INTERNATIONAL CONFERENCE ON **ENGINEERING AND PRODUCT DESIGN EDUCATION**
4 & 5 SEPTEMBER 2008, UNIVERSITAT POLITECNICA DE CATALUNYA, BARCELONA, SPAIN

DESIGN ENGINEERING – NEEDS FOR A SYSTEMATIC DESIGN PROCESS

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ABSTRACT
Engineering Design Science, initiated by Dr. Vladimir Hubka, was developed from the mid-1960’s to the present, with connections to other design disciplines and society.
Design engineering, including application of the engineering sciences, can range from *routine*, through *risk*, to *safety* and rational operation. As problems appear less routine, designers need advice to overcome barriers. Engineering Design Science offers theories, models of transformation processes and technical systems, and methods derived from these theories. These models and methods must be familiar to the designer before attempting to use them on a serious problem.
The expertise of engineering designers ranges from *novice*, via *advanced beginner*, *competent*, *proficient*, *expert*, and *master*, to *visionary*. At each stage, advancement to the next is possible by learning the object and design process knowledge, preferably in a non-threatening environment. Especially for design engineering, the theories, models and methods of Engineering Design Science offer a basis for organizing and acquiring this knowledge.
Consequently, education for design engineering should include the considerations of Engineering Design Science, the underlying theory and methods. Instruction should progress throughout the educational curriculum, by exposure to theory and by supervised application on design problems. The mentors for problems should ensure that the methods are followed, and the theories are understood in relationship to the problems. This procedure should ensure that graduates are familiar with the theory and its methods, that they can then ‘fall back’ to their knowledge to attempt ‘safety operation’ on a real problem, and rational learning to increase their level of expertise.

Keywords: design engineering, design operation, design expertise, subject-theory-method

1 INTRODUCTION
Engineering Design Science [1,2], initiated by Dr. Vladimir Hubka, was developed from the mid-1960’s to the present. Significant advances are obvious, compare [3]. In its current state [4], connections are made to other design disciplines, and to the needs and constraints of society.
Concerning the concepts of science, Diamond [5] explains:
“How can one study the collapses of societies ‘scientifically’? Science is often misrepresented as ‘the body of knowledge acquired by performing replicated controlled experiments in the laboratory’. Actually, science is something much broader: *the acquisition of reliable knowledge about the world* (italics by Eder). In some fields, such

as chemistry and molecular biology, replicated controlled experiments in the laboratory are feasible and provide by far the most reliable means to acquire knowledge. ...
When I began studying birds in New Guinea rainforest in 1964, I was immediately confronted with the problem of acquiring reliable knowledge without being able to resort to replicated controlled experiments, whether in the laboratory or outdoors. It's usually neither feasible, legal, nor ethical to gain knowledge about birds by experimentally exterminating or manipulating their populations at one site while maintaining their populations at another site as unmanipulated controls. I had to use different methods. Similar methodological problems arise in many other areas of population biology, as well as in astronomy, epidemiology, geology, and paleontology."

Similar considerations apply to design research, collecting and interpreting information about designed objects, and about design processes, especially concerning design engineering of technical process and tangible objects (systems). Design engineering differs from artistic design:

(a) by necessitating the formal or intuitive application of engineering sciences;
(b) by allowing several abstract models of structures – transformations, technologies, functions, organs, constructional layout, constructional detail, constructional assembly;
(c) by scientifically defining the commonalities among all technical processes and systems, and clarifying their relationships to organizations, societies, cultures, environments, etc. [1,2,4].

2 SUBJECT – THEORY – METHOD

Research and formulation of theories may be classified into 'fundamental' or 'applied'. Research for human activities, aimed at generating knowledge and plausible scientific theories, follows four parallel paths [4]:

(1) the classical experimental, *empirical* way of independent observing, e.g. by protocol studies, experiments, etc.: describing, abstracting, modelling, and formulating hypotheses and theories – yet observations can only capture a small proportion of thinking, usually over short time-spans;
(2) *participative observation*, the observer is a member of the design team and takes part in the observed process, e.g. [6] – observations may be biased by the observer's participation in the process;
(3) the reconstructive, *detective* way of tracing past events and results by looking for clues in various places [7] – reconstructions can never fully capture the original events, human memory is limited, records of information about events are stored in many separate 'chunks' at different locations in the brain, and need to be reconstituted for recall; and
(4) the speculative, reflective, *philosophical* way of hypotheses, theories, modelling, and testing.

In 'designing' as a subject for research, the empirical ways include elements of self-observation, and impartial observation of experimental subjects, humans and/or objects. None of these paths can be self-sufficient, they must be co-ordinated to attain internal consistency and plausibility.

As formulated in cybernetics [8], *'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 internalised in a human mind), and a recommended *method* – the triad 'subject – theory – method'. The theory should describe and provide a foundation for explaining and predicting ‘the behaviour of the (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 (design) method can then be derived from the theory, and take account of available experience. A better theory should allow formulation of a better method.

3 DESIGN PROCESS OPERATION

According to Müller [9], three kinds of action modes exist 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 [10,11,12]. If difficulties arise, the action departs from the normal, and higher 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 behaviour, 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.

Normal, routine, operation is mainly preferred and carried out by an individual. Risk operation 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 [9,13].

Non-routine situations often produce critical situations in a design process [14,15,16,17], e.g. during: (a) defining the task, analysis and decisions about goals; (b) searching for and collecting information; (c) searching for solutions; (d) analysing proposed solutions; (e) deciding about solutions; (f) managing disturbances and conflicts, individual or team.

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 [1,2,4], offers several theories, models of transformation processes and technical systems, methods derived from these theories, and connections to 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 – this familiarity constitutes a problem for education.

4 EXPERTISE

As quoted in Dorst [18], Hubert Dreyfus [19,20] 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 (especially heuristics) are used for guidance through the problem situation.

3. *Competent*: A competent problem solver works in a radically different way. He/she 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 the seeking of opportunities, of alternative candidate solutions, and of building up expectations. At this level of involvement the problem solving process takes on a trial and error character, and there is a clear need for learning and reflection that was absent in the novice and the beginner.
4. *Proficient*: A problem solver that then moves on to be proficient 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; and performs the appropriate action straightaway. There is no problem solving and reasoning that can be distinguished at this level of working. This is actually a very comfortable level to be functioning on, and a lot of 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.

The last sentence of '3. Competent' needs further clarification. Progress from one level to a next higher level requires some 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 (process and/or tangible) product being designed, and about design processes, i.e. an improvement of the mind-internalised theory. The 'trial and error character' is only an apparent phenomenon, it reflects a routine level of operation [9] where the applied theories, steps and methods are no longer conscious and externally recognizable. For the novice, almost all problems appear as requiring risk or safety operation.

An 'intuitive' response from the '5. Expert' is also expected, more or less at all levels of expertise, as the relevant theory and method becomes internalised to run routinely.

Any one designer may show different levels of expertise for different types of problem, progression through these levels is not uniform.

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 environment. Only a few engineering designers need to reach the higher levels – but all engineering graduates should be exposed to Engineering Design Science [1,2,4]. Especially for design engineering, the theories, models and methods of Engineering Design Science offer a basis for organizing, and learning this knowledge in context.

5 EMPIRICAL FINDINGS?

Validation of the statements in this paper is difficult. They are based mainly on the author's experience. He was employed in design engineering in industry for ten years – B.C. (before computers). Since then he has attempted to induce learning about design engineering at various universities in Great Britain and Canada – 19 years from pragmatic interpretation of his experience, plus interaction with others, and 26 years based on the theories of Vladimir Hubka [1,2,4], whilst helping to develop these theories and the appropriate methods coordinated with them – 'subject-theory-method'.

The statements result from self-observation, observation of students, participation in theory development, participation in scientific conferences on design engineering, and a tendency of the author to attempt to relate various theories and experimental results to each other and to the Hubka proposals [1,2,4]. Experimentation on students was usually not possible or permitted. The findings must be regarded as anecdotal – but if wisdom can occur with old age, then maybe it can be allowed to justify the expressed views.

6 CLOSURE

Consequently, education for design engineering should include the basic considerations of Engineering Design Science [1,2,4], especially the underlying theory, and the recommended methods. This should also clarify for the student the understanding, need for and context of the engineering sciences. Instruction in this comprehensive form should progress throughout the educational curriculum, by exposure to the theory and by supervised practical application on engineering design problems. The mentors for the practical problems should ensure that the methods are followed, and the theories are understood in relationship to the problems. This procedure should ensure that graduates are sufficiently familiar with the theory and its associated methods, that they can then 'fall back' to their knowledge to attempt 'safety operation' on a real problem, and rational learning to increase their level of expertise.

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