COMPETENCY AND EXPERTISE IN DESIGN ENGINEERING

W. Ernst Eder

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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. 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.
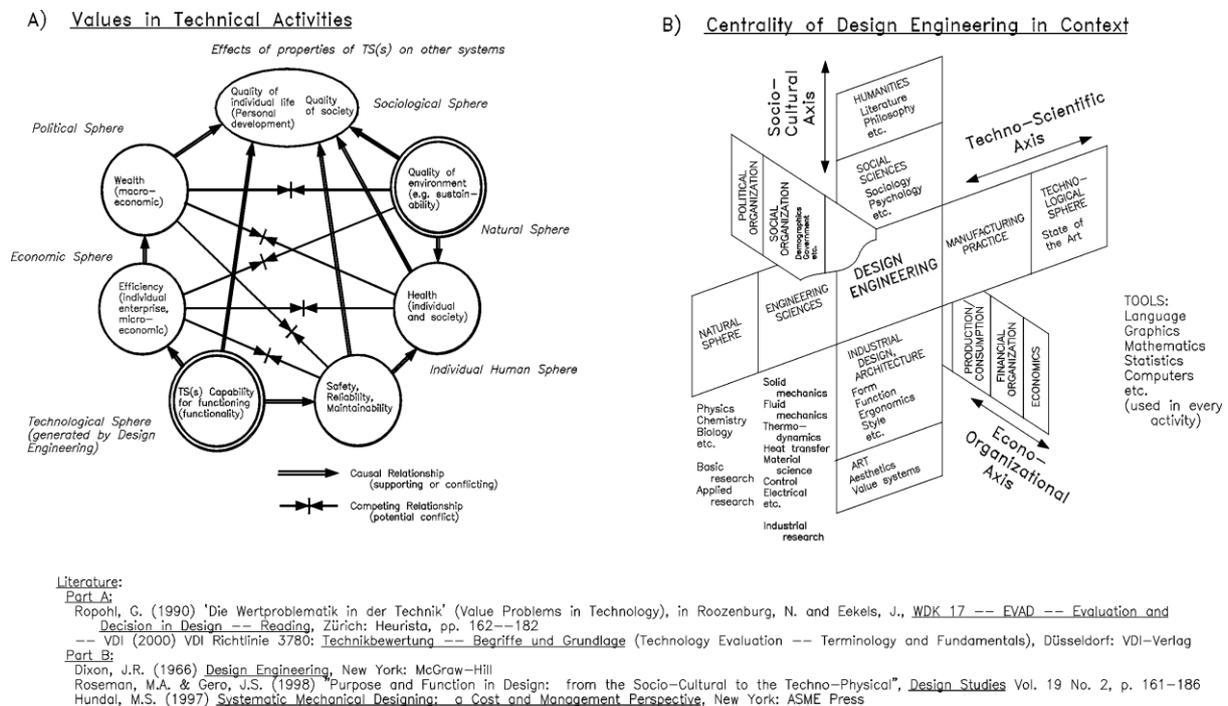

Figure 1 Role of Design Engineering in Context of Technology and Society [10]

The purpose in this paper is to explore several theories of psychology and of education to draw conclusions for engineering education.

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 [11,12,13,14,15,16]. 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 [17]. A change in levels of abstraction or detail is relatively easy, but transferring chunks from one level to another is difficult – overview of a broader 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 ([18, 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 [19]. Predominantly those parts of the procedure which are useful for the given (practiced) task are absorbed. 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 instruction (and method) are being used. The activity will progress 'naturally', intuitively, at low mental energy. Mental structures of different people are probably similar. Recall from long-term memory presents some difficulty.

Damasio [18, 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. sketching, note-taking [20]. **Externalizing thoughts in sketches, and mentally interacting with them, is thus important**. Necessary or 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 TP(s) and/or TS(s), occasional work of abstracting and on different levels of abstraction can help.

! 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 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 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 [21], Hubert Dreyfus [22,23] 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 [24] 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' [25], 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.
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 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 [25], 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 [26,27,28]. 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.

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 [25,29].

Non-routine situations often produce critical situations in a design process [30,31,32,33], 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. In the 'trial and error' behavior resulting from learning, 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, the 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, 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 [34]) 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 [26,27,28]:

! *heuristic and practice related competency* – ability to use experience and precedents [35], design principles [7,10], heuristics [24], information and values (e.g. of technical data) 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 [36,37,38]), and should also show the engineering sciences, pragmatic information, knowledge and data [39,40], 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 [41], innovative thinking, and systematic synthesizing [42,43,44];

! *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 [45,46,47,48,49,50], 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. [51]; 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.

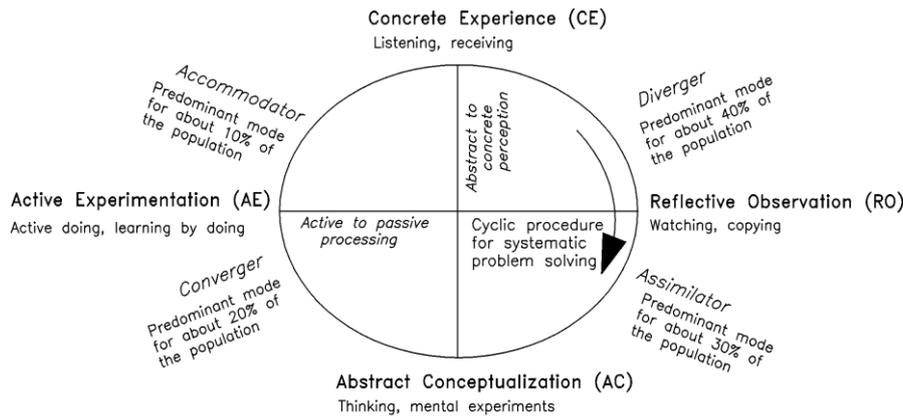These competencies are related to creativity [41].

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 emphasis on analytical mathematical tools.

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 many theories of education, the model according to Kolb [52] is most appropriate, see figure 2. Four different learning styles are identified, on the major and minor axes of the ellipse. This reflects four different attitudes and abilities of learners, on the diagonals. For design engineering, all these learning styles and attitudes are useful and should be learned and practiced.

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:

Concrete Experience (CE)
Listening, receiving

Accommodator Predominant mode for about 10% of the population

Diverger Predominant mode for about 40% of the population

Abstract to concrete perception

Active Experimentation (AE)
Active doing, learning by doing

Active to passive processing

Cyclic procedure for systematic problem solving

Reflective Observation (RO)
Watching, copying

Converger Predominant mode for about 20% for the population

Assimilator Predominant mode for about 30% of the population

Abstract Conceptualization (AC)
Thinking, mental experiments

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 [10]

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 [53]. The last of these items is usually omitted. These statements are best interpreted in combination. Consequently:

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 all other courses.

7. Closure

Design methodology should be introduced in all engineering educational programs. It should preferably be based on a sound theory, such as developed over the years since the early 1960's [1–10].

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W. Ernst Eder
Professor Emeritus, MSc, PEng., Dr.h.c. (University of West Bohemia in Pilsen, Czech Republic)
Royal Military College of Canada, Department of Mechanical Engineering (retired)
Home Address: 107 Rideau Street, Kingston, Ontario, Canada K7K 7B2
Phone: x-1-613-547-5872   E-mail: eder-e@kos.net