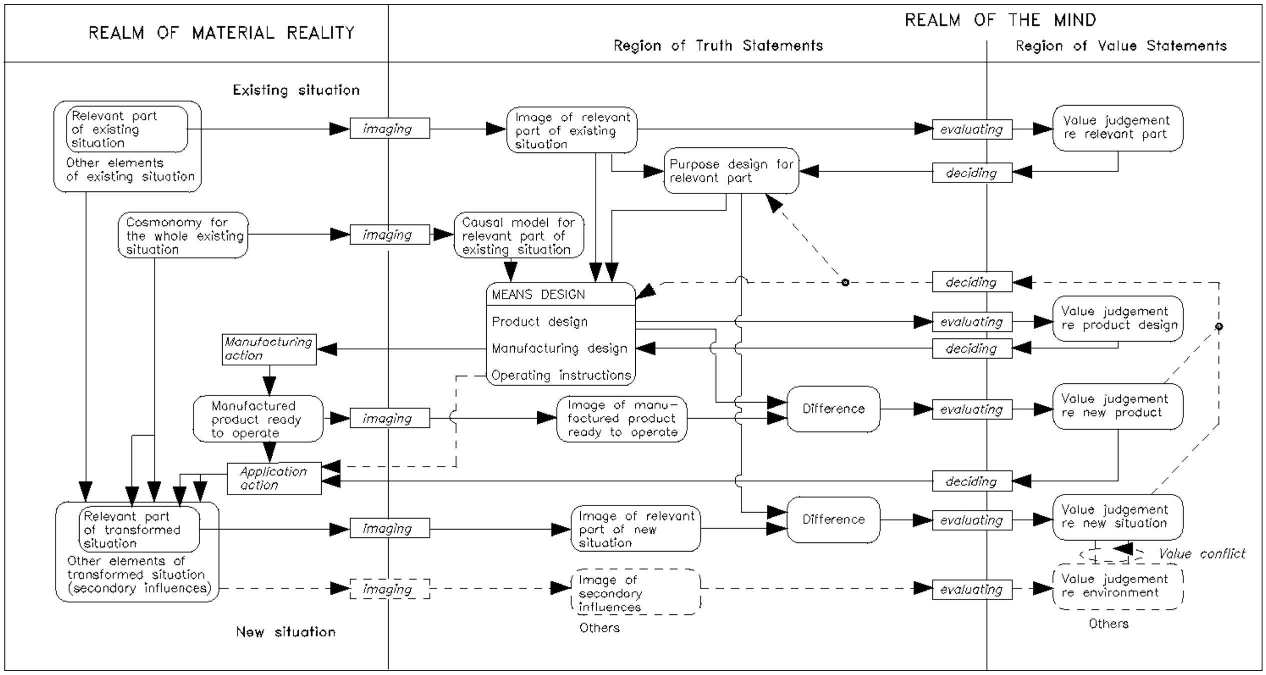


Fig. 2.15. Structure of Context of Designing [Eekels 1994,2000, Roozenburg and Eekels 1995]

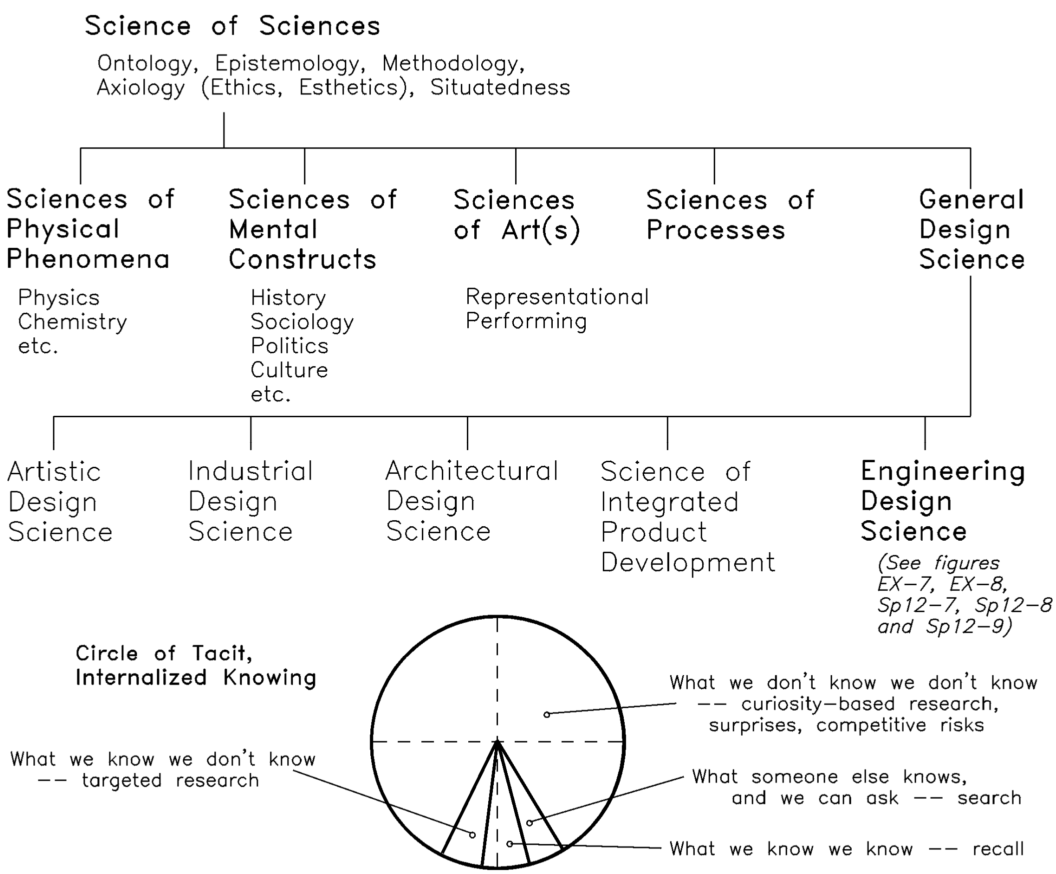


Fig. 2.16. Hierarchy of Sciences [Eder and Hosnedl 2008, McMaster 2004]

A first development cycle consists of four basic steps:

(a) in a synthesis step, some elemental design properties are established with the help of the mediating properties from the 'as should be' requirements for observable properties, including a search for alternatives;

(b) in an analysis step, the resulting 'as is' properties are determined or estimated, and each proposal is checked for errors or faults;

(c) in an evaluation step, the established 'as is' properties are compared to the 'as should be' properties, and a selection is made among the proposals,

(d) conclusions are drawn from the comparison of 'as is' with 'as should be', and drive and control the continuing process of convergence towards an acceptable solution to the design problem.

The similarity to the problem solving process in figure 2.10 is obvious, the formalization by Weber is probably an improvement for computer processing. Additional development cycles are needed [Weber 2008a, Vajna *et al* 2005,2006] to resolve conflicts as they arise, and to iteratively and recursively progress towards a final designed solution to the problem. Progressively better simulations are possible using Weber's four-pole modeling methods [Weber 2005a,2008a]. This theoretical framework seems to be more applicable to the TS-constructional structure, stages (P5) and (P6), and less to the more abstract TS-structures. The mathematical formalization [Weber et al 2004] may lead to a more rational computer-aided design process, possibly even in the stages of conceptualizing if semantic information can be computer-processed. These considerations have resulted in a reappraisal of the interaction of problem solving (figure 2.10) and the properties of and requirements for TrfP(s) and TS(s) [Eder and Hosnedl 2008,2010, Eder 2008], see figure 2.11.

The Autogenic Design Theory, ADT [Vajna et al 2005,2006], claims that design is evolutionary. Designers develop over time from 'm-designers' with good education in methodical and systematic design, to 'p-designers' whose procedures are driven by intuition and experience. 'P-designers' achieve results in shorter time, but their processes and results are not transparent and traceable. 'M-designers' during their experience and time learn the methods so well that eventually they do not need to refer to the instructions, they then act intuitively, in a routine manner, compare [Eder 2009a, Vajna *et al* 2006]. This process has been explained by Eder [Eder 2008a,2009a, Eder and Hosnedl 2010] with the help of Müller's [1990] 'action modes', Dreyfus' [2003a,2003b] 'levels of expertise' (as reported in [Dorst and Reymen 2004]), and Pahl's [1994] 'competencies'. Designed solutions tend to become more complex in time and with progressive concretization, a procedure called *autogenesis* within evolutionary theory [Csanyi 1988]. ADT uses this analogy for product development, and applies genetic algorithms to drive the evolutionary process. This seems to be mainly applicable to optimization problems of parametrization in the TS-constructional structure, stages (P5) and (P6), by randomly searching for mutations that produce better performance.

2.13. Closure

Engineering Design Science and the Theory of Technical Systems [Hubka and Eder 1988, 1996, Eder and Hosnedl 2008, 2010] need some intensive study and some practical application in design engineering, preferably mentored by a knowledgable instructor, to be well understood by any practitioner, as distinct from many other design methods that only apply to limited situations of the engineering design process.

The design methodology based on Engineering Design Science, and especially the Theory of Technical Systems, as proposed by Vladimir Hubka, encourages full documentation of the design process followed for any project, with particular emphasis on the stages of conceptualizing, and on properties and requirements. Managers should demand, but must also allow time, for engineering designers to generate this documentation, especially for complex and innovative systems, because it is the best insurance in the event of product liability litigation.

Most of the ‘design theories’ from other sources as described in Hubka and Eder [1996 (Ch. 3, p. 49-66)], and in this paper seem to be restricted to existing products and ‘their design’ (noun – the appearance and other properties), to design methods with little theoretical underpinning, to computation, or to cognitive matters of humans. Mostly, they do not refer to a transformation system (TrfS), its transformation process (TrfP), its technology (Tg), and the effects (Ef) needed from the operators, see figure 2.4. They do not refer to the TS-life cycle, TrfP- and/or TS-properties, and development in time of TS, and many other aspects included in TTS. Mostly, they confuse the Theory of (‘as is’, existing, tangible or process) Systems with the *methods* of the design process for ‘as should be’ future systems. In the view of the author, existing ‘as is’ operational TrfP and TS as described in TTS are always assumed to be concrete (tangible) and complete. Not yet existing ‘as should be’ TrfS/TrfP and TS are being designed and are under the influence of design processes and methods. Engineering Design Science [Hubka and Eder 1992b,1996, Eder and Hosnedl 2008,2010] has attempted to incorporate these approaches as far as possible, and has been recognized as the most complete and comprehensive approach [Weber 2008b,2009]. This systematic and methodical approach is only necessary in some design situations [Eder 2009], especially where traditional intuitive, methodical and/or computational approaches are inadequate.

2.14. Acknowledgements

Thanks are due to Professor Christian Weber, previously at the University of the Saarland (Germany), now at the Technical University of Ilmenau (Germany), for providing extensive references and copies of papers and book extracts to support this work.

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