INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

DESIGN ENGINEERING AND NEEDS FOR METHODOLOGY

W. Ernst Eder
Royal Military College of Canada (retired)

ABSTRACT

In order to explore the need for a formalized engineering design methodology, several grounded theories are reviewed and brought into mutual context. The theories refer to memory and thinking operations, expertise, human action modes, competencies, and learning styles. The discussion reveals a need for specific instructions for a methodical and systematic engineering design procedure, when the design problem is seen as non-routine, and expertise is lacking. A design methodology based on the insights of Engineering Design Science is outlined, to give guidance on available design procedures for situations where it is needed.

Keywords: Design engineering, Engineering Design Science, expertise, competency, action modes

1 INTRODUCTION

A life ambition of Professor Dr. Vladimir Hubka (29 March 1924 – 29 October 2006) was to develop a comprehensive theory and related method for design engineering. During his 25 years of industrial experience, and especially in the early to mid 1960's, he and colleagues in Czechoslovakia (as it then was) started to develop such a theory, first reported in [1]. After departing from Czechoslovakia in 1968, he continued his reflective research with several other colleagues, to produce many papers in conferences and journals, and a significant series of books in German and English [2,3,4,5,6,7,8,9], until the onset of his medical difficulties in 2002. Since then, further progress has been made [10], and continues with this paper.

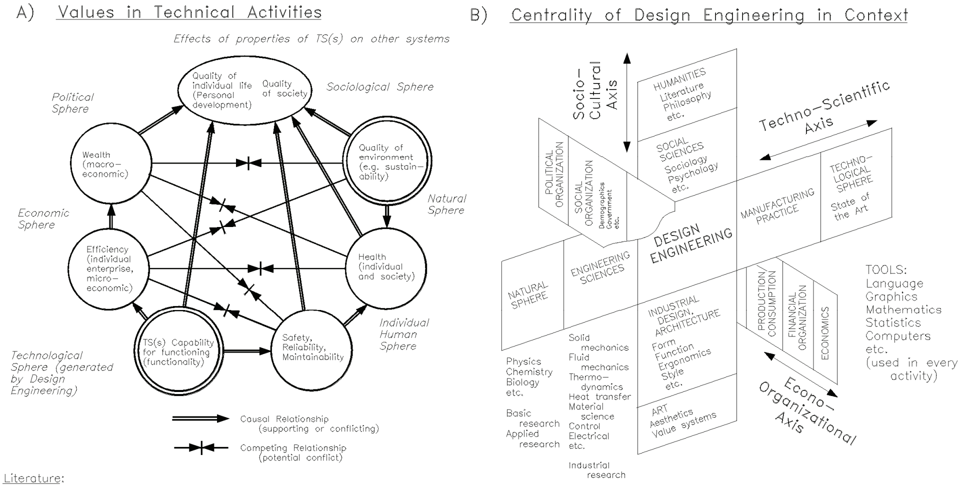
Designing in engineering has technical, economic, human, sociological and psychological dimensions, see figure 1, which need some aspects, context and consequences of psychology.

The purpose in this paper is to explore several theories and plausible conjectures of psychology and education, mainly based on observations in the spirit of grounded theory [11], to draw conclusions for engineering education. Because designing is probably the most important activity within engineering, a coordinated consideration of theories in designing and in education may be useful [12].

2 MEMORY AND THINKING OPERATIONS

In a simplified view we can distinguish between working (short-term) and long-term memory. Working memory is restricted to 7±2 'thought chunks' or less for intellectual processing [13,14,15,16, 17,18]. Each thought chunk (and its information content) can be simple or complicated, and details or extended connections need further thought chunks. Three items, and three relationships among them constitute six chunks. If mental capacity is exceeded, something is lost and the outcome may be failure [19]. Externalizing thoughts in sketches, and mentally interacting with them, is thus important. A change in levels of abstraction or detail is relatively easy, but transferring chunks from one level to another is difficult – overview of a broad situation can hardly be maintained whilst considering detail.

Working memory can hold a seven-digit number in mind long enough to recite three or four digits backwards, or hold a ten-digit number in mind ([20, p. 200]). Working memory is retained for about a maximum of 25 seconds, parts of the contents are continually refreshed or deleted, and parts can be transferred into long-term memory. Transfer into long-term memory needs 'rehearsal', by reciting, reformulating, repeating in working memory, repeated reacting, reviewing a conversation during pauses. Any organized procedure, whether physical or mental, systematic, methodical, stereotype, or guided by prejudices, is internalized into the subconscious by learning, repetition and practice [21]. Predominantly those parts of the procedure that are useful for the given (practiced) task are absorbed.



Literature:
Part A:
Ropohl, G. (1990) 'Die Wertproblematik in der Technik' (Value Problems in Technology), in Roozenburg, N. and Eekels, J., WDK 17 -- EVAD -- Evaluation and Decision in Design -- Reading, Zürich: Heurista, pp. 162--182
-- VDI (2000) VDI Richtlinie 3780: Technikbewertung -- Begriffe und Grundlage (Technology Evaluation -- Terminology and Fundamentals), Düsseldorf: VDI-Verlag
Part B:
Dixon, J.R. (1966) Design Engineering, New York: McGraw-Hill
Roseman, M.A. & Gero, J.S. (1998) "Purpose and Function in Design: from the Socio-Cultural to the Techno-Physical", Design Studies Vol. 19 No. 2, p. 161-186
Hundal, M.S. (1997) Systematic Mechanical Designing: a Cost and Management Perspective, New York: ASME Press

Figure 1 Role of Design Engineering in Context of Technology and Society [10]

The transferred contents are normally incorporated and structured or restructured in a person's idiosyncratic way, into learned and experienced 'tacit' knowledge – 'knowing', a process that can only be performed by the mind.

After internalizing, a person does not need the formal instructions, can forget them, and even forget that the instructions (and methods) are being used. The activity will progress 'naturally', intuitively, at low mental energy (see below). Mental structures of different people are probably similar. Recall from long-term memory presents some difficulty.

Damasio [20, p.227] states: '... memories are not stored in facsimile fashion and must undergo a complex process of reconstruction during retrieval, ... events may not be fully reconstructed, may be reconstructed in ways that differ from the original, or may never again see the light of consciousness.'

Working memory, and transfer between working and long-term memory, can be aided by external representations, e.g. sketches, notes [22]. Useful modes of operation in thinking and acting include:

- an *iterative* mode – a task is repeated (systematically, intuitively, or mixed), each time with better understanding and knowledge about the circumstances and proposed solutions, and thus a preferred solution is approached;
- a *recursive* (decomposing) mode – a task is decomposed into smaller parts, each part task treated by itself (but at least under partial consideration of other parts), and the resulting partial solutions are combined;
- an *interactive* mode – one or several thought chunks are captured and considered in sketches or other notes, e.g. on a computer screen – the interplay between working memory and the activity help to expand the thoughts, adding completeness and precision;
- a *searching and selecting* (problem solving) mode – initially several solution principles are proposed and processed to a certain maturity, and only then a selection is made;
- an *abstracting and concretizing* mode – although the goal is a concrete TrfP(s) and/or TS(s), occasional work of abstracting and on different levels of abstraction can help. The addition of "(s)" signifies that this transformation process, TrfP, and technical system, TS, is the intended subject of designing.
- a *sequential* mode – a (partial) problem is treated one step at a time, a reductionist way;
- a *simultaneous*, concurrent, parallel mode (usually only possible if performed in a team) – several (partial) problems or steps are treated at the same time, holistically.

These modes of operation can and should be learned, and utilized in continuous interplay, adapted to the problem. Neither the path of the solution process, nor the solution preferred by a certain examiner can be predicted, both can be guided by consciously applying suitable theories and methods. Higher management of an organization may demand recorded evidence about the product against possible law suits for product liability, after the pattern of a systematic and methodical procedure. Any results obtained in an 'intuitive' way (in normal operation) must then be brought into the method retrospectively, which can also serve as control and audit.

3 EXPERTISE

As adapted from Dorst [23], Hubert Dreyfus [24,25] distinguishes seven levels of expertise, corresponding with seven ways of perceiving, interpreting, structuring and solving problems within an amalgam of three worlds – a theory world, a subjective internal world, and an objective external world:

1. *Novice*: A novice will consider the objective features of a situation, as they are given by the experts, and will follow strict rules to deal with the problem.
2. *Advanced Beginner*: For an advanced beginner the situational aspects are important, there is a sensitivity to exceptions to the 'hard' rules of the novice. Maxims and heuristics [26] are used for guidance through the problem situation.
3. *Competent*: A competent problem solver selects the elements in a situation that are relevant, and chooses a plan to achieve the goals. This selection and choice can only be made on the basis of a much higher involvement in the design situation than displayed by a novice or an advanced beginner. Problem solving at this level involves activities of seeking of opportunities, and building up expectations. At this level of involvement the problem solving process takes on a 'trial and error' character (but see below), and there is a clear need for learning and reflection that was absent in the novice and the beginner .
4. *Proficient*: A proficient problem solver immediately sees the most important issues and appropriate plan, and then reasons out what to do.
5. *Expert*: The real expert responds to a situation intuitively, i.e. in 'normal operation' [27], see section 4; and performs the appropriate action straight away. There is no obvious (externally observable) problem solving and reasoning that can be distinguished at this level of working. This is actually a very comfortable level at which to function, and many professionals do not progress beyond this point – most do not need to.
6. *Master*: With the next level, the master, a new uneasiness creeps in. The master sees the standard ways of working that experienced professionals use not as natural but as contingent. A master displays a deeper involvement into the professional field as a whole, dwelling on success and failure. This attitude requires an acute sense of context, and openness to subtle cues. In his/her own work the master will perform more nuanced appropriate actions than the expert.
7. *Visionary*: The world discloser or 'visionary' consciously strives to extend the domain in which he/she works. The world discloser develops new ways things could be, defines the issues, opens new worlds and creates new domains. To do this a world discloser operates more on the margins of a domain, paying attention to other domains as well, and to anomalies and marginal practices that hold promises for a new vision of the domain.

Vladimir Hubka was obviously a visionary in this sense with respect to design engineering, its products and its processes [5,9,10].

The last sentence of item '3. Competent' needs further clarification. Progress from one level to a next higher level requires some added learning and reflection – formal or informal learning by experience, obtaining relevant information from other people or publications, etc. This learning must of necessity include both object information about the product being designed, and about design processes, i.e. an improvement of the mind-internalized theory. The 'trial and error character' is only an apparent phenomenon, it should be recognized as a 'directed trial and error correction' procedure.

An 'intuitive' response, as claimed for the '5. Expert', is also more or less to be expected at all levels of expertise, as the relevant theory and method becomes well enough internalized to run routinely, and examination o the use and/or awareness of method becomes more difficult.

At each of these stages, advancement to the next higher level is possible by learning the necessary object and design process knowledge, preferably in a non-threatening (educational) environment. Only a few engineering designers need to reach the highest levels – but all engineering graduates should be exposed to this discipline of Engineering Design Science [5,9,10]. Especially for design engineering, the theories, models and methods of Engineering Design Science offer a basis for organizing, acquiring and understanding this knowledge in context.

Any one designer necessarily shows different levels of expertise for different types of problem, and progression through these levels is not uniform.

4 ACTION OPERATIONS

According to Müller [27], human designers exhibit three kinds of action modes in design engineering:

(a) *Normal operation* (intuitive, second nature procedure, routine) runs activities from the subconscious in a learned and experienced way, at low mental energy, giving an impression of competence [28,29,30]. If difficulties arise, the action departs from the normal, and higher mental energy is needed.

(b) *Risk operation* uses the available experiences (and methods) together with partially conscious rational and more formalized methods, in an unplanned 'trial and error' behavior (but see comments in section 3), which can occasionally be very effective.

(c) *Safety* or *rational operation* needs conscious planning for systematic and methodical work, with conscious processing of a plan, because competence is in question, but this mode must be learned before attempting to use it.

Forms (a) and (b) are obviously also available to industrial designers and practitioners of integrated product development.

The proportion of systematic and methodical work should ideally be increased, especially for team consultations. This systematic and methods-conscious mode of working, and appropriately documented results, should be demanded by higher management – and therefore should be learned during formal education.

Normal, routine, operation is mainly preferred and carried out by an individual. The engineering designer is working below his/her highest level of expertise.

Risk operation, when the engineering designer is working close to or at his/her highest level of expertise, tends to demand team activity. The task becomes non-routine, consultations can and should take place – 'bouncing ideas off one another', obtaining information and advice from experts, reaching a consensus on possibilities and preferred actions, etc. Consultations are best if the participants are of approximately equal experience or status, or if there is a large gap in experience from questioner to consultant. Personal contact tends to be quicker at lower mental energy than obtaining information from (written) records [27,31].

Non-routine situations often produce critical situations in a design process [32,33,34,35], e.g. during: (a) defining the task, analysis and decisions about goals; (b) searching for and collecting information; (c) searching for solutions; (d) analyzing proposed solutions; (e) deciding about solutions; (f) managing disturbances and conflicts, individual or team. Especially in critical situations, the local level of expertise is low. For the novice, almost all problems appear as requiring risk or safety operation, systematic working is essential, and needs to be learned.

In the resulting 'trial and error' behavior, see section 3, the applied theories, steps and methods are no longer conscious and externally recognizable. For this reason it becomes difficult (e.g. in an educational situation) to perform an examination of the existing internalized design process knowing of a designer.

For safety or rational operation, as a problem of design engineering appears less routine, designers need advice how they can proceed to overcome the barriers. Design engineering, especially with the help of Engineering Design Science [5,9,10], offers several theories, models of transformation processes and technical systems (see section 7 of this paper), methods derived from these theories, and other pragmatically developed methods, that are generally not available to artistic design disciplines. **But these models and methods must be familiar to the designer before he/she attempts to use them on a serious problem – a problem of education**.

It is only in safety/rational operation that a full record of all transactions and decisions can be generated and recorded. Normal and risk operation requires a post-hoc recovery of this information to generate a reasonably full record.

5 COMPETENCIES

Engineering education, and continuing learning during practice (see also [36]) should aim to achieve *competency* of engineers, technologists, technicians, etc., in analyzing and (more importantly) in synthesizing (designing) technical systems. This requires knowing, internalized information of objects and design processes, and awareness of where to find recorded and experiential available information. Competency includes [28,29,30]:

- *heuristic and practice related competency* – ability to use experience and precedents [37], design principles [7,10], heuristics [26], information (e.g. of technical data, including values) as initial assumptions and guidelines, etc.;
- *branch and subject related competency* – knowledge of a TS-‘sort’ within which designing is expected (completed during employment); typical examples of TS-‘sorts’ should be included in education (i.e. in addition to conventional and newer machine elements [38,39,40]), and should also show the engineering sciences, pragmatic information, knowledge and data [41,42], and examples of realized systems;
- *methods related competency* – knowledge of and ability to use methods, following the methodical instructions under controlled conditions, and eventually learning them well enough to use them intuitively – for diagnostics, analysis, experimentation, information searching, representing (in sketches and computer models), creativity [43], innovative thinking, and systematic synthesizing [44,45,46];
- *systems related competency* – ability to see beyond the immediate task, analytically/reductionistically and synthetically/holistically, to take account of the complex situation and its implications, e.g. life-cycle engineering [47,48,49,50,51,52], or economics;
- *personal and social competency* – including team work, people skills, trans-disciplinary cooperation, obtaining and using advice, managing subordinates, micro- and macro-economics, social and environmental awareness, and cultural aspects, etc. [53]; and the associated leadership and management skills; and
- *socio-economic competency* – including awareness of costs, prices, returns on investment, micro- and macro-economics, politics, entrepreneurial and business skills, etc.

These competencies are related to creativity [43].

Methods-related competency is probably the least emphasized among the skills and abilities acquired during the usual educational curricula in engineeriug, followed closely by personal/social and socio-economic competencies. Even the heuristic and branch-related competencies are swamped by the conventional emphasis on the analytical mathematical tools of the engineering sciences.

When a method is well known to the designer, it can at best be run from the sub-conscious, and the users can then even deny that they are using the method – a ‘routine’ action mode. For the other action modes, **it is necessary for engineering designers to learn methodology during their engineering education.**

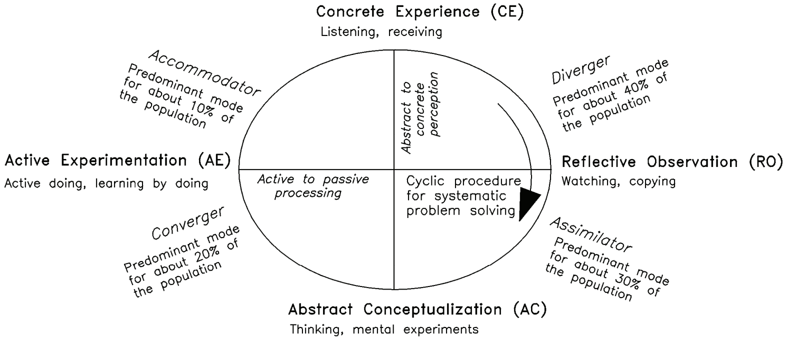
6 LEARNING

Among the theories of education [54], the model according to Kolb [55] is most appropriate, figure 2.

Four different learning styles are identified, on the major and minor axes of the ellipse. Concrete experience involves listening and receiving, a relatively passive learning style. Reflective observation involves watching and copying, which needs a somewhat higher activity level. Abstract conceptualization involves more independent thinking, with mental experimenting. Active experimentation is learning by doing, the classical procedure of ‘directed trial, and error correction’. Looking at each style in isolation, the role of the teacher is progressively reduced in this cycle of styles, but the risk of attaining a wrong result increases.

The four learning styles are reflected in four different attitudes and abilities of learners, on the diagonals. Divergers prefer to work between CE and RO. Assimilators prefer activity between RO and AC. Convergers are preferably active between AC and AE. Accommodators live between AE and CE.

What should be the role of lectures, recitations, practice problems, experiments, projects, etc. individual, (Whimbey) pair, and team (collaborative) work, etc., for presentation and acquisition of object knowledge and (design) process/methods knowledge? Is experiential learning and project-based learning necessary (definitely ‘yes’), and is it sufficient by itself (definitely ‘no’)? An old Chinese piece of wisdom credited to Confucius says:



Literature:
Kolb, D.A. (1984) Experiential Learning: Experience as the Source of Learning and Development,
Englewood Cliffs, NJ: Prentiuce–Hall

Figure 2. Kolb's Model of Thinking Styles for Learning

Tell me and I will forget
Show me and I will remember
Involve me and I will understand
Take one step back and I will act.

In the usual interpretation as separate statements, the first two of this set of items are used to deny the effectiveness of lectures and demonstrations, and to advocate only project-based and/or problem-based learning [56]. The last of these items is usually omitted. These statements are best interpreted in combination. Consequently, we would add:

Do all four and I will become competent.

There is a need in teaching and learning to provide a theoretical explanation (by lecture, or at least by assigned reading); demonstration (e.g. by sample case studies such as presented in [6,7,10]); problems and projects on relatively simple design tasks involving conceptualizing, laying out and detailing (preferably with continual supervision of an experienced and knowledgeable engineering designer who understands the theory); and more comprehensive design projects with progressively less supervision. This should be distributed throughout all years of the curriculum, with cross-referencing from the engineering science and humanities courses [57,58].

7 ENGINEERING DESIGN METHODOLOGY AND PROBLEM SOLVING

The concept of the system of Engineering Design Science (EDS) [9,10] is based on the triad 'theory – subject – method'. As formulated in cybernetics [59] , *'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 product), a basic *theory* (formal or informal, recorded or in a human mind), and a recommended *method* for voluntary application. A *theory* about a subject allows a *method* to be defined and heuristically applied, for using or for designing the subject. The system of EDS is focused on the subject of design engineering of transformation processes (TrfP = TS-operational process) and/or technical systems (TS), and includes design engineering information about TP and TS, and engineering design processes.

The procedural model of design engineering (the methodology) as proposed by Hubka [3,5,7,8,9,10] follows from the general model of a transformation system, figure 3, and is laid out in several hierarchical groupings. At the highest level, the whole design process is divided into five administrative phases: product planning, task defining, conceptualizing, embodying/laying out, and detailing. At the second level, the stages and steps of a novel design process are summarized as:

(P1) establish a design specification for the required system, a list of requirements;
(P2) establish the desirable and required output (operand in state Od2) of the transformation;
(P3) establish a suitable transformation process, including input (Od1) if not given as a requirement;
(P4) decide which of the operations in the transformation process will be performed by technical systems, alone or in mutual cooperation with other operators;
(P5) which technical systems (or parts of them) need to be designed – the TS(s);

(P6) establish a technology (structure, with alternatives) for the transformation operation for the TS(s) of stage (P5), and therefore the effects (as outputs) needed from the technical system;

(P7) establish what the technical system needs to be able to do (its internal and cross-boundary functions, with alternatives);

(P8) establish what organs (function-carriers in principle and their structure, with alternatives) can perform these functions. These organs can be found mainly in prior art, especially the machine elements, in a revised arrangement as proposed by Weber [38,39,40];

(P9) establish with what constructional parts (in sketch-outline, in rough layout, in dimensional-definitive layout, then in detail and assembly drawings, with alternatives) are needed.

Only those parts of this engineering design process that are thought to be useful are employed. Such an 'idealized' procedure cannot be accomplished in a linear fashion. Iterative working is essential, as is shown in [60,61], especially with respect to the relationships among (a) the stated requirements, (b) the elemental design properties that the designer establishes during designing, (c) the estimated properties expected from the TrfP(s)/TS(s) in its currently designed state, and (d) the differences between the estimated properties and the requirements – a cycle that coincides with the problem solving cycle outlined below.

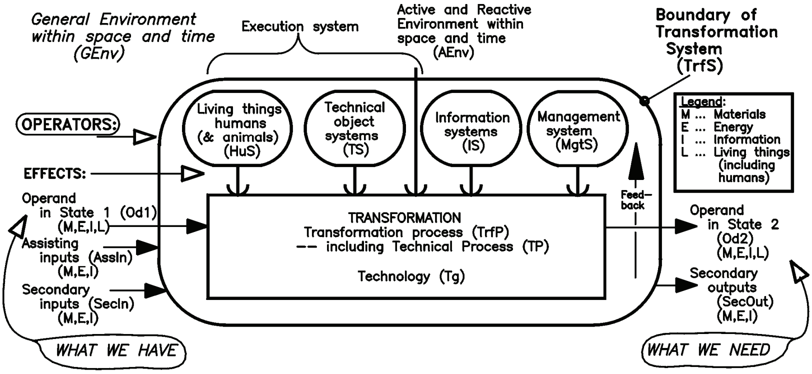


Figure 3. General Model of a Transformation System [10]

Redesign can be accomplished by:

(Pa) establishing a design specification for the revised system (step P1);

(Pb) analyzing the existing system into its organs and (if needed) its functions (reversing steps (P8) and (P7) of the novel procedure);

(Pc) then following the last one or two parts of the procedure listed above for a novel system.

Superimposed on the set of design operations, at the third level of the hierarchy, is a cycle of basic operations of problem solving, see figure 4, which consists of:

Op-H3.1 State the problem;
Op-H3.2 Search for solutions;
Op-H3.3 Evaluate, decide;
Op-H3.4 Communicate solution.

These are supported by auxiliary operations of:

Op-H3.5 Prepare information;
Op-H3.6 Check, verify, reflect;
Op-H3.7 Represent.

These last three were recognized by Hubka as essential, but are hardly ever found in other schemes of problem solving.

The utility of this procedure has been demonstrated in various case studies [6,7,10], including industrial projects involving collaboration between engineering and industrial design [62]. Industry's needs, as perceived and analyzed from outside, should also be taken into account [63].

The beneficial results of teaching design methodology have been demonstrated [64,65,66], after 25 years of teaching in Germany, and after some graduates entered industry as engineering designers.

Especially the benefits of teaching formalized problem solving have been demonstrated [67,68] in Canada and the U.S.A.
For learning design engineering [69],

(a) ‘what has been heard is not yet understood’,
(b) ‘what is understood does not yet give the ability to act’, and
(c) ‘being able to act does not mean being able to act optimally’.

Successful learning of object information and of design process information (including design methodology) requires education. This is more than transmitting information, and more than exposing students to design projects, it needs a coordinated presentation of information, mentoring and personal supervised experience. Use of methods, and understanding their theories, must be exercised and practiced. Successful use requires experience of use, and capability to select the appropriate methods. ‘We know much about stimulating and guiding learning, and need not wait for final or conclusive answers from experimental educational research’ [70].

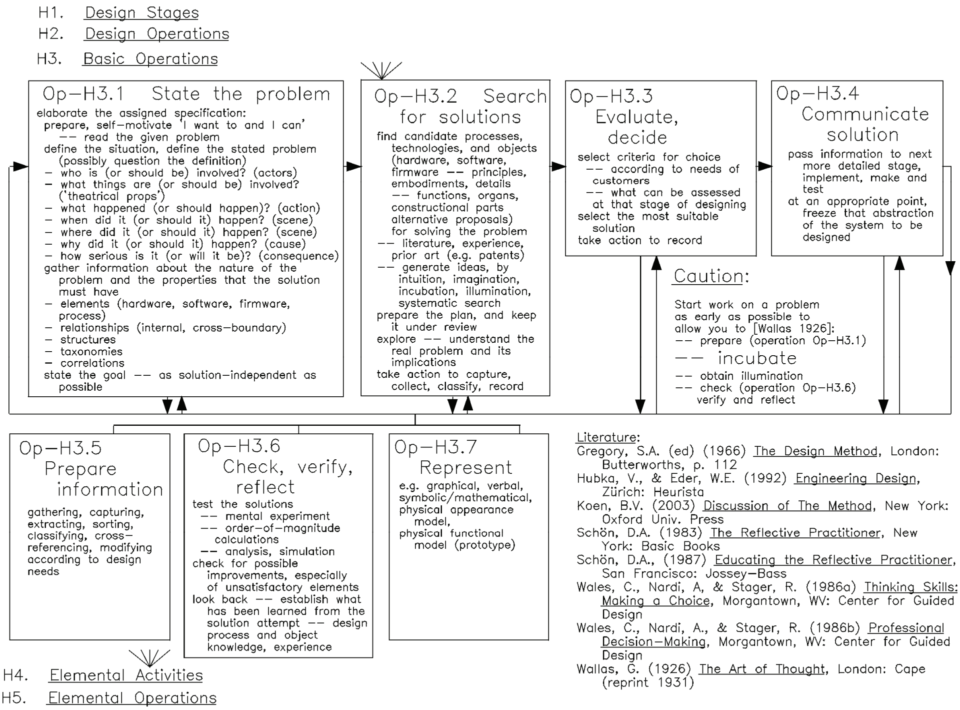


Figure 4. Problem Solving (modified from [10])

8 CLOSURE

Design methodology should be introduced in all engineering educational programs, at every level of study (first to final year, freshman through senior, and graduate study). In addition, several conventional and ‘industry best practices’ methods should be introduced to students. The educational need to explicitly teach and use these methods arises from the described aspects of memory and thinking operations, expertise and its development, action operations and their risks and rationality, competencies that engineering designers will need in their practical life, and the teaching/learning situation and learning styles. This design methodology should preferably be based on a sound theory, such as developed over the years since the early 1960’s [1–10], and outlined in section 7 of this paper.

REFERENCES

[1] Hubka, V. (1967) ‘Der grundlegende Algorithmus für die Lösung von Konstruktionsaufgaben’ (Fundamental Algorithm for the Solution of Design Problems) in **XII. Internationales**

Wissenschaftliches Kolloquium der Technischen Hochschule Ilmenau, **Heft 12** Sektion L - Konstruktion, Ilmenau: T.H.I., p. 69-74

[2] Hubka, V. (1974) **Theorie der Maschinensysteme**, Berlin: Springer-Verlag

[3] Hubka, V. (1976) **Theorie der Konstruktionsprozesse** (Theory of Design Processes), Berlin: Springer-Verlag

[4] Hubka, V. (1978) **Konstruktionsunterricht an Technischen Hochschulen** (Design Education in Universities), Konstanz: Leuchtturm Verlag

[5] Hubka, V. and Eder, W.E. (1988) **Theory of Technical Systems: A Total Concept Theory for Engineering Design**, New York: Springer-Verlag (completely revised translation of Hubka, V., Theorie Technischer Systeme 2 ed, Berlin: Springer-Verlag, 1984)

[6] Hubka, V., Andreasen, M.M. and Eder, W.E. (1988) **Practical Studies in Systematic Design**, London: Butterworths – English edition of (1980) **WDK 4 – Fallbeispiele**

[7] Hubka, V. and W.E. Eder (1992) **Engineering Design**, Zürich: Heurista (2nd edition of Hubka, V., **Principles of Engineering Design**, London: Butterworth Scientific, 1982, translated and edited by W.E. Eder from Hubka, V., **WDK 1 – Allgemeines Vorgehensmodell des Konstruierens** (General Procedural Model of Designing), Zürich, Heurista, 1980)

[8] Hubka, V. and Eder, W.E. (1992) **Einführung in die Konstruktionswissenschaft** (Introduction to Design Science), Berlin, Springer-Verlag

[9] Hubka, V., & Eder, W.E. (1996) **Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge**, London: Springer-Verlag (completely revised edition of [8])

[10] Eder, W.E. and Hosnedl, S (2008) **Design Engineering: A Manual for Enhanced Creativity**, Boca Raton: CRC-Press

[11] Glaser, B.L. and Strauss, A.L., **The Discovery of Grounded Theory: Strategies for Qualitative Research**, Chicago, IL: Aldine Publ., 1967

[12] Eder, W.E., 'Comparisons – Learning Theories, Design Theory, Science', in **Proc. 1993 ASEE Annual Conference** (ERM Division), Washington, DC: ASEE, 1993, p. 1620-1628

[13] Cowan, N., 'The Magical Number 4 in Short-term Memory: A Reconsideration of Mental Storage Capacity', *Behav. and Brain Sci.* Vol. 24 No.1, 2001

[14] Miller, G.A., 'The Magical Number Seven, plus or minus two: Some Limits on our Capacity for Processing Information', *Psychological Review*, Vol. 63, 1956, p. 81-97

[15] Miller, G.A., 'Information and Memory', *Scientific American*, Vol. 195, 1956, p. 42-46

[16] Miller, G.A., 'Human Memory and the Storage of Information', *IRE Trans. on Information Theory*, Vol. IT-2 No. 3, 1956, p. 128-137

[17] Miller, G.A., Galanter, E. and Pribram, K., **Plans and the Structure of Behavior**, New York: Holt, Rinehart & Winston, 1960

[18] Miller, G.A., 'Assessment of Psychotechnology', *American Psychologist*,Vol. **25** No. 11, 1970, p. 911-1001

[19] Nevala, K., **Content-based Design Engineering Thinking**, Academic Dissertation, University of Jyväskalä, Finland, Jyväskalä: University Printing House, 2005

[20] Damasio, A., **The Feeling of What Happens: Body and Emotion in the Making of Consciousness**, London: Heinemann, 1999

[21] Eder, W.E., 'Benchmarking – Bedeutung für Konstruktionswissenschaft' (Benchmarking – Importance for Design Science), WDK Workshop Alpina 96, March 1996

[22] Anderson, J.R., **Cognitive Psychology and its Implications**, New York: Freeman, 1995

[23] K. Dorst and Reymen, I. Levels of expertise in design education. In **Proc. International Engineering and Product Design Education Conference**, 2-3 September 2004, Delft, The Netherlands, 2004

[24] Dreyfus H.L., 'From Socrates to Artificial Intelligence: The Limits of Rule-Based Rationality', unpublished lecture notes of the first 2003 Spinoza Lecture at the University of Amsterdam, 2003.

[25] Dreyfus H.L., 'Can there be a better source of meaning than everyday practices?', unpublished lecture notes of the second 2003 Spinoza Lecture at the University of Amsterdam, 2003.

[26] Koen, B.V. (2003) **Discussion of The Method: Conducting the Engineer's Approach to Problem Solving**, New York: Oxford Univ. Press

[27] Müller, J., **Arbeitsmethoden der Technikwissenschaften – Systematik, Heuristik, Kreativität**

(Working Methods of Engineering Sciences, systematics, heuristics, creativity), Berlin: Springer-Verlag, 1990

[28] Eder, W.E. and Hubka, V. Curriculum, Pedagogics, and Didactics for Design Education. In **WDK 28: Proc. International Conference on Engineering Design, ICED01 Glasgow**, Vol 4, 2001, London: IMechE, p. 285-292

[29] Pahl, G. (scientific director) 'Ergebnisse der Diskussion' (Results of the Discussions). In G. Pahl (ed.), **Psychologische und Pädagogische Fragen beim methodischen Konstruieren: Ergebnisse des Ladenburger Diskurses vom Mai 1992 bis Oktober 1993** (Psychological and Pedagogic Questions in Systematic Designing: Results of a Discourse at Ladenburg from May 1992 to October 1993), Köln: Verlag TÜV Rheinland, 1994, p. 1-37

[30] Pahl, G. 'Transfer Ability as Educational Goal – Results of a Discourse at Ladenburg'. In Eder, W.E. (ed.) **WDK 24 – EDC – Engineering Design and Creativity – Proceedings of the Workshop EDC**, Pilsen, Czech Republic, November 1995, Zürich: Heurista, 1996 133-138; and Hubka, V. (ed.) **WDK 23 – Proc. International Conference on Engineering Design – ICED 95 Praha**, Zürich, Heurista, 1995, p. 247-252

[31] Ahmed, S. and Wallace, K., 'Identifying and Supporting the Knowledge Needs of Novice Designers within the Aerospace Industry', *Jnl. Eng. Design*, 15(5), 2004, p. 475-492

[32] Frankenberger, E., Badke-Schaub, P. and Birkhofer, H., 'Factors Influencing Design Work: Empirical Investigations of Teamwork in Engineering Design Practice'. In Riitahuhta, A. (ed.), **WDK 25 – Proc. ICED 97 Tampere**, Tampere University, 1997 Vol. 2, p. 387-392

[33] Frankenberger, E. and Badke-Schaub, P., 'Integration of Group, Individual and External Influences in the Design Process'. In Frankenberger, E., Badke-Schaub, P. and Birkhofer, H. (eds.), **Designers: The Key to Successful Product Development**, Berlin/Heidelberg: Springer-Verlag, 1997

[34] Frankenberger, E. (1997) **Arbeitsteilige Produktentwicklung** (Product Development with Task Distribution), Fortschrittsberichte VDI Reihe 1, Nr. 291, Düsseldorf: VDI, 1997

[35] Frankenberger, E. and Badke-Schaub, P. Role of Critical Situations in Design Processes and Education. In **Proc. WDK International Workshop PDE – Pedagogics in Design Education**, Pilsen: West Bohemia University, 1998; on CD-ROM

[36] Eder, W.E., 'Education for Engineering and Designing', in **Proc. International Design Conference - Design 2002**, Dubrovnik, May 14 - 17, 2002, on CD-ROM, 2002

[37] Booker, P.J., 'Principles and Precedents in Engineering Design', London: Inst. of Engineering Designers, 1962

[38] Weber, C. and Vajna, S. (1997) 'A New Approach to Design Elements (Machine Elements)', Elements'. In Riitahuhta, A. (ed.) **WDK 25 – Proc. ICED 97 Tampere**, Tampere University, Vol. 3, 1997, p. 685-690

[39] Eder, W.E. (2004) 'Machine Elements – Integration Of Some Proposals', **Proc. AEDS 2004 Workshop**, The Design Society – AEDS-SIG, 11-12 Nov 2004, Pilsen, Czech Republic, on CD-ROM

[40] Eder, W.E. (2005) 'Machine Elements – Revision and Outlook for Design Education', in **Proc. Second CDEN International Conference**, University of Calgary, Alberta, 18-19 July 2005 at Kananaskis Resort, paper 10006 on CD-ROM

[41] Corbitt, R.A. (ed.), **Standard Handbook of Environmental Engineering**, New York: McGraw-Hill, 1990, p. 4.42-4.49

[42] Vincenti, W.G., **What Engineers Know and How They Know It** – Analytical Studies from Aeronautical History, Baltimore: Johns Hopkins Univ. Press, 1990

[43] Eder, W.E. (ed.), **WDK 24 – EDC – Engineering Design and Creativity – Proceedings of the Workshop EDC**, Pilsen, Czech Republic, November 1995, Zürich: Heurista, 1996

[44] Hubka, V. and Schregenberger, J.W., 'Eine neue Systematik konstruktionswissenschaftlicher Aussagen – Ihre Struktur und Funktion' (A New Systematic Order for Design-Scientific Statements – its Structure and Function), in Hubka, V., Baratossy, J. and Pighini, U. (eds.), **WDK 16: Proceedings of ICED 88**, Budapest: GTE and Zürich: Heurista,, Vol. 1, 1988, p. 103-117

[45] Hubka, V., 'A Curriculum Model – Applying the Theory of Technical Systems', in W.E. Eder and G. Kardos (guest eds.), Special Issue on Education for Engineering Design, *Int.J.Appl.Engng.Ed.* Vol. 4 No. 3, 1988, p. 185-192

[46] Hubka, V. and Eder, W.E., 'Theory of technical systems and engineering design synthesis', in

Amaresh Chkrabarti (ed.), **Engineering Design Synthesis**, London: Springer-Verlag, 2001, p. 49-66

[47] Berendt, S., Jasch, Chr., Peneda, M.C. and Weenen, H.van, **Life Cycle Design, A Manual for Small and Medium-Sized Enterprises**, Berlin: Springer-Verlag, 1997

[48] Eder, W.E., 'Designing and Life Cycle Engineering - A Systematic Approach to Designing', Proc. Inst. Mech. Eng. (UK), Part B, *Jnl. of Eng. Manufacture*, Vol. 215, No. B5, 2001, p. 657-672

[49] Ernzer, M. and Birkhofer, H., 'Life Cycle Design for Companies – Scaling Life Cycle Design Methods to the Individual Needs of a Company', in Folkeson, A., Gralén, K., Norell, M. and Seligren, U. (eds.), **DS 31 – Proc. ICED 2003 Stockholm**, Glasgow: The Design Society, 2003, p. 393-394

[50] Graedel, T.E., **Streamlined Life Cycle Assessment**, Upper Saddle River, NJ: Prentice-Hall, 1998

[51] Guine, J.G. (ed.), **Handbook on Life Cycle Assessment**, Dordrecht: Kluwer Academic, 2002

[52] Wimmer, W. and Züst, R., **Ecodesign Pilot**, Dordrecht: Kluwer, 2003

[53] Eder, W.E., 'Social, Cultural and Economic Awareness for Engineers', in **CSME Forum 2002**, Queen's University, Kingston, ON, abstract p. 130, on CD-ROM, 2002

[54] Eder, W.E., 'Survey of Pedagogics Applicable to Design Education, An English-Language Viewpoint', in **Proc. International Workshop Pedagogics in Design Education – PDE**, Pilsen, University of West Bohemia Pilsen and WDK Zurich, 19-20 November 1998, p. 23-39

[55] Kolb, D.A., **Experiential Learning: Experience as the Source of Learning and Development**, Englewood Cliffs, NJ: Prentice-Hall, 1984

[56] Eder, W.E. (1998b) 'Einstein Got it Wrong (for once) – Some Consequences for Problem_based Learning', in **Proc ASEE Annual Conference**, Educational Research and Methods Division, Seattle, WA, 28 June - 1 July 1998, Washington, DC: ASEE, (CD-ROM)

[57] V. Hubka and W.E. Eder, 'Pedagogics of Engineering Design Education', **International Journal of Engineering Education**, Vol 19, No 6, 2003, pp. 798-809

[58] W.E. Eder and V. Hubka, 'Curriculum, Pedagogics and Didactics for Design Education', **Journal of Engineering Design**, Vol 16, No 1, 2005, pp. 45-61

[59] Klaus, G. (1965) **Kybernetik in philosophischer Sicht** (Cybernetics in Philosophical View) 4th ed., Berlin: Dietz Verlag

[60] Eder, W.E. (2008) 'Requirements to Properties – Iterative Problem Solving', in **Proc. AEDS 2008 Workshop**, Pilsen, Czech Republic: University of West Bohemia, p. 49-65

[61] Eder, W.E. (2009) 'Analysis, Synthesis, and Problem Solving in Design Engineering', in review for ICED 09 Stanford

[62] Hosnedl, S., Srp, Z. and Dvorak, J. (2008) 'Cooperation of Engineering and Industrial Designers on Industrial Projects', in **Proc. 10th International Design Conference - DESIGN 2008**, D. Marjanovic (Ed.), FMENA, Zagreb, p. 1227-1234

[63] Eder, W.E., 'Self-Starting Graduates – An Impression of Industry's Needs', *IJEE* Vol. 24, No, 5, 2008, pp. 965-979

[64] Dörner, D., Ehrlenspiel, K., Eisentraut, R. and Günther, J. (1995) 'Empirical Investigation of Representations in Conceptual and Embodiment Design,' in Hubka, V. (ed.) (1995) **WDK 23 – Proc. International Conference on Engineering Design – ICED 95 Praha**, Zürich, Heurista, p. 631-637

[65] Fricke, G. and Pahl, G. (1991) 'Zusammenhang zwischen Personenbedingtem Vorgehen und Lösungsgüte' (Relationship between Personally Conditioned Procedure and Quality of Solution), in Hubka, V. (ed.) **WDK 20: Proc. of ICED 91 Zürich**, Zürich: Heurista, 1991, p. 331-341

[66] Günther, J. and Ehrlenspiel, K. (1997) 'How Do Designers from Practice Design?' in Frankenberger, E., Badke-Schaub, P. and Birkhofer, H. (eds.) (1997) **Designers: The Key to Successful Product Development**, Berlin/Heidelberg: Springer-Verlag, p. 85-97, 1997

[67] Woods, D.R., **Problem-based Learning**: How to Gain the Most from PBL, Waterdown, ON: D.R. Woods, 1994

[68] Jablokow, K.W., 'Developing Problem Solving Leadership: A Cognitive Approach', *IJEE* Vol. 24, No. 5, pp. 936-954

[69] Pahl, G. (1990) 'Notwendigkeit und Grenzen der Konstruktionsmethodik' (Necessity and Limitations of Design Methodology', in **WDK 19: Proc. of the 1990 International Conference**

on Engineering Design, ICED 90 Dubrovnik, Zürich: Heurista and Judeko, p. 15-30
[70] Tyler, L.E. (1978) **Individuality: Human Possibilities and Personal Choice in the Psychological Development of Men and Women**, San Francisco, CA: Jossey-Bass

Contact: W. Ernst Eder
Royal Military College of Canada (retired)
Department of Mechanical Engineering
(Home Address) 107 Rideau Street
Kingston, ON K7K 7B2
Canada
Phone x-1-613-547-5872
E-mail eder-e@kos.net

Ernst Eder is Professor Emeritus, fully retired in 2006 from the Department of Mechanical Engineering at The Royal Military College of Canada. Professor Eder received his MSc in the field of design engineering. He has collaborated with Dr. Vladimir Hubka since 1980, and has continued that work. He was admitted to the degree of Dr.h.c. of the University of West Bohemia in 2005.