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Self-Starting Graduates—An Impression of Industry's Needs*

W. ERNST EDER
107 Rideau Street, Kingston, ON, K7K 7B2, Canada. E-mail: eder-e@kos.net

Industry has some perceived needs with respect to graduates. Here, the scope of Design Engineering is outlined, and compared with the more artistic and management aspects. Engineering designers follow some principles in their work, and display expertise and competence when trying to solve design problems. Formalizing methods should prove useful from a safety/rational operating approach. These methods are best derived from Engineering Design Science, using the model of a general transformation system as the basis. Engineering students should learn such rational operation and the theory on which the methods are based.

Keywords: design engineering; engineering design science; education

INTRODUCTION

EDUCATIONAL INSTITUTIONS have several duties, one of which is to provide a useful education in a limited range of subjects for students. Another is to provide society with graduates who can function within that culture. Industry is part of society, and is therefore a customer for the graduates produced by the educational institutions.

The question this paper addresses is 'How can an Engineering Design Science course help to educate engineering students to obtain the ability to initiate actions to solve engineering (design) problems themselves?'

One problem in this respect is in obtaining a good grasp of the needs of industry. It seems that industry is too close to its own problems, and has too little time to spend on useful analysis, to define the problems sufficiently well for educational institutions to act. Industry is, after all, in business to make marketable products, to achieve financial success, and to maintain a long-term presence in the marketplace. Over many years, the American Society for Engineering Education (ASEE) has asked industry to comment on the deficiencies in graduates of engineering programs—and have received several single-concept (therefore usually simplistic) statements, such as: 'graduates need to be educated in . . .'; the reported deficiencies have, at various times, included 'communication skills', 'teamwork' and 'report writing', amongst others. As a consequence, a number of educational institutions have changed their programs from time to time to emphasize these topics, but not in the wider context of a 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 academic staff members in a number of universities—and thus have a cross-cultural outlook on these problems. They have also been instrumental in defining a coherent science about the processes of design engineering. It is on this basis that the author has developed a grasp of the unspoken needs of industry with respect to design engineering, and the ways of meeting those needs.

The fairly recent trend in private industry towards globalization, and the pressure towards innovation, has made it imperative that engineering graduates should be capable of initiating actions within a short time of entering industry. This is especially true in design engineering, where in recent times much skill and experience has been lost because of the limitations of computer processing—acknowledging the obvious benefits of computers. 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 reduced, by providing students with a well-formulated education in integrated design engineering.

DESIGN ENGINEERING

One of the important duties of engineering graduates in industry is to design (and/or supervise the design of) technical products—technical processes (TP) and technical systems (TS). A rough definition of types (sorts) of *products* is needed [1, 2] in order to: (a) compare types of *design processes* (processes that are intended to create the manufacturing and/or implementation instructions for a product) and to investigate their scope, and (b) to give some guidelines for design education in various disciplines. 'Products' according to ISO 9000:2005 [3] are the 'results of a set of interrelated or interacting activities which transform inputs into outputs', and include 'services',

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'software', 'hardware', and 'processed materials', also known as goods and services, or as artifacts and processes. Some of these have a substantial contribution from engineering, technical systems and technical processes [4–6].

Products may be characterized in various ways, see [5 (pp. 9–13), 6 (pp. 23–28; 334–342)]. This characterization of products cannot be complete, and many of these classes overlap and have fuzzy boundaries. A (non-linear, branched) 'scale' of artifacts begins at *artistic works*. *Consumer products* are consumable items and materials. *Consumer durables* have appropriate appearance and operability, project the 'right' image, and perform useful tasks at a suitable cost. *Bulk or continuous engineering products* act as raw materials for other manufacturers. *Industry products* are bought by a manufacturing organization for assembling into their own products. *Industrial equipment products* are self-contained devices that perform more or less complex functions. *Special purpose equipment*, include jigs, tooling, fixtures, and specialized manufacturing machines, robotics, handling and packaging machines, but also ocean-going ships and buildings for which appearance is very important. *Industrial plant* usually consists of industrial equipment products, and devices to control and/or connect them. *Configuration products* are items of equipment and/or industrial plant for which the parts are quantity-produced and standardized industrial equipment products (OEM, COTS) designed as modular interchangeable technical systems, which are assembled to the customers' requirements with little further modification. *Infrastructure products* provide the means for supplying services according to ISO 9000:2005 [3], such as transportation, power delivery, water and fuels. *Intangible products* are typically documents, as tangible items that record a specification of the services provided by an organization. *Software products* are intangible products presented as computer programs. They may be delivered on a transportable medium (floppy disk, CD-ROM, DVD-ROM, etc.), by down-load from a computer source, or loaded into a programmable controller.

Technical products need to be designed—anticipated in concepts and detail—before they can be manufactured and used. Designing in most cases involves a re-design of a previous product, and can range from the innovative to the routine. In some cases, a previous product does not exist, or must be altered so radically that a novel design process is more appropriate.

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 areas of this activity for generic products, including processes and tangible products ISO 9000:2005 [3], see Fig. 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.

Design processes for design engineering, although they have much in common with other forms of designing, have substantially more constraints than those of other disciplines. The products of design engineering should provide a useful functionality. Their design (the process and the resulting documentation of the proposed system) therefore needs the designer to have available a wide range of information (see Fig. 2), an extensive amount of experience (knowing), to make a judgment of the feasibility and apply engineering scientific analysis. However, design engineering also has available, for use by engineering designers in their search for candidate solutions, several more abstract models of technical systems. These include transformation processes,

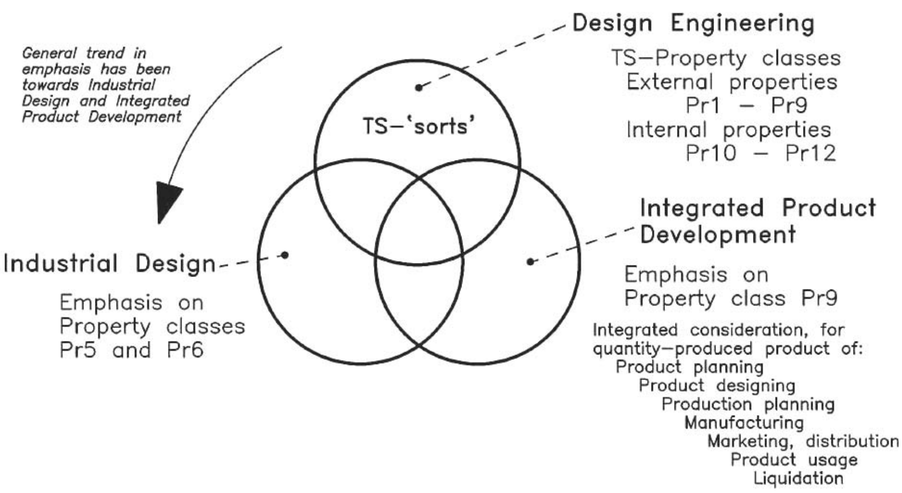

Fig. 1. Scope of types of designing [6].

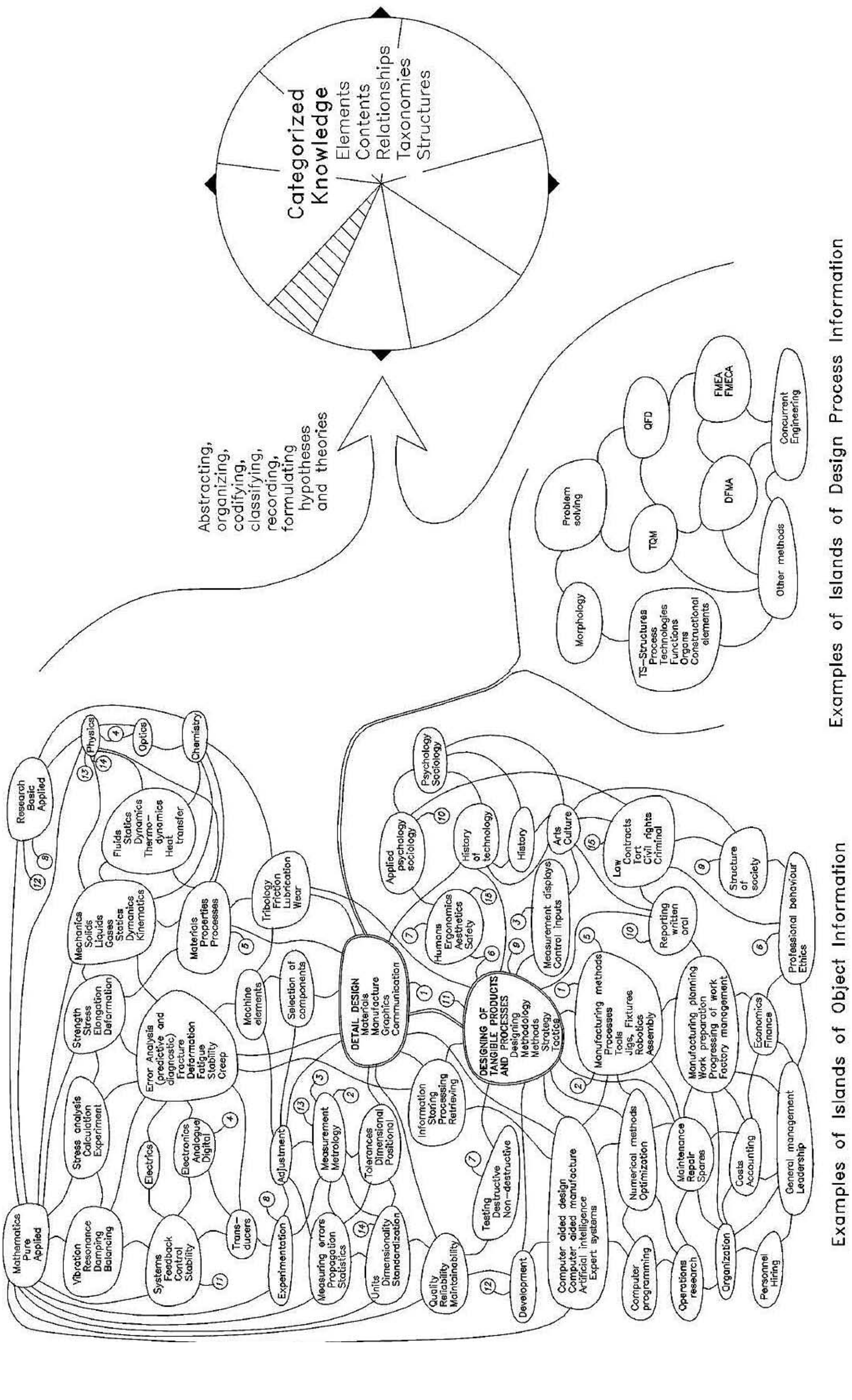

Fig. 2. Transition from scattered information to categorized knowledge [6].

technologies, function structures, organ structures, and constructional structures in preliminary or definitive layout, detail, and stages of assembly [4, 5, 6], which allow a more systematic and methodical approach to conceptualization, 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 in other design disciplines, and these items of information are extensively interconnected; see Fig. 2. An extended search of the possible solution field is useful in order to ensure that a currently optimal solution can be found—optimal in the technical, economic, environmental, social, cultural and other senses.

Industrial designers tend to be the primary designers of consumer products and durables; engineering designers tend to deal primarily with technical systems. Both types of designers cooperate in design teams, which should include experts in manufacturing, sales, and other fields.

Industrial designers and engineering designers may be employed in an organization-wide process of 'integrated product development' (IPD), working in three parallel streams: (1) marketing and sales, (2) designing, and (3) preparing for manufacture. Products from IPD are generally made in larger quantities, intended for a consumer market, and do not necessarily have an engineering content. The process of IPD has been adapted for small-quantity and single-item engineering products. Those IPD-products that are technical systems (TS) need both design engineering and industrial design. Some engineering products do not need industrial design.

A major difference between design engineering and industrial design is the interpretation of the word 'conceptualization'. *Industrial designers* tend to solve the problems of appearance, desirability, attractiveness and usability. Novelty and innovation may be a strong consideration. Their conceptualizing consists mainly of preliminary sketches of external possibilities—a direct entry into hardware (the constructional structure) and its representation. The sketches are progressively refined, and eventually *'rendered'* (drawn and colored, and/or modeled by computer or in tangible materials) into visually assessable presentation material, full artistic views of the proposed artifact. Considerations of the necessary engineering take place, but often at a rudimentary level. Industrial design and IPD usually work '*outside inwards*', defining the envelope, thus constraining the internal actions. Presenting the results to higher management is an important part of the range of skills of industrial designers. Similar considerations apply to architecture. Technical problems are passed on to design engineers: the engineering designers are expected to follow the decisions of the industrial design—the TP/TS solutions remain within the limitations imposed by the chosen appearance solution.

In contrast, *engineering designers* tend to solve the problems of how to make something work, and look at the manufacturability and other life-cycle related properties. They work from critical zones for capability of functioning, e.g. form-giving zones, '*inside outwards*', defining the internal operational means first that constrain the outside. Novelty may be a consideration, but reliability (control of risks), operational safety, and achievability of functioning is usually the primary concern.

Design engineering exhibits several dimensions that characterize the design problem, and indicate useful design processes. The tangible technical system may range from the simple to the very complex—four typical levels of complexity have been defined [4 (p. 97), 6 (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 has many sub-levels. Technical systems are therefore hierarchical, level IV consists of the TS of level III; these consist of the TS of level II; and these in turn consist of the TS of level I.

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.

The designers may range from experienced to inexperienced—in total, or in the particular TS-'sort' with which they are currently concerned.

Design engineering—action principles

In designing, the engineering principle [7] states that: 'Engineering designers should produce their proposals only as accurately and completely as necessary, but also as coarsely, crudely and applicably as possible to achieve the necessary accuracy and completeness.' This is the normal working mode of engineering designers, who usually work on a project close to the deadline. This leaves little time to complete the project, search for alternatives, optimize, or reflect. A first idea is carried through until an acceptable solution is found, or the project is terminated—'satisficing' [8, 9]. If a project is started when it is first received, one's subconscious mind can work on the problems, using incubation [10]. Systematic working demands starting early, and consistent steady working.

Engineering designers must take responsibility for proposals, but should not perform work beyond their level of confidence. Designing must finish when the proposals can be accepted in the situation: optimal in principles, layout, embodiment and detail. The risk in this procedure must be accepted by the designers, with a realistic view of their capabilities.

Design engineering [7], consists of *anticipating* a possible change based on a future implementation of a TP(s)/TS(s) —the 'subject' of the design process. Designing depends on the available information and theory about the systems [4–6, 11] and about designing [5, 6, 11]. 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 as 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 that they have considered all the factors. Then, a potential 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 ways acceptable to the user, customer, organization, legal and political authorities, the economy, culture, environment, etc.

Then also, a prospective 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 experiment, simulations, models, samples and prototypes of the complete system and/or of suitable parts. Proposals should be confirmed before their release for manufacture or implementation.

The engineering principle [7] must be tempered by a human trend to over-estimate one's own capabilities and knowledge—over-confidence. Over-confidence seems to be prevalent when defining design tasks—designers (even when their preparation has been inadequate) frequently think they understand the problem when they don't.

Design engineering—action modes

For design engineering, there are three types of action modes [7]: (1) *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 [12], see the section on 'Competencies' below. If difficulties arise, the action departs from the normal, and higher mental energy is needed. (2) *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. (3) *Safety* or *rational operation* needs conscious planning for systematic and methodical work, with conscious processing of a plan, because competence is in question. *Systematic* design engineering is the heuristic-strategic use of a theory to guide the design process. *Methodical* design engineering is the heuristic use of established and newly developed methods in engineering design, including theory-based and 'industry best practice', strategic and tactical, formalized and intuitive methods.

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 [5, 6]. *This systematic and methodical working mode must be learned before attempting to use it in practice, preferably in the 'safe' environment of an educational institution.*

Normal, routine operation is mainly the preferred mode of operation of 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 faster at lower mental energy than obtaining information from (written) records [13].

Non-routine situations often produce critical situations in a design process [14–17], e.g. when: (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.

Expertise

As adapted from Dorst [18], Hubert Dreyfus [19, 20] distinguishes seven levels of expertise, corresponding to 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 [21] 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 be made only 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 building up of 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' [7]; 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 [4–6].

The last sentence of item '3. Competent' needs further clarification. Progress from one level to a next higher level requires some additional 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 reflects a normal/routine level of operation [7] where the applied theories, steps and methods are no longer conscious and mental-externally recognizable. For this reason it becomes difficult (e.g. in an educational situation) to perform an examination of the existing internalized design process of a designer.

When a method is well known to the designer, it can at best be run from the sub-conscious, and users may then even deny that they are using the method. It is necessary for engineering designers to learn methodology during their engineering education, and to continue to expand their expertise in life-long learning. Then the methods are familiar enough to apply, even if there is resistance from a supervisor.

For the novice, almost all problems appear to require risk or safety operation. Therefore students need to learn routine design operations, and especially the available novel, systematic and methodical approaches, preferably based on Engineering Design Science [5, 6], to enable them to reach the higher levels of expertise more easily.

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 sufficiently well internalized to run routinely, and examination becomes more difficult.

An individual 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 (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 [4–6]. For design engineering in particular, the theories, models and methods of Engineering Design Science offer a basis for organizing, acquiring and understanding this knowledge in context.

Competencies

Engineering education, and continuing learning during practice (see also [22]) should aim to achieve the *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 [23–25]:

- heuristic and practice related competency—the ability to use experience and precedents [26], design principles [11], heuristics [21], information and values (e.g. of technical data) as initial assumptions and guidelines, etc.;

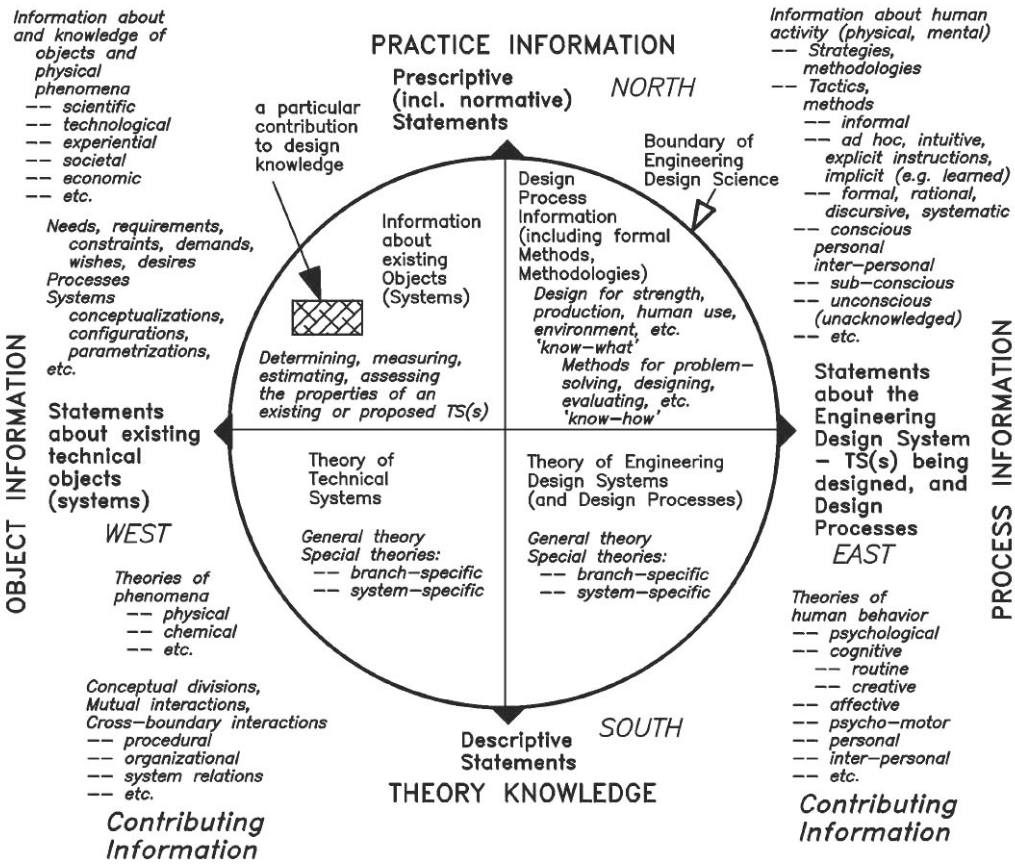

Fig. 3 Map of Engineering Design Science [6].

- 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, see step P6 below), and should also show the engineering sciences, pragmatic information, knowledge and data [27, 28], 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 [29], innovative thinking, and systematic synthesizing [30–32];
- 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 [33–38], 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. [39], 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 [29].

ENGINEERING DESIGN SCIENCE

Perceived knowledge of branch-related objects and of design processes is of differing quality and exhibits varying possibilities for systematizing, as indicated in Fig. 2. In Engineering Design Science (EDS), the information is systematized using a morphology of eight characteristics of statements with their manifestations [5, 6]. Characteristics 1 and 4 are considered most important: (1) Methodological Category of Statement, and (4) Aspects of Designing. They form the major axes of a 'map' (see Fig. 3), which indicates the scope of Engineering Design Science, and the location of information of various kinds that relates to EDS.

The aspect of designing, item (4), is represented in the 'west' by the completed *operand* of designing—the TS and/or TP as it exists, the 'as is' state, and in the 'east' by the *design process*, including

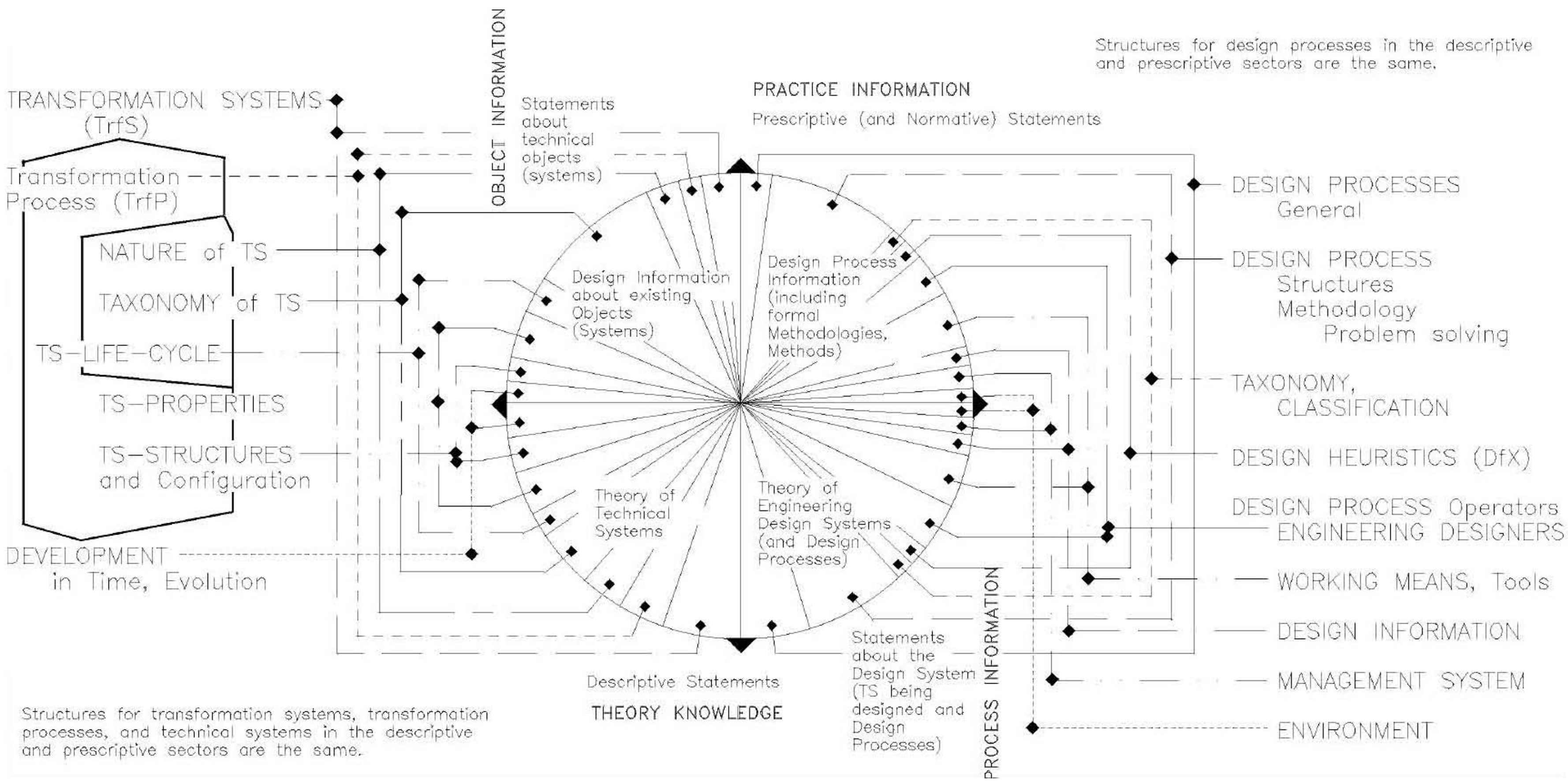

Fig. 4. Elements and structure of Engineering Design Science [6].

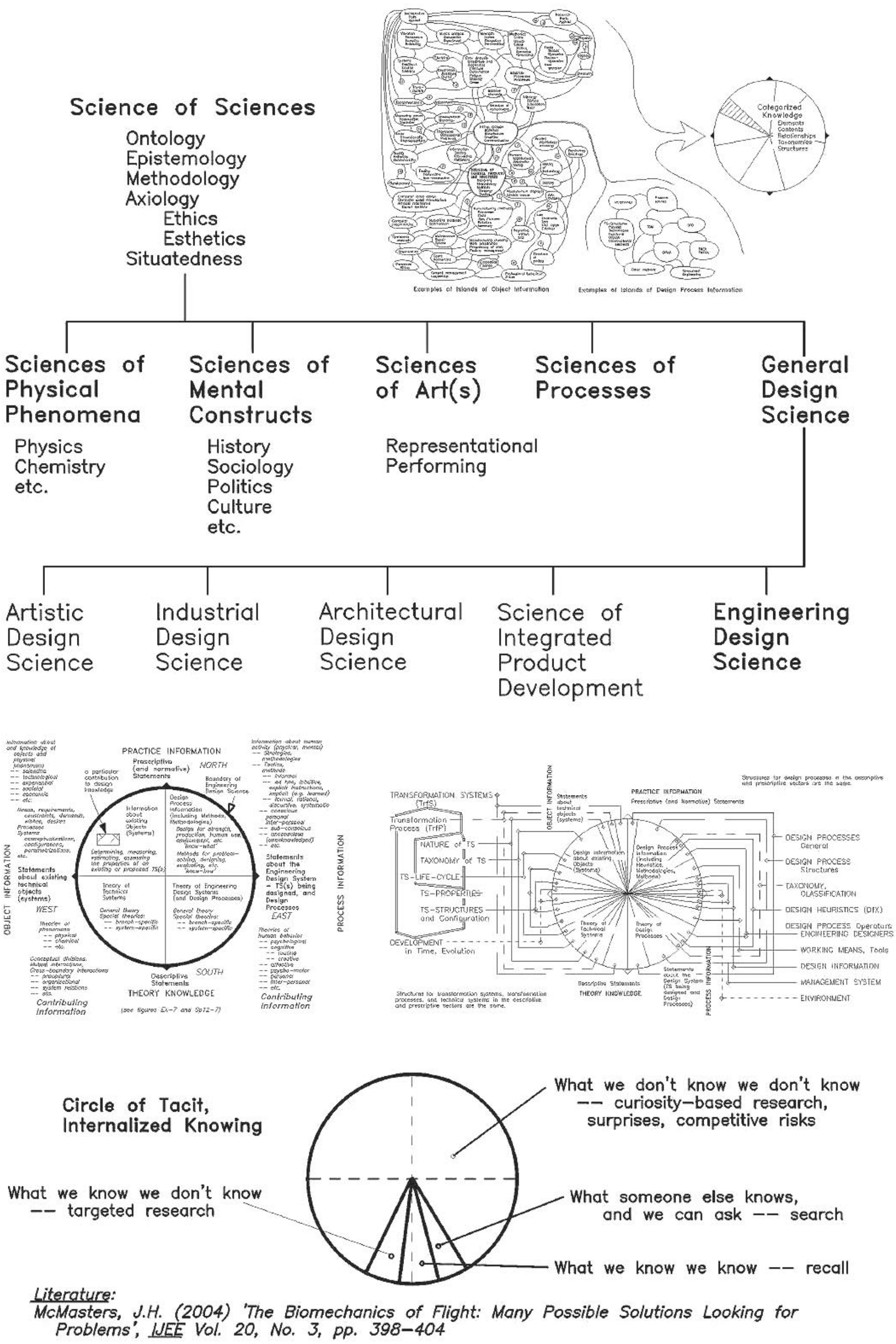

Fig. 5. Hierarchy of sciences [6].

any TP- or TS-related heuristics, the 'as should be' state. The resulting hemispheres are shown in Fig. 3 as sub-sets of EDS. A second division, the methodological category, item (1), distinguishes *descriptive* statements (theoretical—'south'—i.e. not just narrative), from *prescriptive* (practical/advisory—'north') and *normative* (compulsory) statements (practical/compulsory/obligatory, regulative). The contents of the two 'southern' quadrants are clear from the descriptions in Fig. 3. The descriptive (theoretical) knowledge is presented as a set of interrelated models [4–6]. The 'north-east' quadrant contains methods and heuristics based directly on EDS, other methods and heuristics reside around this quadrant. The 'north-west' quadrant contains typical classes of properties

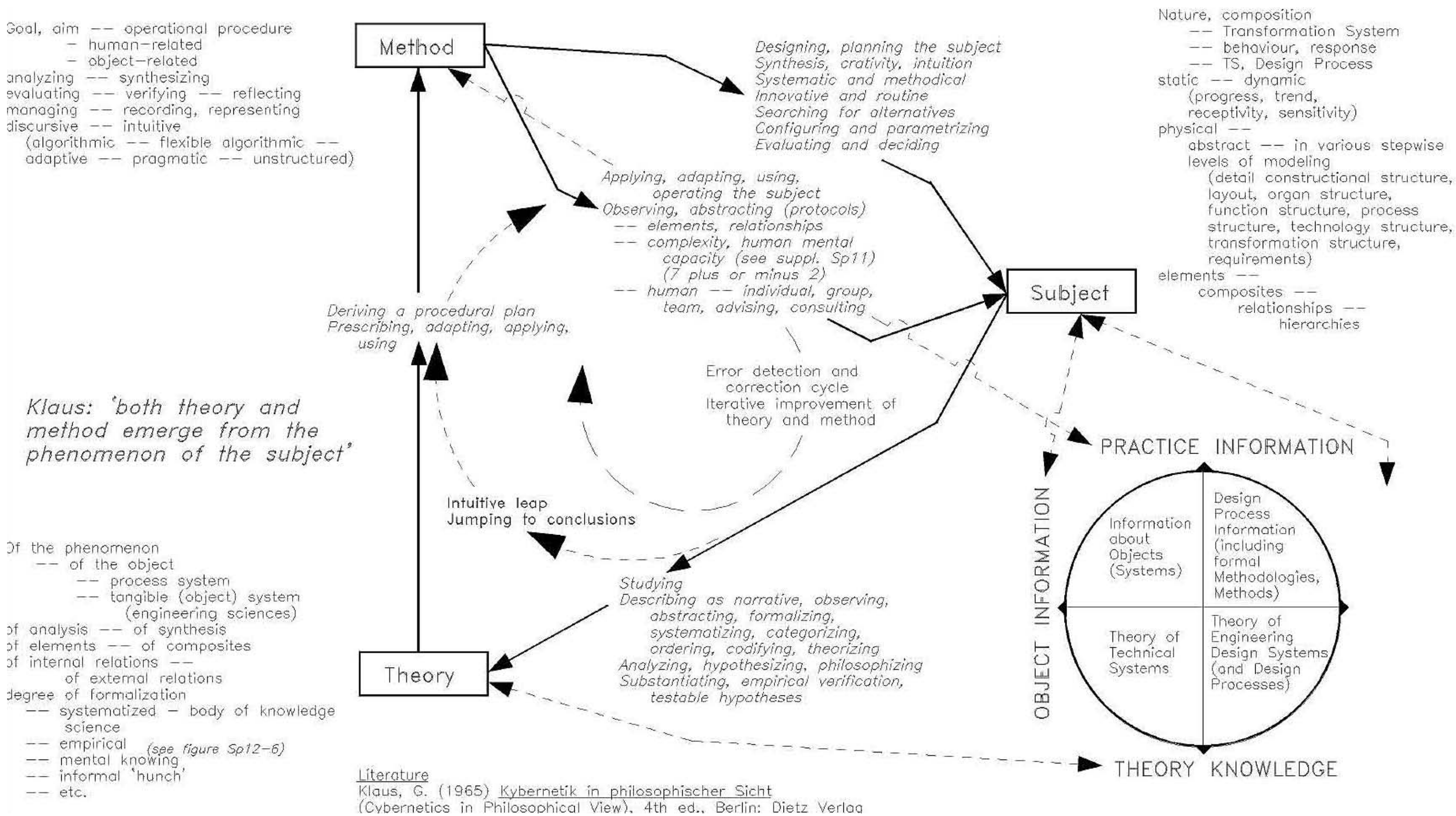

Fig. 6. Relationships between theory, subject and method [6].

and other TS-related information derived from EDS applicable to a particular TS-'sort'.

EDS intends to provide a classification framework for information, and shows the relationships of the included information with other areas; see Fig. 3. The descriptive and prescriptive information are best structured in the same way. The respective structures of information in the 'north' and 'south' quadrants within each hemisphere can be identical; see Fig. 4. The terminology may be different in the related quadrants, e.g. the theory of properties is the descriptive (theoretical) basis for the prescriptive information of requirements for TP(s)/TS(s), and of 'Design for X' (DfX), and provides a structure for this information.

Hubka [5] indicated (in Fig. 2-4 of that book) that knowledge with respect to engineering forms a hierarchy. An extension of this concept was outlined in [40], 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 right, which 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 Fig. 5. One of these sub-divisions is 'Engineering Design Science' [5, 6], the only design science that to date has been developed in any detail. Even this EDS could be sub-divided into 'Specialized Engineering Design Sciences' at various more detailed levels of abstraction and applicability.

A hierarchical representation of these dependencies is not totally adequate. The arrangement of concepts and the interpretation of intentions depend on the order in which the criteria are considered. Any cross-connections between 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 Fig. 2 [5, 6]. 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 centers of interest for other specialties. Figure 2 allows a demonstration of this grouping by separating 'object information' from 'design process information', as also shown in Fig. 3.

The concept of the system of EDS [5, 6] 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 Fig. 6. The system focuses 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.

As formulated in cybernetics [41], '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 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 behavior 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.

In design engineering, the TP(s) and/or TS(s) are the subject of the theory and the method. The *theory* should answer the questions of 'why,' 'when,' 'where,' 'how' (with what means), 'who' (for whom and by whom), with sufficient precision. The theory should support the *methods* used, i.e. 'how' (procedure), 'to what' (object), for the operating subject (the process or tangible object) or the subject being operated, and for planning, designing, manufacturing, marketing, distributing, operating, liquidating (etc.) the subject. The method should also be sufficiently well adapted to the subject, its 'what' (existence), and 'for what' (its anticipated and actual purpose). The phenomena of subject, theory and method are of equal status. Using the convention suggested by Koen [26], underscoring the second letter of a word indicates its heuristic nature: 'a method is a prescription for anticipated future action, for which it is heuristically imperative that you adapt it flexibly to your current (ever changing) situation'—and nearly all words in this paper should have the second letters underscored.

Methods are heuristic, ' . . . a plausible aid or direction . . . is in the final analysis unjustified, incapable of justification, and potentially fallible' [26 (p. 24)]. 'The *engineering method* is the use of heuristics to cause the best change in a poorly understood situation within the available resources' [26 (p. 59)].

A basic model for Engineering Design Science [5, 6] is that of the *transformation system*; see Fig. 7. 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

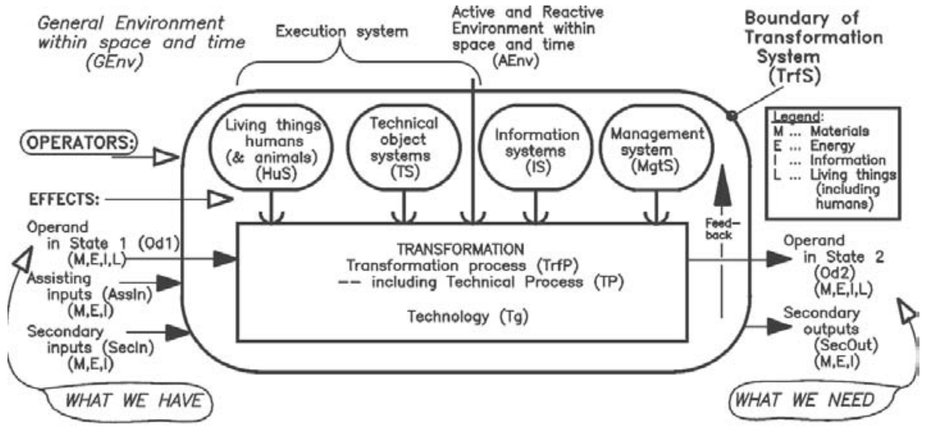

Fig. 7. Model of transformation system [6].

are needed, and secondary inputs and outputs can occur for the operand and for the operators.

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.

Once the transformation system shown in Fig. 5 is understood, designers can develop a theory-based method for a novel system—TP(s) and/or TS(s)—to be designed [4–6, 11], as follows:

(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 and requirements of transformation processes and technical system as guidelines [42];
(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) decide 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, 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 [43–46];
(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(s) in the shortest time and at lowest cost.

Only those parts of this engineering design process that are thought to be useful are employed. Such an 'idealized' procedure cannot be accomplished in a linear fashion; iterative working is essential. Intuitive working is usual; the systematic procedure is intended as an aid for partial problems where intuitive working proves inadequate. Nevertheless, the intuitive results should be brought into the system to maintain consistent and complete records of design decisions. Larger and more complex design problems can be broken down into smaller ones, the systematic procedure can in principle be applied, and the proposed solutions can be recursively re-combined.

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 are presented in several steps—is this not the essence of creativity [47]? Possible analysis by engineering sciences exists at several stages. Each step should conclude with a cycle of review, including keywords such as 'substantiate', 'evaluate', 'select', 'decide', 'improve', 'optimize', 'verify', 'check', 'audit' and 'reflect'.

DESIGN ENGINEERING APPLICATION

Examples of applications of the recommended systematic method have been published [2, 4, 6, 48]. This method has been taught at various universities, especially ETH Zürich (whilst Dr. Vladimir Hubka was active), RMC Kingston Ontario, and The University of West Bohemia (by Professor Hosnedl). In the latter case, instruction and mentoring was provided at the undergraduate and post-graduate levels, and in various industry organizations. Projects for undergraduate and post-graduate levels have been sponsored by industry, as collaborative team activities; the teams included industrial design students, e.g. [49].

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 [48]. The full procedure outlined in the last section 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, the student knows about methods to overcome roadblocks during design engineering.

The beneficial results of teaching design methodology have been demonstrated [50–52], after 25 years of teaching, and now that some graduates have entered industry as engineering designers. For learning design engineering [53], (a) 'what has been heard is not yet understood', (b) 'what is understood does not yet give the ability to act', and (c) 'being able to act does not mean being able to act optimally'. Successful learning of object information and of design process information (including design methodology) requires education. This involves more than transmitting information, and more than exposing students to design projects; it needs a coordinated presentation of information, mentoring and personal supervised experience. The use of methods, and understanding their theories, must be exercised and practiced. Successful use requires experience of use and the capability to select the appropriate methods. 'We know much about stimulating and guiding learning, and need not wait for final or conclusive answers from experimental educational research' [54].

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 in design engineering.

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Ernst Eder was educated in England and Austria. He graduated in Vienna in 1951, after which he had ten years of industrial experience. His academic appointments include the University College of Swansea, The University of Calgary, Loughborough University of Technology and the Royal Military College of Canada. Ernst has published over 150 papers, and co-authored or edited 14 technical books. He was a founder member of the Design Research Society (UK) in 1966, and of The Design Society in 2000. He joined the American Society for Engineering Education (ASEE) in 1968, and is now a life member. He received the 1990 ASEE Fred Merryfield Design Award, and Doctor *honoris causa* at the University of West Bohemia in 2005.