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INDUSTRY'S NEEDS - SELF-STARTING GRADUATES

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1. Introduction

Educational institutions have several duties. One is to provide a useful education in a limited range of subjects to students. Another is to provide society with people who can function within that culture. Industry is part of that society, and is therefore a customer for the human products generated by the educational institutions.

The leading question for this paper is "*How can Engineering Design Science help to educate engineering students towards a capability for self-initiated action to solve engineering (design) problems*?"

It seems that industry is too close to its own problems, and has too little time to spend on usable analysis (industry is in business to make products and achieve financial success), to define these problems well enough for educational institutions to act. Over many years, the American Society for Engineering Education (ASEE) has attempted to ask industry about deficiencies in graduates of engineering programs – the results have been several single-concept (therefore simplistic) statements: "graduates need to be educated in ..." – the subjects at various times have included 'communication skills', 'teamwork', 'report writing' and others. In consequence, various educational institutions have changed their programs from time to time to emphasize these topics, but not in a wider context of capability for engineering action. The author, and his close collaborators – Vladimir Hubka and Stanislav Hosnedl – have had extensive experience in private industry of designing various products, and have been active as academic staff members in various universities – indicating a cross-cultural outlook on these problems.

A fairly recent trend in private industry towards globalization, and pressure towards innovation, have made it imperative that engineering graduates should be capable of self-initiated action within a short time of entering industry. Typically, up to the 1970's it was estimated that a new graduate would take about ten years to become fully competent as an engineering designer. This time needs to be shortened, by a well-formulated education.

2. Design Engineering

One of the important duties of engineering graduates in industry is to design (and/or supervise designing of) technical products – technical processes (TP) and technical systems (TS). Products may be characterized in various ways, see [Hubka 1996, p. 9-13; Eder 2007a, p. 23-28 and 334-342]. Technical products need to be designed – anticipated in concepts and details – before they can be manufactured and used.

In earlier publications, designing has been considered as a general process, especially in the artistic world of architecture, graphics, performing arts, etc. We must nevertheless distinguish various scopes of this activity for generic products, including processes and tangible products [ISO 2000], see figure 1. 'Industrial design' covers mainly the appearance and usability, aesthetics and ergonomics, of tangible products in general. For tangible products aimed at consumers and made in large quantities, the management process has been formalized into 'integrated product development'. 'Design engineering' is concerned with functioning to produce certain desired effects, safety and reliability, and many other technical considerations. There is substantial overlap among these three forms of designing, but they do not coincide.

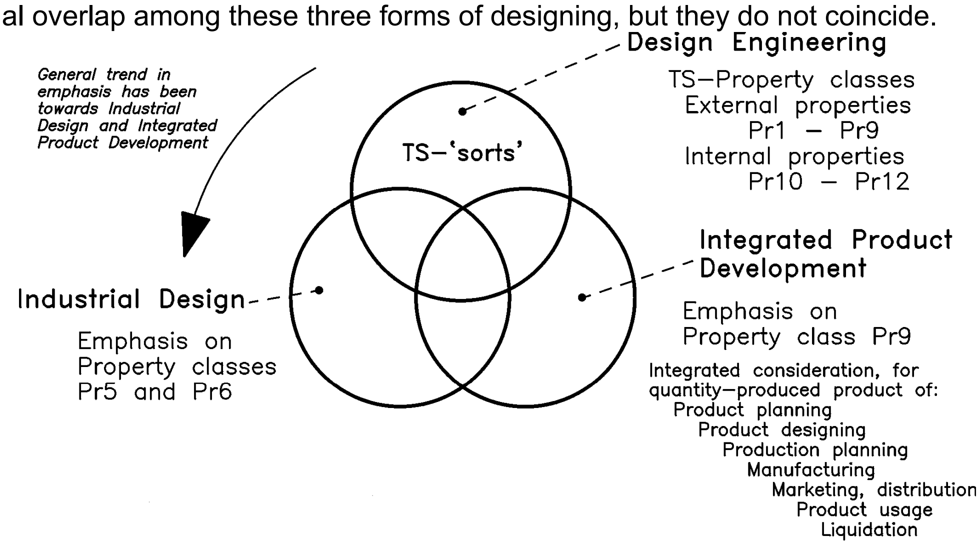

Figure 1. Scope of Sorts of Designing

Design processes for design engineering, although they have much in common with other forms of designing, show substantially more constraints than in other disciplines. Products of design engineering should provide a useful functionality. Their design (the process and the resulting documentation of the proposed system) therefore need a wide range of information (see figure 2), an extensive amount of experience (knowing), judgement of feasibility and application of engineering scientific analysis. In addition, design engineering has available, for use by engineering designers in their search for candidate solutions, several more abstract models of technical systems – transformation processes, technologies, function structures, organ structures, and constructional structures in preliminary or definitive layout, detail, and stages of assembly [Hubka 1988a and 1996, Eder 2007a] – which allow a more systematic and methodical approach to conceptualizing, based on a more theoretical categorizing of information. The need for information of a technological, economic, environmental, cultural, political (etc.) nature also colors the engineering design process in a far greater way than for other disciplines, and these items of information are extensively interconnected. An extended search of the possible solution field is useful to ensure that a currently optimal solution can be found – optimal in technical, economic, environmental, social, cultural and other senses.
Industrial designers tend to be the primary designers for consumer products and durables, engineering designers tend to be primary for technical systems. Both kinds of designers cooperate in design teams, which should include manufacturing, sales, and other experts.
Design engineering exhibits several dimensions that characterize the design problem, and indicate useful design processes. The tangible technical system may range from simple to very complex – four typical levels of complexity have been defined [Hubka 1988a, p. 97; Eder 2007a, p. 300]:

level I - constructional part;
level II - group, sub-assembly;
level III - machine, apparatus, device;
level IV - plant, equipment.

In practice, each of these consists of many sub-levels. Technical systems are therefore hierarchical, level IV consists of TS of level III; these consist of TS of level II; and these in turn consist of TS of level I.

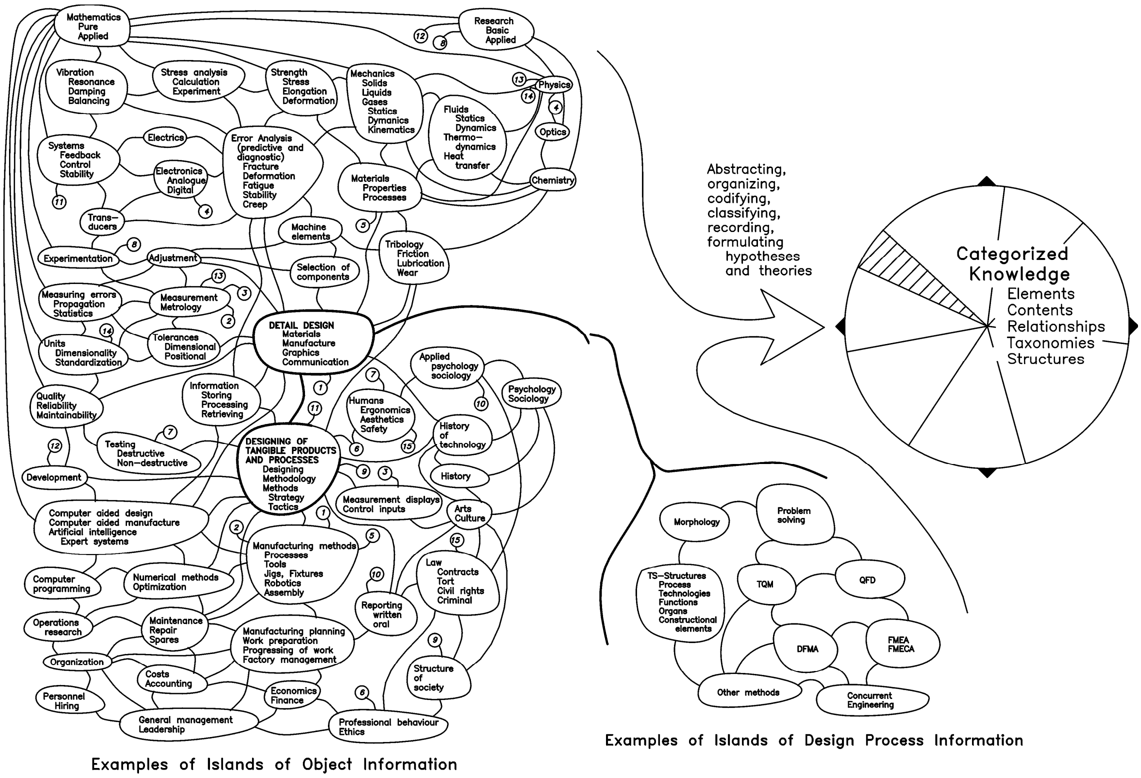

Figure 2. Transition from Scattered Information to Categorized Knowledge

Design problems may range from routine to novel. Routine problems exhibit few difficulties, previous experience can guide both the design process, and the constitution of the TS. Novel problems may demand novel procedures for solving, and/or novel TS configurations – a connection to innovation.

Designers may range from experienced to inexperienced – in total, or in the particular TS-'sort' with which they are concerned at that time.

2.1 Design Engineering – Action Modes

Design engineering [Müller 1990], consists of *anticipating* a possible change based on a future implementation of a TP(s)/TS(s) – the 'subject' of design engineering. Designing depends on available information and theory about systems [Hubka 1988a, 1992 and 1996, Eder 2007a] and about designing [Hubka 1992 and 1996, Eder 2007a]. The products of design engineering are proposals. These cannot be *evaluated* as 'true' or 'false', or 'probable' or 'improbable', they can only be evaluated and simulated as realizable or not, and valued better or worse than competing proposals.

Design engineering can only result in sufficiently complete and reliable information about the anticipated TP(s)/TS(s) if the designers can be sure to have considered all factors. Then, an anticipating proposal (and its documentation) for a designed TP(s)/TS(s) can be *evaluated as technically accomplishable*, if it can be confirmed with sufficient credibility and confidence that: (a) the TS(s) will fulfill the requirements under the circumstances of operation with sufficient reliability; (b) it is implementable or manufacturable under the given circumstances; (c) it complies sufficiently with the requirements of the manufacturing processes; and (d) all other requirements are fulfilled in acceptable ways to the user, customer, organization, legal and political authorities, the economy, culture, environment, etc.

Then also, an anticipating proposal (and its documentation) for implementing a TP(s) and/or manufacturing a TS(s) can be *evaluated as technically realizable*, if it can be confirmed with sufficient credibility and confidence: (a) that it can be implemented and/or manufactured under the given circumstances; (b) that the proposed sequence of implementing and/or manufacturing operations as specified will fulfill the required purposes of the TP(s)/TS(s) with sufficient reliability; and (c) that the requirements of the field are acceptably fulfilled.

To verify the accomplishability and realizability, the proposals must be tested in a design audit, by experiments, simulations, models, samples and prototypes of the complete system and/or of suitable parts. Proposals should be confirmed before release for manufacture or implementation.

For design engineering, three kinds of action modes exist [Müller 1990]: (a) *Normal operation* (intuitive, second nature procedure) runs activities from the subconscious in a learned and experienced way, at low mental energy, giving an impression of competence [Pahl 1994]. 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 behavior, 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.

Both risk operation and safety/rational operation need guidelines and learning/experience of systematic and methodical approaches, preferably based on a coherent and complete (but not necessarily mathematical) theory [Hubka 1996, Eder 2007a]. **This systematic and methodical working mode must be learned before attempting to use it, preferably in the 'safe' environment of an educational institution.**

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.

Non-routine situations often produce critical situations in a design process [Frankenberger 1997a, 1997b, 1997c and 1998], 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.

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. It is necessary for engineering designers to learn methodology during their engineering education. Then the methods are familiar enough to apply, even if there is resistance from a supervisor. The beneficial results of teaching design methodology have been demonstrated [Dörner 1995, Fricke 1991, Günther 1997, Pahl 2007], after 25 years of teaching, and after some graduates entered industry as engineering designers.

2.2 Expertise

A major advantage of accepting that every designer operates within an amalgam of three worlds (a theory world, a subjective internal world, and an objective external world), is that we can identify levels of design expertise through each of the three.

As quoted in Dorst [2004], Hubert Dreyfus [2003a and 2003b], distinguishes seven levels of expertise, corresponding with seven ways of perceiving, interpreting, structuring and solving problems (i.e., the three worlds):

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 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, 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, defmes 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 product being designed, and about design processes. The 'trial and error character' is only an apparent phenomenon, it reflects a routine level of operation where the steps and methods are no longer conscious and externally recognizable.
An 'intuitive' response from the '5. Expert' is also to be expected, more or less at all levels of expertise, as the relevant method becomes well enough internalized to run routinely.
Any one designer may show different levels of expertise for different types of problem, progression through these levels is not uniform.

3. Design Science

[Hubka 1996] indicated (in figure 2-4 of that book) that knowledge with respect to engineering forms a hierarchy. An extension if this concept was outlined in [Eder 2005c], that sciences form a hierarchical network, from a 'science of sciences' to a set of more specific sciences that can be further sub-divided. Each such sub-division eventually claims to be a science in its own rights, that inherits the properties of the higher level, but adds further detail that is no longer generally valid.
In this way, 'design sciences' can be also sub-divided, see figure 3. One of these sub-divisions is 'Engineering Design Science' [Hubka 1996, Eder 2007a], the only design science that to date has been developed in any detail. Even this Engineering Design Science could be sub-divided into

'Specialized Engineering Design Sciences' at various more detailed levels of abstraction and applicability.

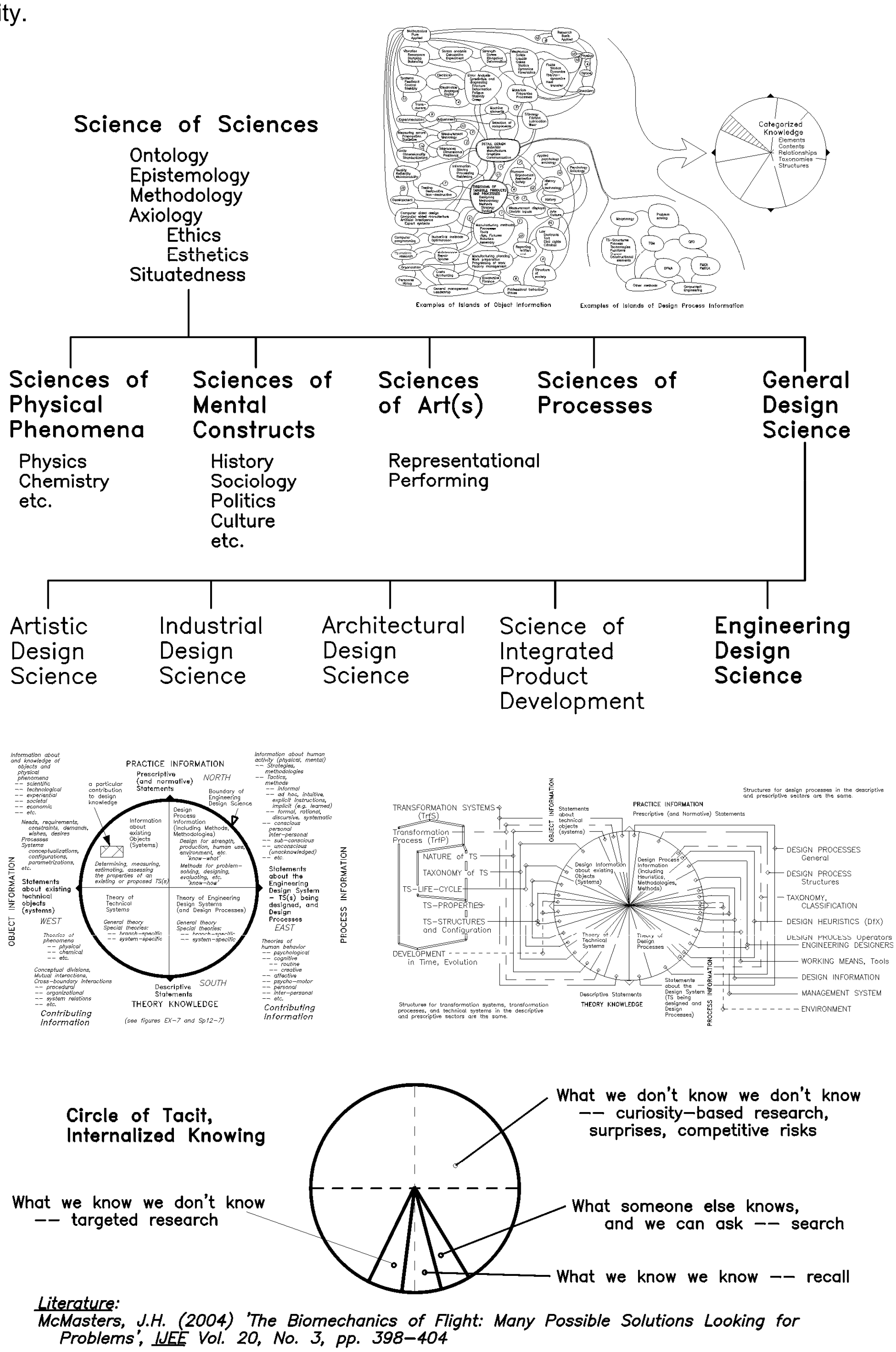

Figure 3. Hierarchy of Sciences

A hierarchical representation of these dependencies is not fully adequate. The arrangement of concepts and the interpretation of intentions depends on the order in which the criteria are considered. Any cross-connections among branches of the hierarchy are often neglected. Yet all information is multiply cross-connected, and some information should appear at several levels of such a hierarchy. In some respects, a better representation of relationships can be shown in a concept map, for instance figure 2 [Hubka 1996, Eder 2007a]. The central concepts for this paper, 'Designing of Products' and 'Detail Design', are surrounded by contributing concepts that are also interconnected. A hierarchy is perceivable, concepts that are more distant from the central concepts appear to be placed lower in the hierarchy. The contributing concepts are grouped into related formations, and boundaries could be drawn around these groupings. These can form the centres of interest for other specialities. Figure 2 allows a demonstration of this grouping by separating 'object information' from 'design process information'.
The concept of the system of EDS [Hubka 1996, Eder 2007a] is based on the triad 'theory – subject – method', i.e. a *theory* about a *subject* allows a *method* to be defined and heuristically applied, for using or for designing the subject, see figure 4. The system is focused on design engineering of technical processes (TP = TS-operational process) and/or technical systems (TS), and includes design engineering information about TP and TS, and engineering design processes.

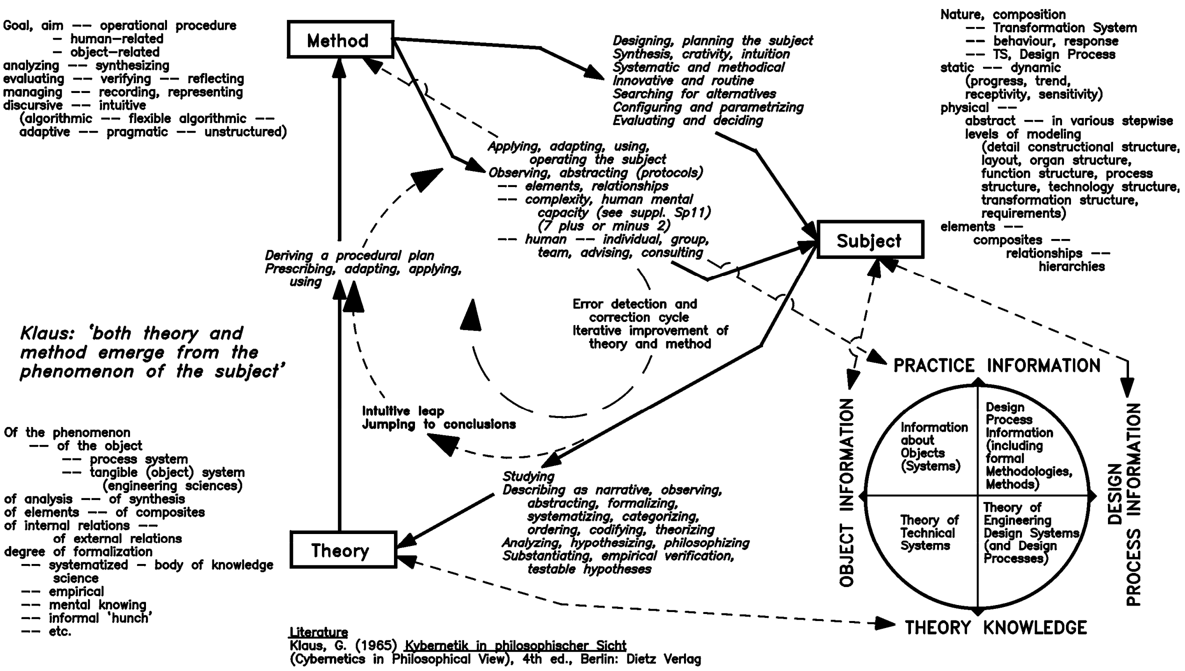

Figure 4. Relationships Among Theory, Subject and Method

A basic model for Engineering Design Science [Hubka 1996, Eder 2007a] is that of the *transformation system*, see figure 5. The model for an existing transformation system declares:

- An *operand* (materials, energy, information, and/or living things – M, E, I, L) in state Od1 is transformed into state Od2, using the active and reactive *effects* (consisting of materials, energy and/or information – M, E, I) exerted continuously, intermittently or instantaneously by the *operators* (human systems, technical systems, active and reactive environment, information systems, and management systems, as outputs from their internal processes), by applying a suitable technology Tg (which mediates the exchange of M, E, I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.

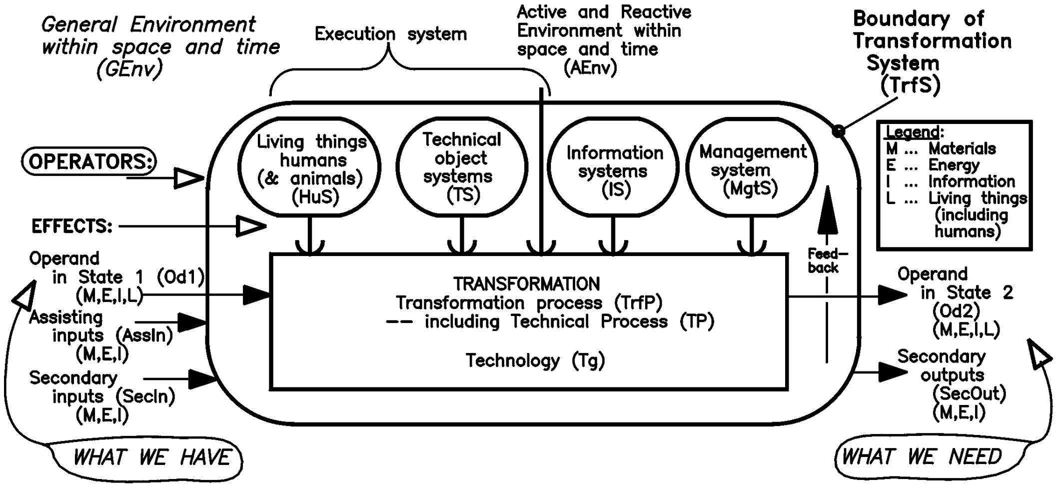

Figure 5. General Model of a Transformation System

The transformation *process*, TrfP, in which the operand is transformed, and the five *operators*, HuS, TS, AEnv, IS and MgtS, are constituent parts of the transformation *system*, TrfS, and all operators interact to initiate and perform the process.

With the transformation system shown in figure 5, designers can develop a theory-based method for a novel system to be designed [Hubka 1988, 1992 and 1996, Eder 2007a]:

(P1) establish a design specification for the required system, by re-formulating the customers' needs into a full list of requirements as understood by the engineering designer, and by obtaining agreement with the customers (or their representative) and the management of the manufacturing organization, e.g using the properties of transformation processes and technical system as guideline [Eder 2007b];

(P2) establish the desirable and required output (operand in state Od2) of the transformation, the ultimate purpose of the product;

(P3) establish a suitable transformation process (structure, with possible alternatives) to change the operand from state Od1 to state Od2, its operations in detail, investigating possible alternative operations and their sequencing, and (if needed) establishing suitable inputs (operand in state Od1);

(P4) decide which of the operations in the transformation process will be performed by humans, and which of them by technical systems, alone or in mutual cooperation;

(P5) which technical systems (or parts of them) need to be designed at that point (i.e. do not yet exist);

(P6) establish a technology (structure, with possible alternatives) for that transformation operation for which the technical system needs to be designed, and therefore the effects (as outputs) needed from the technical system to cause the transformation;

(P7) establish what the technical system needs to be able to do (its internal and cross-boundary functions and function structure, with possible alternatives) to produce these effects/outputs, and what its inputs need to be;

(P8) establish what organs (function-carriers in principle, and their structure, with possible alternatives) can perform these functions, and what added functions (and organs) are recognized as needed (a function-means chain). A morphological matrix is useful for exploring candidate organs to solve each function, and to allow combining them into organ structures (as concepts). These organs can be found mainly in prior art, especially the machine elements, in a revised arrangement as proposed by Weber [Weber 1997, Eder 2004a, 2005a and 2005b];

(P9) establish with what constructional parts (in sketch-outline, in rough layout, in dimensional-definitive layout, then in detail and assembly drawings, with possible alternatives) are needed, and what additional functions (and organs, and constructional parts) are now revealed (evoked) as being needed (a more extended function-means chaining), to produce a full description of a future TS in the shortest time at lowest cost.

Only those parts of this engineering design process that are thought to be useful are employed.

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.

Consideration of life cycle issues is included in the outlined methodology, which necessarily also involves 'Design for X' knowledge and advice.

Neither novel design engineering nor re-designing can possibly be done in a linear procedure; feedback, iteration (repeating the operations with better understanding of the problem) and recursion (dividing a problem into smaller parts, solving, then re-combining) are always needed. The possibilities of searching for alternatives is presented in several steps – is this not the essence of creativity [Eder 1996]? Possible analysis by engineering sciences exist at several stages. Each step should conclude with a cycle of review, including key-words such as 'substantiate', 'evaluate', 'select', 'decide', 'improve', 'optimize', 'verify', 'check', 'audit' and 'reflect'.

5. Design Engineering Application

Examples of application of the recommended systematic method have been published [Hubka 1988b, Eder 2007a].

It is obvious that routine design situations can be handled from experience by normal (i.e. intuitive) procedures. Students inevitably encounter such situations as novel, either from the viewpoint of the TP(s)/TS(s) they are asked to design, or from the viewpoint of the design process and methods they can or should use. They therefore should learn to use the more formal safety or rational operation during their education. This learning should take place on simple problems at first, and progress to more complex and novel problems in the course of their studies [Eder 2004b]. The full procedure outlined in section 3 leads to a full documentation of the design process that can be reviewed, and audited. It is useful as an adjunct to intuition and opportunism, and leads to a fuller consideration of alternatives at several levels of abstraction.

Once a student has learned this methodology well enough, the methods become internalized and run from the sub-conscious in a risk or routine operation. Nevertheless, that student knows about methods to overcome roadblocks during design engineering.

Graduates should then be able to self-start, because they know what they can do (and why) to proceed with diagnosing, solving and documenting an engineering problem, especially for design engineering.

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