TEACHING AND LEARNING MODES FOR DESIGN ENGINEERING

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Abstract – *Important learning outcomes include students' ability for effective communication (verbal and written, but also graphical for sketching and data interpretation) and teamwork. The ability to apply a systematic engineering design method to design or re-design technical systems is not stated, yet that capability distinguishes engineers from scientists, and artistic designing from design engineering. It is to some extent related to creativity.*

Applying a systematic engineering design method includes the ability to use the engineering sciences heuristically for 'order-of-magnitude' and 'what-if' estimates of future configurations. This requires understanding the physical behavior of phenomena, individually and in their relationships, both by 'visual feel' and by mathematical exploration, in a student's development of expertise.

These requirements indicate a need for change in the teaching and learning procedures and methods, departing from the mainly science-oriented lecturing and examination assessment that has been conventional, and therefore changes in the curriculum.

A guiding premiss, also valid for design engineering, is formulated by Klaus: 'Both theory and method emerge from the phenomenon of the subject'.

Keywords: Educational theories, learning, design theories, design engineering, engineering design science

1. INTRODUCTION

This paper is dedicated to the memory of Professor Dr.-Ing. Dr.h.c. Vladimir Hubka, 29 March 1924 to 29 October 2006, who initiated and developed Engineering Design Science [1] from the mid-1960's on. Further developments are due to [2],[3],[4], including a retrospective of Hubka's life work [5].

Stemming from the relatively recent changes to outcomes-based assessment of students, Felder, Brent and Prince [6] discuss the needs and methods for development of suitably capable faculty to induce the desired learning

outcomes in engineering students. A more formal teacher-training of University and College academic staff seems necessary. Some (but not nearly all) Universities in English-speaking regions have fairly recently implemented teacher-training, it has been compulsory and state-regulated in most European countries. Also, few academic engineering staff in English-speaking regions have experience in engineering industry, but this is a requirement in some parts of Europe.

Important learning outcomes include students' ability for *effective communication* (verbal and written, and use of graphical media for sketching and data interpretation) and *teamwork*. It seems that the ability to apply a *systematic engineering design method* to design and re-design of technical systems is not stated, yet this capability distinguish engineers from scientists, and artistic designing from design engineering [7]. It is important when current experience fails as a guide to possible solutions and solving methods [4].

The outcome of ability to apply a *systematic engineering design method* implies (among others) the abilities of using the *engineering sciences* with their inter-relationships within the process of design engineering [8], both for analysis of existing or conjectured situations (a staple of engineering education), and heuristically for 'order-of-magnitude' and 'what-if' estimates of future configurations [9] – hardly ever covered in engineering curricula. For the engineering sciences, understanding the behavior of the phenomena, individually and in their relationships, both by 'visual feel' (generally neglected in science-based engineering education) and by mathematical formulation is probably more important for design engineering than for any other professional activity. This presents difficulties for assessment of student abilities. Especially the inter-relationships between engineering sciences needs to be incorporated into engineering education – e.g. thermodynamic media at pressure and temperature need to be contained by material structures.

The ability to apply a systematic engineering design method where needed, especially one based on a well-founded theory [1],[2],[3],[10], requires that suitable instruction and practice is incorporated into the

curriculum, preferably at the appropriate level in all years of education. This in turn requires that most teaching staff in engineering education are familiar with these systematic engineering design methods.

2. EXPERTISE AND ITS CONTEXT

Three interconnected regions influence design capability: levels of expertise, action operations that use expertise, and competencies that influence expertise.

Corresponding with seven ways of perceiving, interpreting, structuring and solving problems within three worlds – theory, subjective internal, and objective external – Dreyfus [11],[12] distinguishes seven *levels of expertise* (adapted from [13]):

1. *Novice* – views objective features of a situation, follows strict rules.
2. *Advanced Beginner* – situational aspects are important, looks for exceptions to ‘hard’ rules, maxims and heuristics [14] guide the problem situation.
3. *Competent* – selects relevant elements, chooses a plan, higher involvement in the design situation – seeks opportunities, builds up expectations, ‘trial and error’ character.
4. *Proficient* – sees important issues and an appropriate plan, and then reasons actions.
5. *Expert* – responds to situation intuitively (‘normal operation’ [15]), and acts straight away. Problem solving and reasoning is not externally observable.
6. *Master* – a standard ways of working is seen as contingent, not as natural.
7. *Visionary* – the world discloser consciously strives to extend the domain.

The ‘trial and error character’ (item 3) should be recognized as ‘directed trial and error correction, aiming towards success’.

Only a few engineering designers need to reach the highest levels. A designer necessarily shows different expertise for different types of problem, progression through these levels is not uniform. Such progress requires added learning and reflection – formal or informal learning, experience, obtaining relevant information, etc. This learning must include object information about the product being designed (transformation process, TrfP, and/or technical system, TS), and (of at least equal importance) information about engineering design processes, an improvement of the mind-internalized theory and the derived methods. This learning preferably takes place in a non-threatening educational environment. The learner should be provided with a sequence of small successes in applying the engineering design methods, to reinforce learning. Attempting to learn a method ‘on the job’, where the

results are of economic significance, mostly leads to failure, the mental capacity of the learner/practitioner is overloaded. Learning about design processes for all engineering graduates should involve a theory-based systematic approach at an appropriate level of instruction, such as shown in [1],[2],[3],[16],[17].

An ‘intuitive’ response, claimed for the ‘5. Expert’, is to be expected at all levels of expertise – the relevant theory and method becomes sufficiently well internalized to run routinely [18]. Once the method has been learned and transferred into ‘tacit knowing’, it becomes increasingly more difficult to detect a person’s ‘knowing’ of a method by the usual formal (oral or written) examinations in the conventional educational format.

Development of expertise [4],[19] requires a change in the teaching and learning procedures and methods from the conventional science-oriented lecturing and examination assessment, and thus changes in the curriculum.

According to Müller [15],[20], human designers use three *action modes* in design engineering:

- (a) *Normal operation* (routine, intuitive, second nature procedure) runs from the subconscious in a learned and experienced way, at low mental energy [21],[22],[23].
- (b) *Risk operation* uses the available experiences (and methods) together with partially conscious rational and more formalized methods, in a ‘trial and error’ behavior.
- (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*.

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 occurs when the engineering designer is working close to or at his/her highest level of expertise, and 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. In risk operation, the applied theories and methods are often no longer conscious and externally recognizable – it becomes difficult (e.g. in educational situations) to examine the existing internalized design process ‘knowing’ of a designer.

In *safety or rational operation*, designers need advice how they can proceed (i.e. what methods can help) to overcome the barriers. For the novice, almost all problems appear to require risk or safety operation – preparation for coming professional duties is helped by introducing and practicing a systematic and methodical approach to design engineering. A full record of all

transactions and decisions can only be generated and recorded in safety/rational operation.

Normal and risk operation 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 and management of more complex engineering design processes. This systematic and methods-conscious mode of working, and documented results, should be demanded by higher management.

At times, especially where the problem needs *safety* or *rational operation*, the creative right brain can find very useful support from the left brain in systematic design procedural aspects, aided by the *corpus callosum*, which provides a strong inter-connection between the brain hemispheres. This is where engineering design methodology scores, if students during their education become familiar with design theory and its methodology.

Engineering education, and continuing learning during practice (see also [24],[25]) should aim to achieve *competency* of engineers, technologists, technicians, etc., in analyzing and, more importantly, in synthesizing (designing) transformation systems, TrfS. This requires 'knowing', internalized information of objects and of design processes, and awareness of where to find recorded and experiential available information. Competencies include [21],[22],[23]:

- *heuristic and practice related competency* – ability to use experience, precedents [26], design principles [1], heuristics [14], information and values (e.g. 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, in addition to conventional and newer machine elements [27],[28],[29], and should also show the engineering sciences, pragmatic information, knowledge and data [30],[31], and examples of realized systems;
- *methods related competency* – knowledge of and ability to use methods, 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 [32], innovative thinking, and systematic synthesizing [10],[21],[33];
- *systems related competency* – ability to see beyond the immediate task to take account of the complex situation and its implications, both

analytically/reductionistically and synthetically/holistically, e.g. as in life-cycle engineering [34],[35],[36],[37],[38],[39];

- *personal and social competency* – including team work, people skills, trans-disciplinary cooperation, obtaining and using advice, managing subordinates, social and environmental awareness, and cultural aspects, etc. [24]; and the associated leadership and management skills; and
- *socio-economic competency* – including awareness of cost, price, return on investment, micro- and macro-economics, politics, entrepreneurial and business skills, etc.

Competencies are related to creativity [40]. Engineering education should emphasize these competencies, each contributes to the holistic and reductionistic understanding possessed by the future engineer, especially for designing a TrfP(s) and/or TS(s) – the addition of ‘(s)’ signifies the TrfP and/or TS as subject of design engineering.

One aim in this paper is to show a relationship of some existing knowledge about systematic engineering design and its underlying theory with the needs to develop design expertise, and therefore to enhance faculty and curriculum development for effective engineering design education.

3. ENGINEERING DESIGN SCIENCE

Design engineering ‘is’ neither an art nor a science (both ‘art’ and ‘science’ are bodies of experience and knowledge, objects) – engineering design is a process. ‘The design’ (noun) refers to an actual manifestation of a product, a tangible object, an idea, a concept, a pattern, etc. – the result of an intention. The verb ‘designing’ refers to the mental and other processes that occur during this activity in order to establish ‘the design’. Design Practice at times looks for guidance to overcome problems – when the situation is non-routine, when expertise and competence is lacking [4], for instance in educating novices, or in allowing experienced engineering designers to reach beyond their level of competence, to raise their expertise.

Quoting Klaus [41]: ‘*Both theory and method emerge from the phenomenon of the subject*’. Close relationships should exist between the subject under consideration (its nature as a concept, product, artifact or process), the basic theory (formal or informal, recorded or in a human mind), and the recommended method. The theory should describe and provide a foundation for the behaviour of the (natural or artificial, tangible or process) object, and should support the utilized methods, by providing advice for voluntary adoption. The method should also be sufficiently well adapted to the subject. All methods must

be adapted, usually by the applying designer, to the immediate situation on which the designer is active. These three phenomena of theory, method and subject are of equivalent status to each other.

With our subject, design engineering, the underlying theory should describe the general nature of all engineering products, what they have in common, as a Theory of Technical Systems, TTS [2],[3],[10]. This includes a basic model of a transformation system (TrfS), a typical life cycle of a technical system (TS) consisting of seven typical TrfS, structures and properties of technical systems, modes of action, development in time, etc. Based on this theory [1],[2],[3], and using the circumstances of design engineering as a process, a comprehensive approach (theory and method) to designing and re-designing (of technical products) can be proposed that can be applied (voluntarily) for safety and rational operation, and for management of design processes, when needed. Interrelationships with engineering sciences are obvious [8].

4. ROLE FOR EDUCATIONAL THEORIES

Any change in the curriculum should be consistent with acknowledged educational theories (discussed and compared in [42]), and should be made to accord with positive and negative experiences derived from current practices. For instance, Kolb's [43],[44] model, see figure 1, suggests four ways of experiencing and learning from a situation:

- Concrete experience (CE) – tendency to experience something 'concretely' and to analyze that experience;
- Reflective observation (RO) – tendency to reflect on an experience, observe and describe;
- Abstract conceptualization (AC) – tendency to conceptualize observations by means of abstract models, hypotheses and concepts;
- Active experimentation (AE) – tendency to actively experiment to test and extend models.

The model suggests (as verified by psychological tests) that people differ in their abilities for these separate tasks – each person shows a preferential mode of operation, although the ideal would be equal capabilities in all. From these activities, Kolb classified types of people into:

- Accommodators – preferred sector delimited by axes AE and CE;
- Divergers – prefer CE - RO;
- Assimilators – prefer RO - AC;
- Convergers – prefer AC - AE.

Kolb also indicates that the axes represent steps that should be followed, preferably sequentially, to effectively learn a new concept, or to solve a problem. This also

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

Figure 1. Kolb's Model of Thinking Styles for Learning [43],[44]

implies that each engineer should, as far as possible, acquire the abilities of all four sectors.

The theory, methods, examples and practice for any particular topic should be introduced in suitable stages throughout the curriculum, coordinated with the progressive increase in difficulty and complexity of the problems – it is definitely not advisable to present all the theory (or method, or practice) in one chunk. A useful guideline, attributed to Confucius, says:

*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.*

These four statements are mutually additive. Students need to be clear about what and why we (as teachers) expect them to learn, including factual object information (much of it based on experience, not scientific), methods information, precedent existing systems, and experience, and especially the contexts and relationships among the learning subjects. Inducing learning requires a combination of explanation (telling), demonstration (showing), coaching (involving, mentoring), and gradual release from supervision (stepping back). Consequently:

Do all four and I will become competent.

Often the best teaching goes unrecognized, it is subtle, learners do not recognize the teaching, yet it produces the best learning.

Explicit learning and application of methods is often overlooked, especially for design engineering. Once a method or procedure is sufficiently well learned, the details of the instructions for that method are no longer consciously needed, the method can be run from sub-conscious thought. But human memory is unreliable, therefore the need to use check-lists for repeated critical tasks, e.g. aircraft pilot's pre-take-off routine. Much of the methods information, and especially its application for realistic or real tasks (e.g. of design engineering) would then be difficult to assess in a conventional written examination, other assessment methods would need to be applied [6],[19].

This points to a general mode of operation in engineering education, containing:

- a need for *explanation* – lectures and/or hand-outs/textbooks are essential, preferably enhanced by some graphic/visual displays – students need to be informed about what we expect them to learn, in mutual context (for engineering), with respect to three aspects of ‘knowing’: (a) engineering science knowledge and phenomena awareness, (b) existing current best practice and state of the art in their field of engineering, and (c) engineering design methodologies and methods;
- a need for *demonstration* – preferably by worked case examples, and/or the demonstrated and explained activity of a living and experienced role model – 21 such case examples have been produced to date for systematic engineering design methods, e.g. three in each of [2 (ch. 1, p. 79-132)] and [3 (ch. 13, p. 285-327)];
- a need for *mentored practice* – feedback from staff to student about the student’s understanding and application of all three aspects of ‘knowing’;
- a need for *gradual withdrawal* – to allow student to gain independence and confidence.

The last two of these can be summarized as ‘learning by doing’ – which is far more effective if the first two are consistently applied.

Extensive comparisons of several design theories and methods is available [2 (ch. 8, p. 377-408)], [3 (ch. 15, p. 337-352)], [45].

The systematic design process based on a consistent theory [1], as presented in [2], [3], is essential for good record-keeping of the generated information and the decisions made, to be able to retrace and revise a previous decision in case of difficulties recognized during designing. These records are needed in case of liability litigation. concerning liability.

5. KNOWLEDGE, KNOWING AND UNDERSTANDING

Obviously, engineering education must include the engineering sciences [8], they are absolutely essential as means to analyze an existing or proposed situation. But they are not nearly sufficient for preparing future engineers for their professional practice. Future engineers must learn to use these engineering sciences as conceptual frameworks in their (heuristic) search for solutions, and as ‘what if’ heuristic tools for exploring to find suitable values for these solutions – this application of the engineering sciences is largely neglected in education. The individual phenomena must be understood, in a ‘visual-feel’ way as general descriptive behaviour, by ‘order-of-magnitude’ estimations (as was practiced when slide rules were in common use), as well as by

analytical/mathematical tools. They also must learn information about human societies, needs, organizational, financial (macro- and micro-economics), cultural, legal and political arrangements, manufacturing, historical, resources, and many other items.

Other subjects for engineering design education should include intellectual property, its uses and discussions about its currency (patents [46], trade marks, copyrights, industrial designs, and integrated circuit topographies); standards for voluntary and legally required applications; organization management, finance and (elements of) accounting, economics, supply chain, distribution chain, publicity; manufacturing methods, capabilities and their influences on properties of materials and constructional parts; available precedents (samples of actual technical systems in current use), available OEM resources (COTS – commercial off-the-shelf products); and several others. Over-emphasizing the engineering sciences during engineering education, and leaving the ‘other subjects for industry to introduce to students’ (as was advocated at one time in one English-speaking country) is inadequate for current engineering education. Also inadequate is the idea that the humanities can be effectively studied in separate courses with no connection to the engineering curriculum – connections need to be established to give the student a basis for developing his/her own opinions.

6. CLOSURE

Engineering curricula and the constituent courses need to be periodically revised. Recent trends have indicated that new directions need to be investigated and implemented. Some of the consideration for revising the curricula are outlined. Especially, the introduction of Engineering Design Science and its concomitant engineering design methodology is recommended as basis for education in design engineering, and to help create a robust connection among all other courses in the engineering curriculum.

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