COGNITIVE AND SYSTEMATIC DESIGN

W. Ernst EDER
Royal Military College of Canada (retired), Kingston, Ontario, Canada

Following a lively discussion at the AEDS-SIG Workshop 2005, I had the pleasure of reading the doctoral thesis by Kalevi Nevala [2005a]. The following is a summary and interpretation of comments I made to Dr. Nevala. In discussions or considerations of design engineering problems and engineering designers, different words are often used. Designing is a process of transforming information about a future technical process and/or technical system, performed by iterative interacting between external representations and mental models. My comments are based on the pioneering work of Vladimir Hubka [1974, 1976, 1978, 1982, 1984, 1988a, 1988b, 1992 and 1996] with additions [Eder 1992, 1996 and 2008].

Keywords
cognitive approaches, systematic and methodical approaches

1. Introduction

According to Nevala [2005a, p.12], we need to incorporate knowledge about designing *minds* in our expositions of design engineering. The basic unit and the true enigma in engineering design process is an individual engineering designer, nothing happens without the contri-bution of the individual. Every idea or transformation of the transformation process, TrfP(s), and/or technical system, TS(s), being designed is channeled through somebody's cognitive 'machinery', and is subject to the restrictions and intrinsic laws of the human mind.

Yet there is no denying that computer aids and other technical means (including paper and pencil) to assist designing are necessary, at least in part to overcome some of the limitations of the human mind, and to expand the possibilities of analysis using engineering sciences.

We also have to be able to manage design engineering as a whole, otherwise we cannot obtain an optimal solution. We need to improve the level of creativity of designing in order to answer to the growing needs of customers and to the challenges presented, e.g. by decreasing natural resources or increasing complexity of new technologies. Finally, we need knowledge about engineering thinking to eliminate costly and harmful errors. Consequently, we cannot afford to set the mental processes of engineers outside our considerations in design engineering, we need to consider the cognitive system in the context of designing.

The experienced designer automatically recalls a huge amount of detailed information – especially for a re-design problem. The amount and detail of the information for a (rare) novel problem is probably different. Nevala's explanation indicates that usually a 'trigger' is needed to enable recall and association of information, something that had been talked about in psychology for many years. Tacit, internalized 'knowing' is apprehended by designers from their own store of experience, but general knowledge recorded in data banks (e. g. libraries), and out there somewhere (e. g. in someone else's mind), is also available to be apprehended, probably a little more indirectly, see illustrative figure 1.

The designer picks up the relevant information from the available assortment of external representations by directing attention to interesting spots [Nevala 2003a]. Then he/she apperceives and encodes the information into mental representations, based on the mental models that experience has shaped into memory, learned during previous applications. *Apperception*: the mind's perception of itself; perception with recognition or identification by association with previous ideas; to take in and understand in the light of what is already known. Only a fraction of reality can be perceived directly by the human senses. It is impossible to perceive 'things', apperceptive constructs, such as such as force, infinity, process operations, technologies, functions, organs, etc., but we can deal with such concepts and recognize them by apperception.

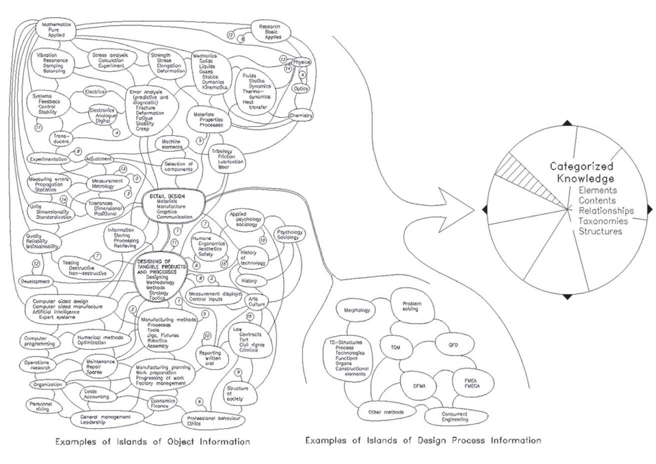

Figure 1. *Information for Design Engineering (on illustrative scheme)*

These representations are revised by producing and interacting with more or less transient written and graphical notations. Then, contemplating these embodiments of thoughts, and comparing them to other available relevant representations of information, the designer refines the thoughts further to mental representations better fitting the requirements of the situation – and externalizes these again. External material provides visual feedback to the human mind, as well as a relatively permanent record to externalize some parts of thinking.

Conceptual thinking, and apperception focuses on the contents of mental representation, but we should also be concerned about the mind--external representations, and how they interact with the mental representations. Do we have any recommendations about the nature and forms of the (transient) written and graphical notations? I do not think that these notations need to be 'transient', they can form a good record of the considerations during designing, and can allow a fall-back if the current trend of work proves to be faulty. Sketches are also drawn during design thinking, and are necessary to help overcome some of the Miller 7 ± 2 (or less) limitations of working memory, as well as provide a basis for discussion with other engineering personnel. Mental *and* externalized *graphical/verbal/symbolic* representations are very important for design thinking. If capacity is exceeded, something is easily lost, but that is the purpose of making written records (verbal, graphical, symbolic, and combinations), which help to extend the capacity by allowing mental interaction with the written records.

Thus design processes occur in the minds of participating individual humans [Nevala 2005a, p. 22] and interacting in teams, aided by the externalized representations that they produce. This externalized material indicates the proceedings and progress of the engineering design process, and constitutes the means for supporting and organizing the internalized core processes of design engineering, the thought processes of individuals. Externalized representations in models of various kinds provide visual feedback – their form is obviously important for supporting the individual mind and for communicating among minds in a team.

The nature and forms of mind-external notations and representations is, in fact, the main subject of our Engineering Design Science –

this is where we can and should connect. I miss any mention of systematic exploration in Nevala's work, possibly using our models of technical systems, which can help with some design problems, but not necessarily with all.

Thinking is usually focused and economical – it can also be systematic and methodical, and still be focused and economical,

Many attempts have been made to 'investigate human thought by computer simulations'. Whether computational modeling can really give any insights into the real workings of the brain is now doubtful. Definitely, the human mind is far more complex than our most powerful computers. Computers can simulate by approximations (especially by what the programmers think might happen), but cannot explain the workings of the human mind. Computers cannot (yet) scan their own output to relate it by association with information stored in its memory to produce new insights, the human can.

'Personal qualities' of engineering designers are, of course, important – but this should also include 'interpersonal qualities and circumstances', because teamwork is also important, within design, and between design and other departments of an organization

2. Guilford

Many years ago I read the work of Guilford [1959 and 1971], see figure 2. I think Nevala has misunderstood this work. *Divergent* thinking occurs at any time when searching for alter-native solutions at any level of abstraction or detail. Associations are called up, but they can be quite directed at a specific small problem, not necessarily 'remote'. It is not necessarily a 'free floating flow of ideas' as in the classical creativity methods, e.g. brainstorming, but even those are to some extent directed. Free floating ideas within a *restricted* solution space are very important for exploring the possibilities for that level of the systems hierarchy (e.g. detail), and selecting the most pro-

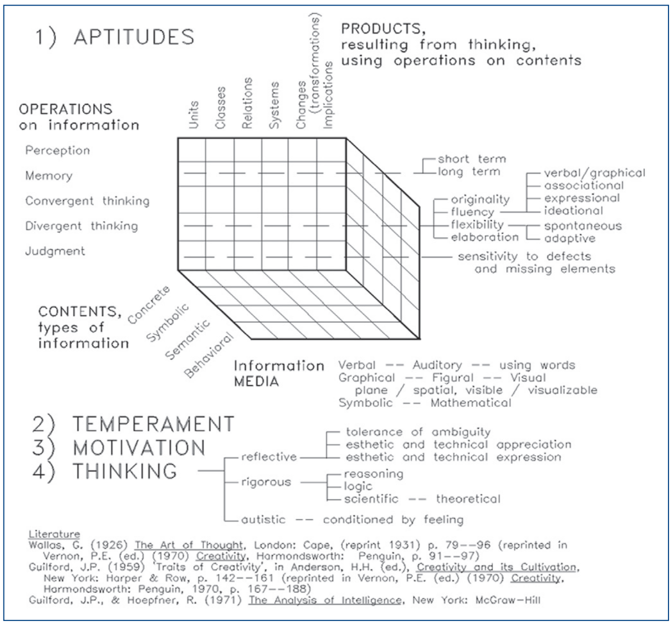

Figure 2. *Guilford's Model of Human Intellect*

mising one for further treatment. 'Weird' ideas should normally not be discarded just because they appear 'weird'. *Convergent* thinking then tries to narrow the solution field to just one preferred way. Nevala's conclusion that *directed creativity* is convergent is not really tenable, it also consists of a divergent 'searching for solutions' at that level, and a convergent 'evaluating, selecting, deciding'. And in *pointed restructuring* of a mental or graphical image, morphological and other methods can help.

There is a need for restructuring the tacit, internalized 'knowing'. Traditional engineers often work *sequentially*, they think of one solution, and try to make it work – *satisficing* according to Schön [1983 and 1987] – until they cannot, when they think of one other solution, etc. This is mentally faulty, psychology has shown that any critical and selective attitude (convergent thinking) will usually inhibit any novelty in thinking (creativity, divergent thinking). It is therefore probably better to think of several possible solutions, and then to evaluate and select – *concurrent* development of solutions, as can be done with a morphological matrix.

The use of the word *'reflection'* as used by Schön [1983, 1987] is different to Nevala's use. In my opinion, Nevala refers to divergent thinking. In [Nevala 2005b], Figure 4 (page 9) clearly shows the graphical representations (not apperceptions) similar to a morphological matrix, which is clearly divergent (from one possible solution to many within the available solution space). This then leads to his 'construction' phase, i.e. *synthesis* of combinations from a morphological matrix into a number of solutions-in-principle, 'organ structures' according to Engineering Design Science.

3. Design Science Models

Nevala claims that 'domain-specific rules cannot be reached by deductive logic'. This statement needs correcting, the claim should be that domain-specific rules cannot be reached *directly* by deductive logic, but they can be reached, and would need to be adapted from the generalized design theories and methods, by the user, for the specific situation – otherwise all our efforts to produce design methodologies, and an engineering design science, are by definition futile, and I do not like to think that I have spent ten years in industry, and especially 45 years in academic life just wasting my time. By learning about these (more physical) models of transformation processes and technical systems, engineering designers can influence the forms of their mental models!

Our model of a transformation process can be used to show these contexts. Whether this form of modeling is useful for the specific project and design team is a different question. We aim for 'the success of the customer process' – what we call the operand in state Od2 at the output of the main transformation process.

Design has traditionally been described as outside the people – our 'Theory of Technical Systems' we may have given that impression, but the book was not about designing, it was about the object being designed. Vladimir Hubka and I were always aware that the designer is the most important contributor to design processes.

Designers face the dilemma of 'where to concentrate and what to do' – this is the purpose of recording the generated ideas in a systematic way, e.g. by a morphological matrix, to obtain reasonable completeness (within the scope of the problem), and allow us to select the most appropriate partial solutions to combine in a few arrangements, and to substitute second-choice partial solutions – in this way a large solution field can be explored economically, and much can be learned about what is workable and what is not.

Nevala's 'central technical attributes' seem to coincide with our definition of the 'elemental engineering design properties', 'engineering design characteristics, and 'general engineering design properties', as requirements for the technical system.

Introspection or biographical experiences were the basis for the methodologies published by Kesselring, Koller, Roth, Pahl & Beitz, and many others. Nevala's claim that these were 'form design theories' is not really true, these authors have usually jumped from their practical experience to formulating a pragmatic design methodology, almost with a minimum of formalizing any theories. Nevala detects 'incompatibility' of the observed behavior of designers with most published methodologies. I agree, the observed behavior needs to be abstracted to detect the methodological classification. We have tried to make things compatible by strictly adhering to logic and scientific definition – Engineering Design Science.

We can accommodate 'functional reasoning' – this is why we have postulated several structures within a technical system, because they may be useful abstractions for designing. Nevala claims that designers produce 'self-consistent structures' in their mental represen-tations – but such self-consistent structures are also important for the mind-external graphical/verbal/symbolic representations, and therefore a theory of design and of the designed objects is necessary. This is where we should fit together.

Restructuring of representations should also take place on the physical level of representation, e.g. methods of variation by Koller [1985] and Ehrlens piel [1987 and 1995].

Normally, a proposed design solution must be 'frozen' at some point, to allow a rational procedure for the next more detailed phase of designing, e.g. detailing. Any later changes in the proposal cause multiple changes in the more detailed work, and therefore are costly.

Nevala quotes a 'non-formal theory language' – why non-formal? A usable theory needs to be formalized. I think we have formalized that language in our Theory of Technical Systems, a major constituent of Engineering Design Science.

Nevala also finds a 'hermeneutical circle' – we usually call this 'iterative and recursive' working. He also finds a need to 'divide big problems' into smaller ones, with the need to then re-integrate the proposed solutions – we call this 'recursive working'.

Systems are hierarchical, a system is always an element in a larger system, and at the same time a collection of smaller systems. Engineers, at any one time, can only think of the chunks of information relevant to one level of the hierarchy. We therefore have to choose our system boundary (consciously or sub-consciously), and change the boundary as we move from one hierarchical level to another, especially as we move towards the detail.

Intuition has its place among the designers' tools. Yet systematic work wins out unless the problem remains only at the most concrete and routine level, i.e. the constructional structure, especially from the dimensional layout onwards into the details. At these concrete levels, the sufficiently trained human mind tends to be quicker if left to itself, using intuitive working modes, i.e. using the learned and internalized object and design process knowledge, without the need to follow a carefully prescribed procedure. But the human mind is unreliable, and therefore a systematic procedure and preferably independent check (design audit, systematic reflection) must be implemented, on the process of design engineering and on the results (the designed technical system), preferably based on Engineering Design Science.

Many claims have been made that designing is 'applying engineering sciences' – whilst engineering sciences are essential, a whole lot of other information that is of little or no interest to science is also needed, as outlined in figure 1.

4. Problem Solving

Newell and Simon [1972] unfortunately did their ground-breaking research on single-solution problem-solving for engineering science analytical problems. Extending this to synthesizing problems for design engineering is not really valid. Wallas [1926] stated four phases, preparation, incubation, illumination, and verification. Newell and Simon used 'generating' to cover preparation, incubation and illumination, and 'testing' to cover verification. Did Newell and Simon know about Wallas?

5. Research

Nevala's *reconstructive approach* needs to be entered into the list of possible research methods in design engineering. It can add to our knowledge of design, and provides another way of trying to find out just how we do it. Thus, *research* (generating knowledge, and formulating plausible scientific theories) generally follows four parallel paths:

(a) the classical experimental, *empirical* way of observing from the outside (e.g. by experiments, protocol studies, etc.), describing, abstracting, modeling, generalizing, and formulating hypotheses and theories – observations can only capture a small proportion of thinking, and usually only over short time-spans;

(b) *participative observation*, the observer is a member of the design team and takes part in the process, e.g. [Hales 1991] – observations may be biased by the involvement in the process of the observer;

(c) the reconstructive, *detective* way of tracing a past set of events and results by looking for clues in various places [Nevala 2003a, 2003b, 2004, 2005a, and 2005b, Saariluoma 2005a and 2005b] – reconstructions can never fully capture the original events, human memory is limited, records of events are stored in many separate chunks at different locations in the brain, and need to be re-constituted for recall; and

(d) the speculative, reflective, *philosophical* way of postulating hypotheses, formulating theories, modeling, and subsequent testing.

In any human-influenced activity, such as for instance 'designing' as a subject for research, the *empirical* way usually includes elements of self-observation, as well as impartial observation of experimental subjects. Regarding *protocol analysis*, we can think at a rate at least three times as fast as we can speak, and at least ten times as fast as we can sketch (meaningfully), we cannot capture all thought by listening to talking or looking at sketches.

Participation can produce bias in the observations, and therefore is not regarded as reliable.

Some recent investigations have shown that any incident is separated and stored in chunks in different parts of the brain. *Reconstructing* means retrieving many different chunks, and bringing them to together. There is no guarantee that the original incident is reconstructed in the same form – even eye-witnesses for courts of law are inherently unreliable. This does not invalidate reconstructive investigation, only makes it somewhat less reliable.

Philosophical speculation can produce theories, but these are only valid if they are based on accepted experience.

It should be obvious that none of these paths can be self-sufficient, and that they must be co-ordinated if an internal consistency and plausibility is to be attained.

6. Education

Nevala says that the 'engineer does not think in abstract terms' – mainly because the experi-enced engineer has not been exposed to these abstract terms. And maybe he does use them, but cannot express that fact in words, because he uses them sub-consciously. Maybe he should (in appropriate places) use them. They were developed mainly for novel design situations (see [Hubka 1988b]), but can also be used for re-design situations. And they can be learned – to change the mental models. This is also why we have emphasized education as a major factor towards design engineering.

I like the distinction of apperception between perceivable and non--perceivable kinds. We need both, but North-American engineering education emphasizes the non-perceivable mathematical. This points to the need for engineering education to include not only perceiv-able information, but also non-perceivable information of various kinds into engineering education. Also, Nevala comments that 'visualization is in engineering education' – it should be, but in North America, since about 1965, the emphasis has been on mathematical analysis, not on engineering.

7. Capture

Engineers have a large amount of 'unspoken knowledge' – an application program to capture information has been developed by Mirakon AG, Switzerland within the KOMPASS Project, a collaboration between ABB-Turbo-Systems, Eidgenössische Technische Hochschule (ETH) Zürich, and Mirakon. The resulting application has found successful use.

Much of the engineering design information used by experienced designers in industry is held as tacit knowledge in the memory of those designers. This tacit knowledge is lost to the organization when a designer retires or resigns, unless it can be captured in some more tangible way. Several computer-based expert systems (a form of artificial intelligence programming) have been used to capture information, mainly for application in diagnostics.

The program application described here [Ferreirinha 1998] is intended to help in capturing design knowledge by relating a design situation and its structure to the elements of the situation and appropriate masters.

8. Conclusions

According to Pahl [2007] 'der Teufel steckt im Detail' (the devil hides in the detail) – not only in design engineering, but in all constructive and creative activity. Detail can ruin a good concept, but cannot rescue a poor concept. Conceptualizing, embodying and detailing are all necessary for producing optimal results in design engineering.

Generally, I see much agreement between the views of Nevala, and our views based on Engineering Design Science, yet the details still need to be clarified.

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Contacts:

Professor Emeritus, W. Ernst Eder P.Eng., Dr. h.c.
Royal Military College of Canada
Collège militaire royal du Canada (retired)
107 Rideau Street, Kingston, Ontario, Canada K7K 7B2
Phone x-1-(613) 547-5872, e-mail: eder-e@rmc.ca