US-China Education Review A, ISSN 2161-623X
April 2013, Vol. 3, No. 4, 259-280

# Engineering Design *vs.* Artistic Design: Some Educational Consequences

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"Design" can be a noun, or a verb. Six paths for research into engineering design (as verb) are identified, they must be coordinated for internal consistency and plausibility. Design research tries to clarify design processes and their underlying theories—for designing in general, and for particular forms, e.g., design engineering. Theories are a basis for deriving theory-based design methods. Both are useful for education. Design engineering and artistic forms of designing, industrial design, have much in common, but also differences. For an attractive and user-friendly product, its form (observable shape) is important—a task for industrial designers, architects, etc.. "Conceptualizing" consists of preliminary sketches, a direct entry to hardware—industrial designers work "outside inwards". For a product that should work and fulfill a purpose and perform a transformation process, its functioning and operation are important—a task for engineering designers. Anticipating and analyzing a capability for operation is a role of the engineering sciences. The outcome of design engineering is a set of manufacturing instructions, and analytical verification of anticipated performance. Engineering designers tend to be primary for TS (technical system), and their operational and manufacturing processes—They work "inside outwards". Design engineering is more constrained than industrial design, but in contrast has available a theory of TS and its associated engineering design science, with several abstract models and representations of structures. Hubka's theory, and consequently design methodology, includes consideration of tasks of a TS(s), typical life cycle, duty cycle, classes of properties (and requirements), mode of action, development in time, and other items of interest for engineering design processes. Students' learning design engineering at times need a good example of procedure for novel design engineering. The systematic heuristic-strategic use of a theory and the methodical design process is only necessary in limited situations. The full procedure should be learned, such that the student can select appropriate parts for other applications. Hubka's methodology is demonstrated by several case examples.

*Keywords:* design research, sorts of designing, scientific investigation of design engineering, engineering design methodology, computer application, case examples

## Introduction

Vladimir Hubka with colleagues professors Umberto Pighini and M. Myrup Andreasen, founded WDK (workshop design—konstruktion) at a meeting in 1978 at Halden, Switzerland. WDK was an informal and international network of people interested in advancing knowledge about engineering design. Hubka also initiated the first international conference on engineering design, ICED (International Conference on Engineering Design) 81 Rome, with emphasis on engineering, and continued to organize and support this

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bi-annual series until 1997. A summary of his work appears in (Eder, 2011). After ICED 95, Praha, the author has noticed an erosion to include all designing and down-play engineering, which has now almost disappeared from this conference series (and from others). A first presentation of the essential discussions of this paper was given in (Eder, 2012d).

In the author's opinion, some strict distinctions need to be made. "Design" in the English language has two usages. As a noun, "the design" refers to that actual manifestation of a product, a tangible man-made object, an idea, a concept, a pattern, an artificial process, etc.—the way it looks, feels, and behaves, the result of a human intention. As a verb, "designing" refers to the mental and other processes that occur during this activity in order to establish "the design". Design practice at times looks for such guidance to overcome problems—when the design situation is non-routine, when expertise and competence are lacking (Eder, 2009b), for instance, in educating novices, or in allowing experienced engineering designers to reach beyond their level of competence.

In design research, the main interest lies in "designing", the verb, and in any underlying theory that can provide guidance for methods to enhance or enable designing. Research for activities, such as design engineering follows at least six parallel paths (Eder & Hosnedl, 2008; 2010):

(1) The classical experimental, "empirical" way of independent observing, e.g., by protocol studies, including self-observation, and impartial observation of experimental subjects, etc.: describing, abstracting, recognizing, perceiving, understanding, modeling, and formulating hypotheses—observations capture a proportion of thinking, usually over short-time spans;

(2) "Participative" observation, the observer also acts as a member of the design team and thus acts in the observed process (Hales, 1991), which in consequence may be biased by the observer's participation;

(3) A "reconstructive", detective way of tracing past events and results by looking for clues in various places (Nevala, 2005)—Reconstructions never fully capture the original events, human memory is limited, and needs to be re-constituted for recall;

(4) Speculative, reflective, and "philosophical" generating of hypotheses, and testing;

(5) Transfer between practical "experience" and the insights of knowledge;

(6) "Development" of not-for-profit products (Howard, 2011).

These paths must be coordinated to attain internal consistency and plausibility. Hubka's developments occurred mainly by paths 4 and 5.

The purpose of design research, to clarify design processes, includes designing in general, and particular forms of designing, e.g., design engineering (see Figure 1), and the scientific treatment of design engineering is currently much farther advanced that for any other form of designing. The underlying theories should provide the basis for deriving theory-based design methods to assist designers in solving their problems. We must also acknowledge the utility of pragmatic and "industry best practice" methods for designing, for which theoretical base is inadequate or lacking. Admittedly, the engineering and other sciences can provide some assistance, especially for heuristic "what-if" investigations, and for analyzing expected behaviors. In addition, design research should explore where these assisting methods may be needed—routine *vs*. non-routine design situations, and the needs of management *vs*. practitioners (Eder, 2009b).

A further necessary distinction is between a theory and a method. From Eder and Hosnedl (2010), as formulated in cybernetics (Klaus, 1965; 1969), "Both theory and method emerge from the phenomenon of the subject" (see Figure 2). A close relationship should exist between a subject (its nature as a concept or object), 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 concept or (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, and consider available experience. One aim is to separate theory from method.

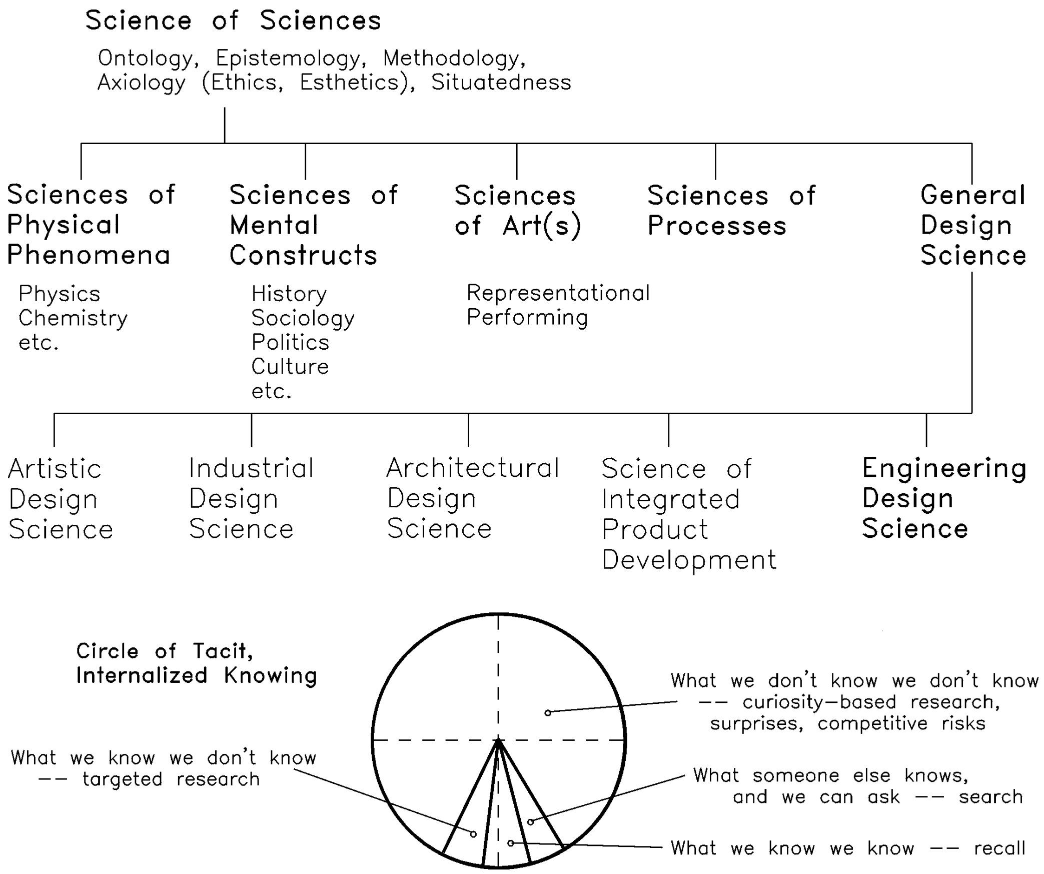



*Figure 1*. Hierarchy of sciences. Source: Eder and Hosnedl (2008); McMasters (2004).

The "theory" should answer the questions of "why", "when", "where", "how" (with what means), and "who" (for whom and by whom) with sufficient precision and fidelity. The theory should support the utilized "methods", 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, and liquidating (etc.) the subject. The method should be sufficiently adapted to the subject, its "what" (existence), and "for what" (anticipated and actual purpose). The phenomena of subject, theory, and method are of equal status. Using Koen's (2003) convention, 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" (Koen, 2003, p. 24). "The 'engineering method' is the use of heuristics to cause the best change in a poorly understood situation within the available resources" (Koen, 2003, p. 59). Methods must be learned, preferably on simplified examples, before they can be used (often from memory) on a problem of any substantial importance (Eder, 2009b).

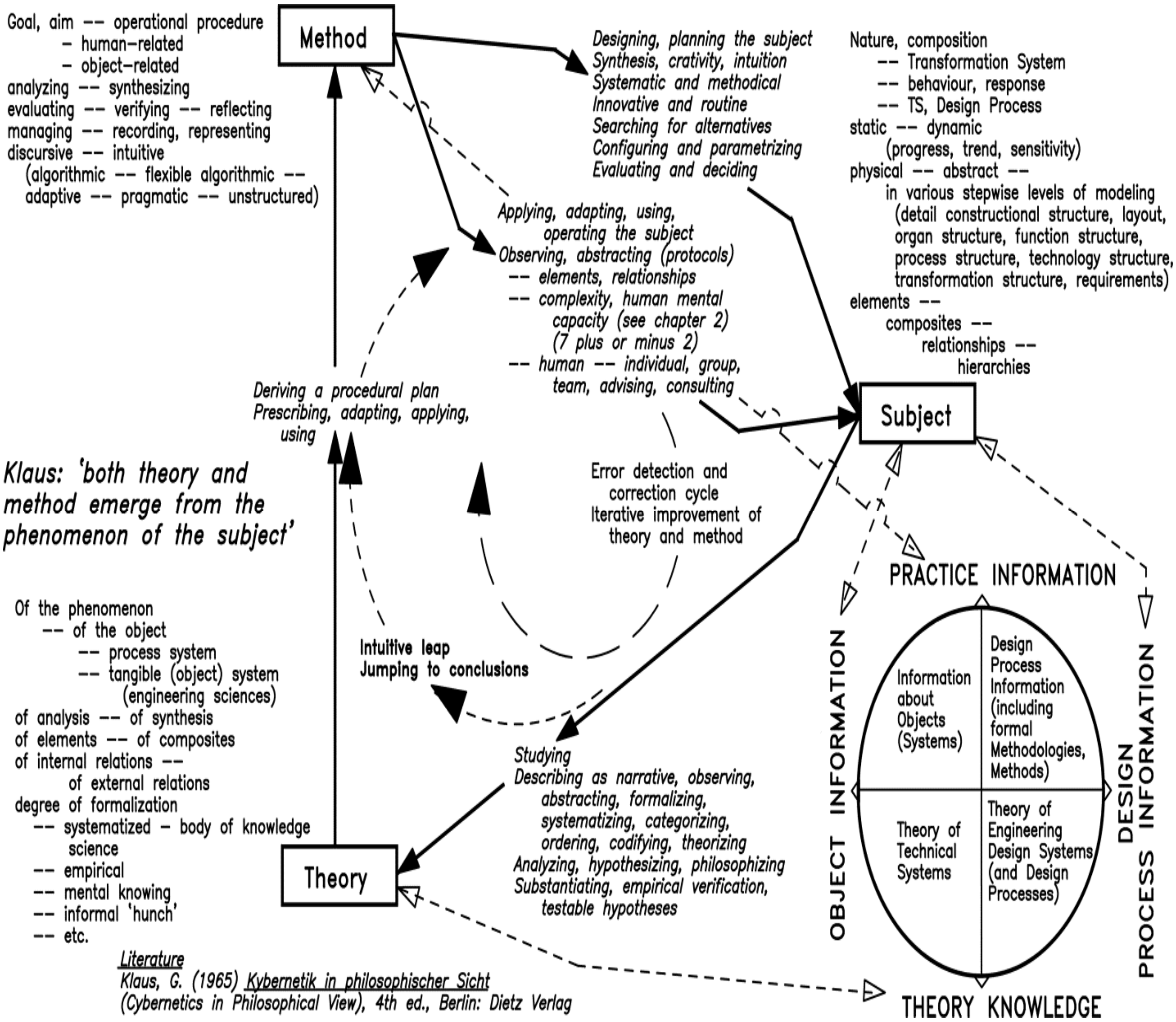



*Figure 2.* Relationship among theory, subject, and method. Source: Eder and Hosnedl (2008; 2010); Klaus (1965; 1969).

The triad "subject—theory—method" is a valuable educational insight. It confirms that forethought is a necessary precursor to establishing a method (for using the subject, or for designing the subject) and accomplishing an action. In addition, some rehearsal and/or training is often needed for effective and efficient action.

This triad "subject—theory—method" is also one cause for the basic arrangement of engineering design science (Hubka & Eder, 1996), as shown in its map (see Figure 3). Engineering design science does not intend to imply that "design is a science", only that scientific methods have been used to investigate engineering design. The left hemisphere of Figure 3 shows the theory (south quadrant) and practice (north quadrant) of existing TS (technical system), the right hemisphere shows the theory (south quadrant), including a fully systematic methodology, and suggested practice (north quadrant) of engineering design processes, including the heuristic and scientific information usable for designing, and the heuristic and systematic advice about the design process itself.

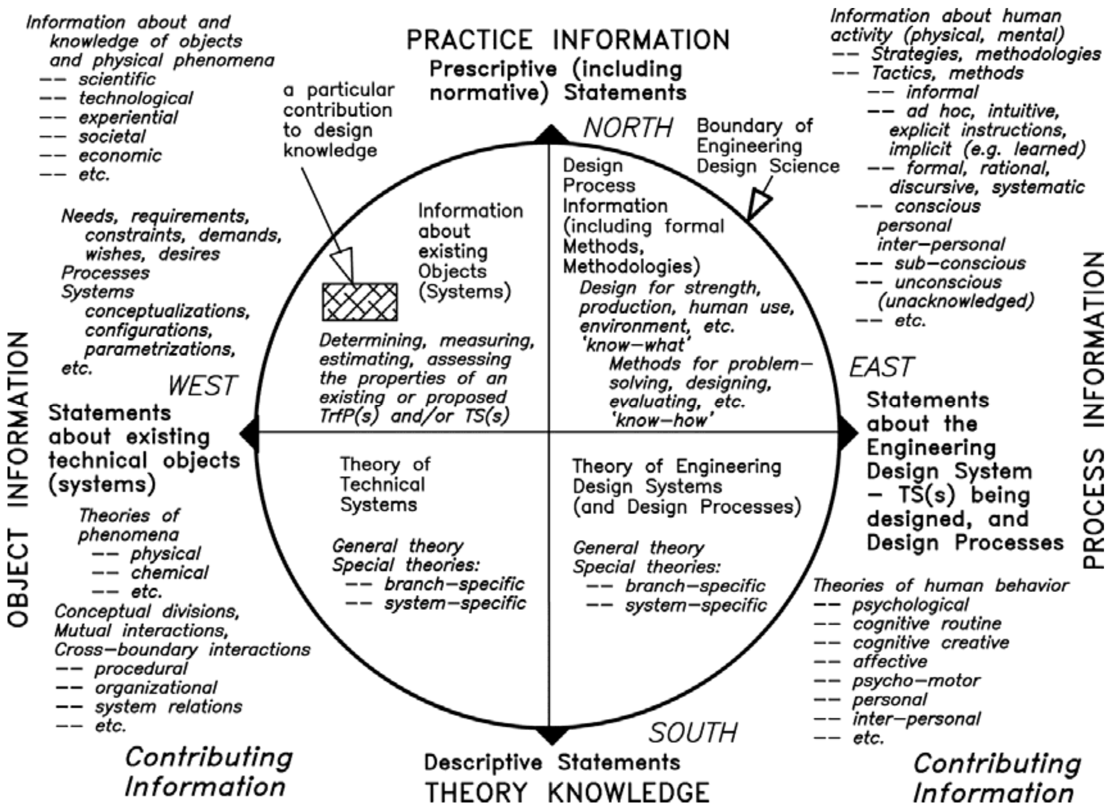



*Figure 3.* Model (map) of engineering design science. Source: Hubka and Eder (1996); Eder and Hosnedl (2008; 2010).

## Basic Considerations

Design engineering and the more artistic forms of designing (e.g., industrial design, architecture, graphic, and sculptural art) have much in common, with partly overlapping duties, but also substantial differences (see Figure 4)—the descriptions show a contrast of extremes, rather than all aspects of designing.

| Objectives, Design Conditions | Design Engineering | Artistic—Architectural—Industrial Design |
|---|---|---|
| The object to be designed, or the existing (designed) object | Transformation Process and/or Technical System; primary: functioning, performing a task | Tangible Product; primary: appearance, functionality |
| Representation and analysis of the object as designed, and its 'captured design intent' | Preparing for TS(s) manufacture, assembly, distribution, etc., AI, CAD/CAM/CIM | Rendering for presentation and display, product range decisions |
| Design process (for the object), methodology, generating the 'design intent' | Theories of designing, Engineering Design Science, formal design methodologies | Intuitive, collaborative, interactive designing |
| Properties of the object as output of designing | Mediating and Elemental Design properties, to establish observable properties | Observable properties to achieve customer satisfaction |
| Design phenomenology | Empirical, experimental and implementation studies | Protocol studies |
| Responsibilities | Professional, ethics, reliability, safety, public, legal liability, enterprise, stakeholders | Organization, stakeholders (Architecture adds organizational and contract responsibility) |
| Location | Design/Drawing Office | Studio |

*Figure 4.* Scope of sorts of designing. Source: Eder and Hosnedl (2008; 2010).

If a product is intended to be visually attractive and user-friendly, its form (especially its observable shape) is important—a task for "industrial designers", architects, and other professions. Industrial design (Flurscheim, 1983; Julier, 2000; Tjalve, 1979; Tjalve, Andreasen, & Schmidt, 1979), in the English interpretation, tends to be primary for consumer products and durables, emphasizes the "artistic elements", appearance (size, shape, etc.), ergonomics, marketing, customer appeal, satisfaction, and other observable properties of a product. This includes color, line, shape, form, pattern, texture, proportion, juxtaposition, emotional reactions (Green & Jordan, 2002), etc., in the terminology adopted by Hubka and modified by Eder (Eder & Hosnedl, 2010), these are mainly "observable properties" of a tangible product. The task given to or chosen by industrial designers is usually specified only in rough terms. The mainly "intuitive" industrial design process emphasizes "creativity" and judgment, is used in a studio setting in architecture, typographic design, fine art, etc.. Industrial designers can introduce new fashion trends in their products.

For industrial designers, "conceptualizing" for a future tangible product consists of preliminary sketches of observable possibilities (even if somewhat abstract)—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—maquettes) into visually assessable presentation material, full artistic views of the proposed artifact, to provide a "final" presentation, for management approval. The tangible model (to scale), or the sample produced by the designer, as it (will) appear(s) or directly represents the final product. Considerations of engineering may take place, depending on circumstances, e.g., stability and self-strength of a sculpture. Industrial designers usually work "outside inwards", defining the observable envelope, thus constraining any internal constituents and actions.

In contrast, for design engineering, the transformation process, TrfP(s), and/or the TS involved in the TrfP(s), the TS(s), are the subjects of the theory and the method. The suffix "(s)" indicates that this TrfP(s) and/or TS(s) signifies the "subject", the product of interest that should be or has been designed. If a tangible product should work and fulfill a purpose by helping to perform a transformation process, TrfP, e.g., by mechanical, electrical, chemical, electronic, etc., means, its "functioning and operating" (note the verb form) are important—a task for engineering designers. Anticipating and analyzing this capability for operation is a role of the engineering sciences. "Engineering" intends to create what does not yet exist, that is likely to work, even if the way it works (its mode of action) is only partially understood by scientific means. Engineering needs designers to be aware of a wide range of existing information (scientific and experience-based heuristic) and its complex interactions, and to consider and accommodate all relevant influences of scientific, technical, economic, societal, political, and other areas to achieve a technically and economically successful and optimal product. The outcome of design engineering is a set of manufacturing instructions (detail and assembly drawings to scale, including tolerances and raw material specifications (Booker, 1979) for a product that is or will be capable of operating, These design outcomes, in more recent times, are likely to be computer-resident for each constructional part, including instructions for assembly, adjustment, testing, use, spare parts, etc. (see Figure 5). These were traditionally produced manually in a design/drawing office, using drafting machines. Computer "seats" have more recently taken over some duties. In addition, documented analytical verification of anticipated performance in all life-cycle phases must be delivered, preferably by a qualified professional engineer. The resulting tangible product is a TS.

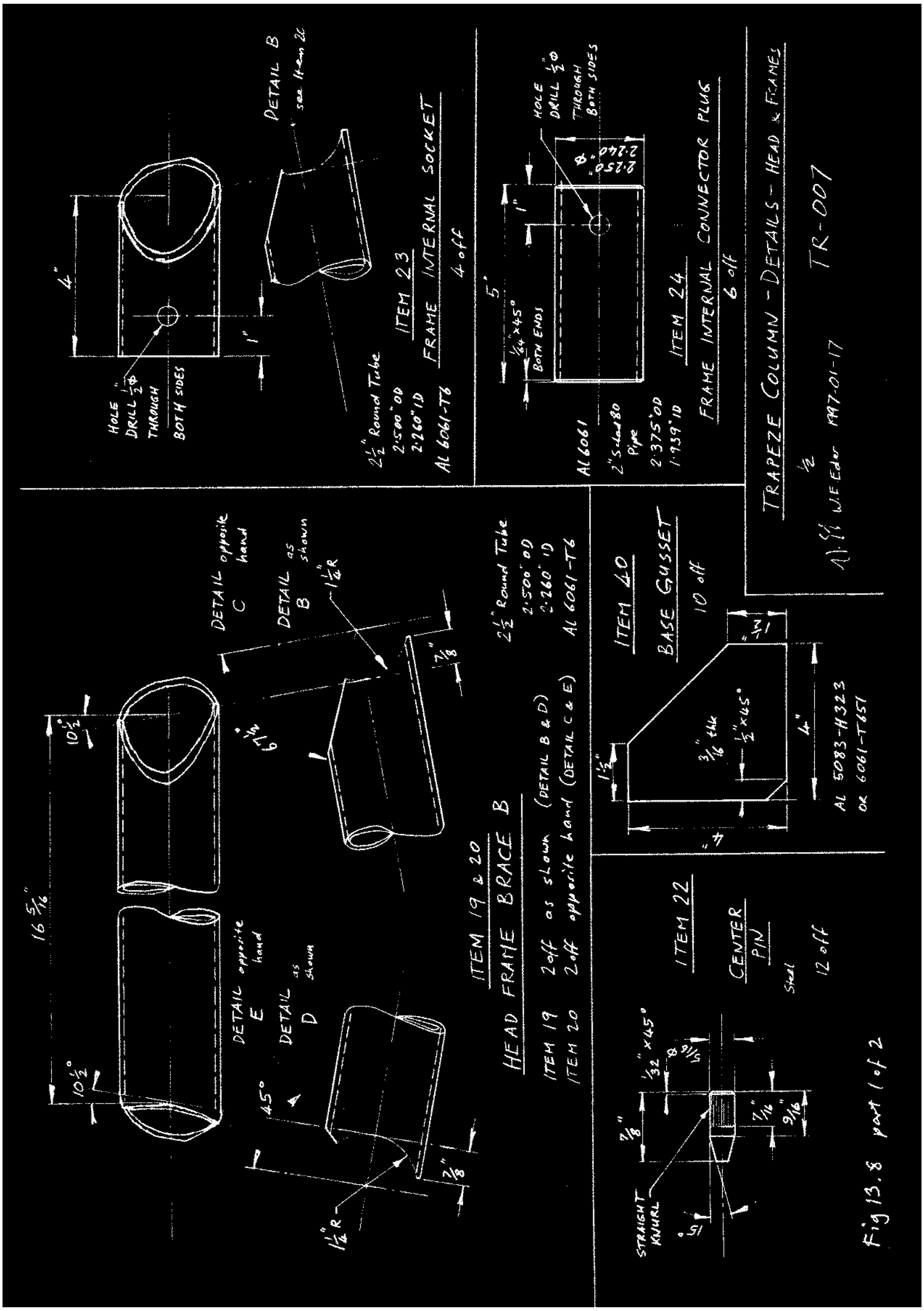



*Figure 5*. Engineering detail drawing with typical geometric features. Source: Eder and Hosnedl (2008).

Design engineering is more constrained than industrial design, because:

(1) A design specification is usually prescribed by a customer or a marketing department, and is often the basis of a legally binding contract for delivery of a desired performance, a transformation process, TrfP;

(2) The relevant engineering sciences must be applied;

(3) Societal norms and regulations (including laws) must be satisfied;

(4) Risks and hazards must be controlled, the existing information must be respected;

(5) Economic considerations apply, e.g., survival and profitability.

Design engineering has a available theory of TS(s) (Hubka & Eder, 1988) and its associated engineering design science (Hubka & Eder, 1996), which suggests several abstract models and representations of structures for transformation processes, TrfPStr(s), and TS(s), TSStr(s), that can be used as tools for establishing requirements, and for verbal, graphical, cognitive, and conceptual modelling of novel or redesigned products (mathematical modelling is well established in the engineering sciences).

In fact, design engineering must consider a wide spectrum of information, and fit into the various cultural schemes applicable to different regions and countries (see Figure 6). This is one of the many challenges facing engineering. Conversely, design engineering influences many of the cultural, social, political, and other environments. The process of implementing any technology (process or tangible object, old or new) almost invariably begins with design engineering.

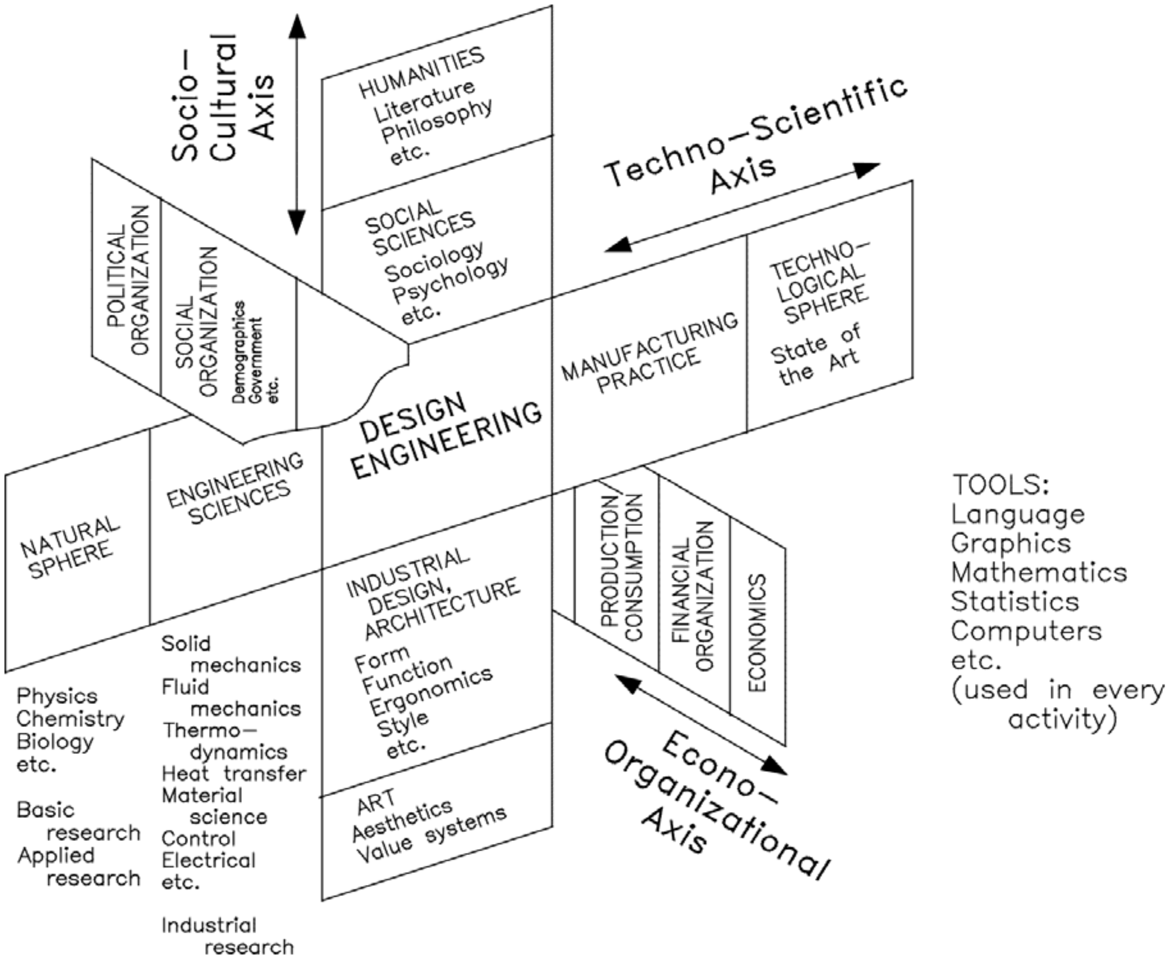



*Figure 6*. Dimensions of design engineering in technology and society. Source: Eder and Hosnedl (2008).

Is a car an engineering product? The steering mechanism, the suspension, the motor and drive train, the instruments, and a whole range of other items internal to the car (and often hidden from view) are certainly engineering products, to which industrial-artistic designers can have little input. Mostly, these items cannot normally be observable for the driver, passenger, or by-stander, they are described by the "mediating" and "elemental design properties" of a TS. Some of the intermediate products are OEM/COTS (original equipment manufacturers, and commercial off-the-shelf) parts (engineering products) manufactured by other organizations, e.g., springs, starter motors, alternators, computers, etc.. Even the interior of doors and other body parts (structural members, stiffeners, etc.) are much more engineering than artistic. The exterior of the body parts (including the enclosed volume of the passenger compartment) is certainly more industrial-artistic, for instance, the arrangement and appearance of the dashboard. Even the arrangement and division of individual body panels are engineered for manufacturability and stiffness—an engineering responsibility. In fact, a car is definitely an engineering product—without the engineering you only have an essentially decorative monument. Without the industrial design, the appearance and appeal of the car may be unsatisfactory, reference the "US Army General Purpose Vehicle (GP)" of the 1940s, the original jeep. Is this a reason why the industrial designer often gets named, but the engineering designers are not ever mentioned, and credit for the engineering items is often given to "science"? In contrast, an electrical power transformer (500 MVA, 110 KV) needs minimal industrial design.

This comparison of artistic *vs.* engineering designers is, of course, extreme and exaggerated, the truth is somewhere in between, many TS need also industrial design, and cooperation is often essential. The comparison is based on the author's personal experience in industry and life—10 years in industry (1951−1961) "on the drawing board" for electrical power transformers and switchgear, vehicles for alpine forestry, and other non-consumer engineering products (Eder, 2011).

## Outline of Theory of (Existing) TS(s)

Figure 7 shows the basic model on which the theory and method are based. This model of the transformation system, TrfS, declares as in Figure 7.

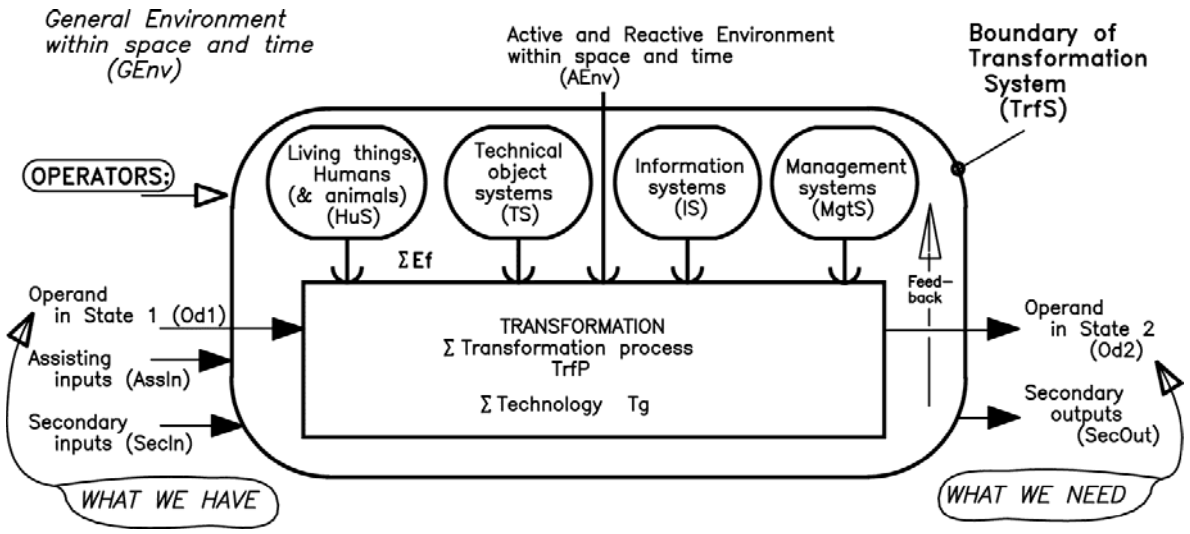



*Figure 7.* General model of a transformation system. Source: Eder and Hosnedl (2008; 2010).

An "operand" (M (materials), E (energy), I (information), and/or L (living things)) in state 1 (Od1) is transformed into state 2 (Od2), using the active and reactive "effects" (in the form of M, E, and/or I) exerted continuously, intermittently, or instantaneously by the "operators" (human systems, TS(s), 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, and I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.

This model, initially proposed in 1974, is now recognized as the prototype for a PSS (product-service-system), recently the focus of research in product development. Hubka's theory and consequently the recommended design methodology (see section 4 of this paper) also includes many other considerations. The operators can be active or reactive in their interaction with each other and in their technology-interaction with the operand. A hand power tool is reactive to its human operator, but active towards the operand. An automotive automatic transmission is mainly active.

The operators of a TrfS can in most cases be regarded as full transformation systems in their own right. For instance, the MgtS (management system) performs its management process, driven by human managers, management TS(s), a management environment, a management information system, and an upper-level management system.

Both the general environment (regional, national, and global) and the active and reactive environment cover physical, chemical, societal, economic, cultural, political, ideological, geographic, ecological, and all other influences directly or indirectly acting on or reacting to the transformation system, its process, and its operators.

The transformation process, TrfP, that is the main purpose of the transformation system, TrfS (and therefore, is the task of the TS as its operator), has a structure of operations and their arrangement or sequencing. The transformation process, TrfP, can take place if (and only if): (1) all operators of the transformation system, TrfS, are in a state of being "operational", they (especially the TS) should be able to operate or be operated, if appropriate inputs are delivered to the operator; (2) an operand in state Od1 is available; and (3) both are brought together in a suitable way, with an appropriate technology. The TrfP must, therefore, be totally external to the operators.

A typical life cycle of a TS is defined as a sequence of TrfS (see Figure 8). For any real TS, each of these seven typical transformation systems represents several to many actual transformations. For education, this life-cycle model helps to explain: (1) the normal operation of an engineering design and manufacture organization; (2) the need for a supply chain to the design and manufacture organization, especially for raw and semi-finished materials for life cycle stage LC4—manufacture; and (3) the need for a sales-distributing-servicing organization and network for the completed TS(s); and several other societal and economic factors.

Various useful structures can be recognized (see Figure 9): (1) transformation process, TrfP(s), and its structure of operations; (2) technology, Tg; (3) TS-function structure, FuStr, a structure of TS-internal and cross-boundary capabilities of operation also adopted in Pahl, Beitz, Feldhusen, and Grote (2007); (4) organ structure, OrgStr, action locations on constructional parts interacting (Pahl et al., 2007) replaces this with "physics"; and (5) constructional structure, CStr, the acting constructional parts—the main emphasis of (Pahl et al., 2007)—for engineering design, this structure is represented (usually graphically (Booker, 1979)) in (e1) preliminary layout, (e2) definitive/dimensional layout, and (e3) detail, assembly, parts-list, etc.. These structures are, of course, closely interrelated, but almost never in a 1:1 relationship.

The TrfP and the TS exhibit properties. These are arranged in classes appropriate to each constituent of the TrfS derived from Figure 7, and the classes are arranged in major groupings of "observable", "mediating", and "elemental design" properties.

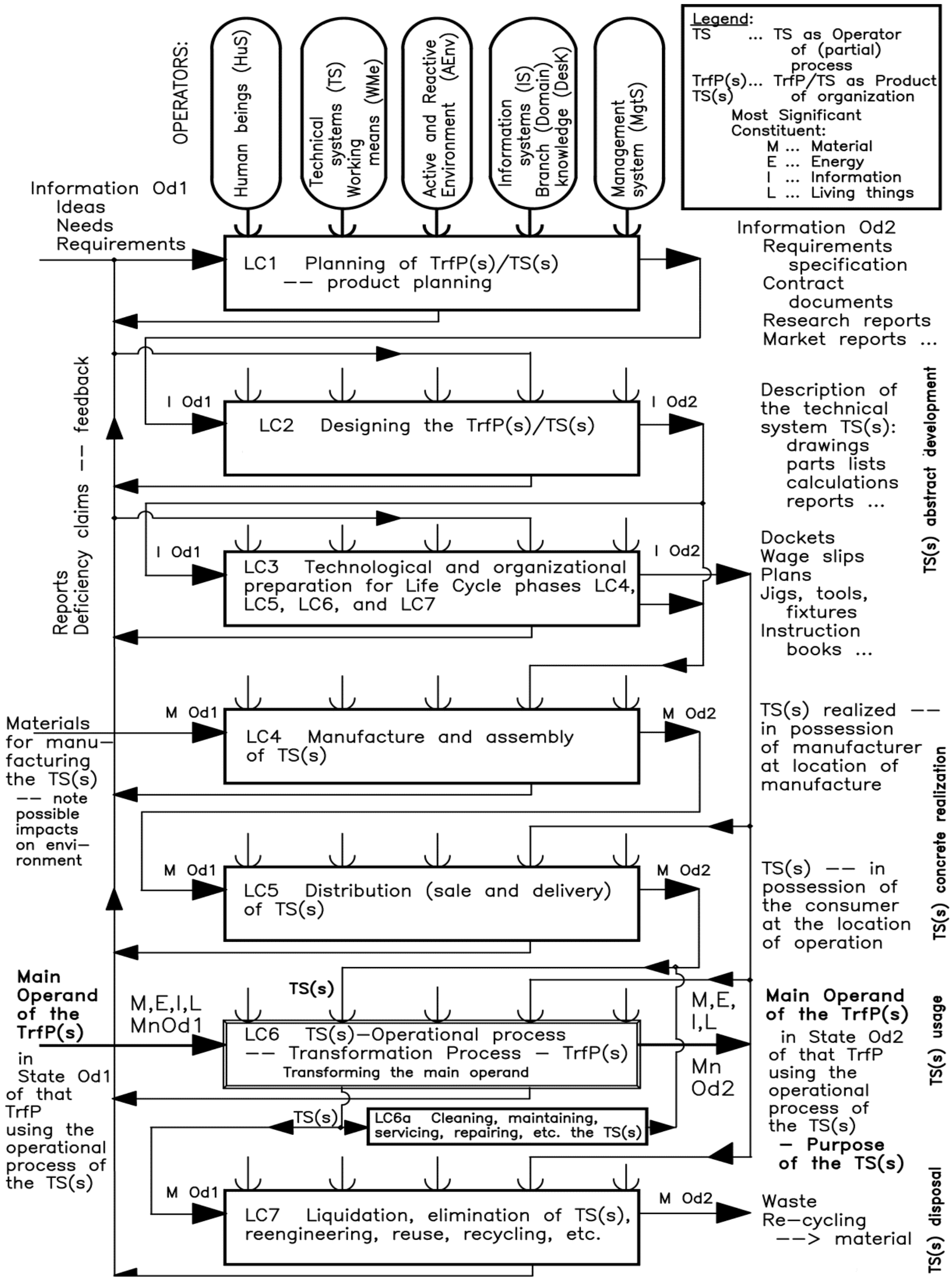



*Figure 8*. Typical life cycle of a TS. Source: Eder and Hosnedl (2008).

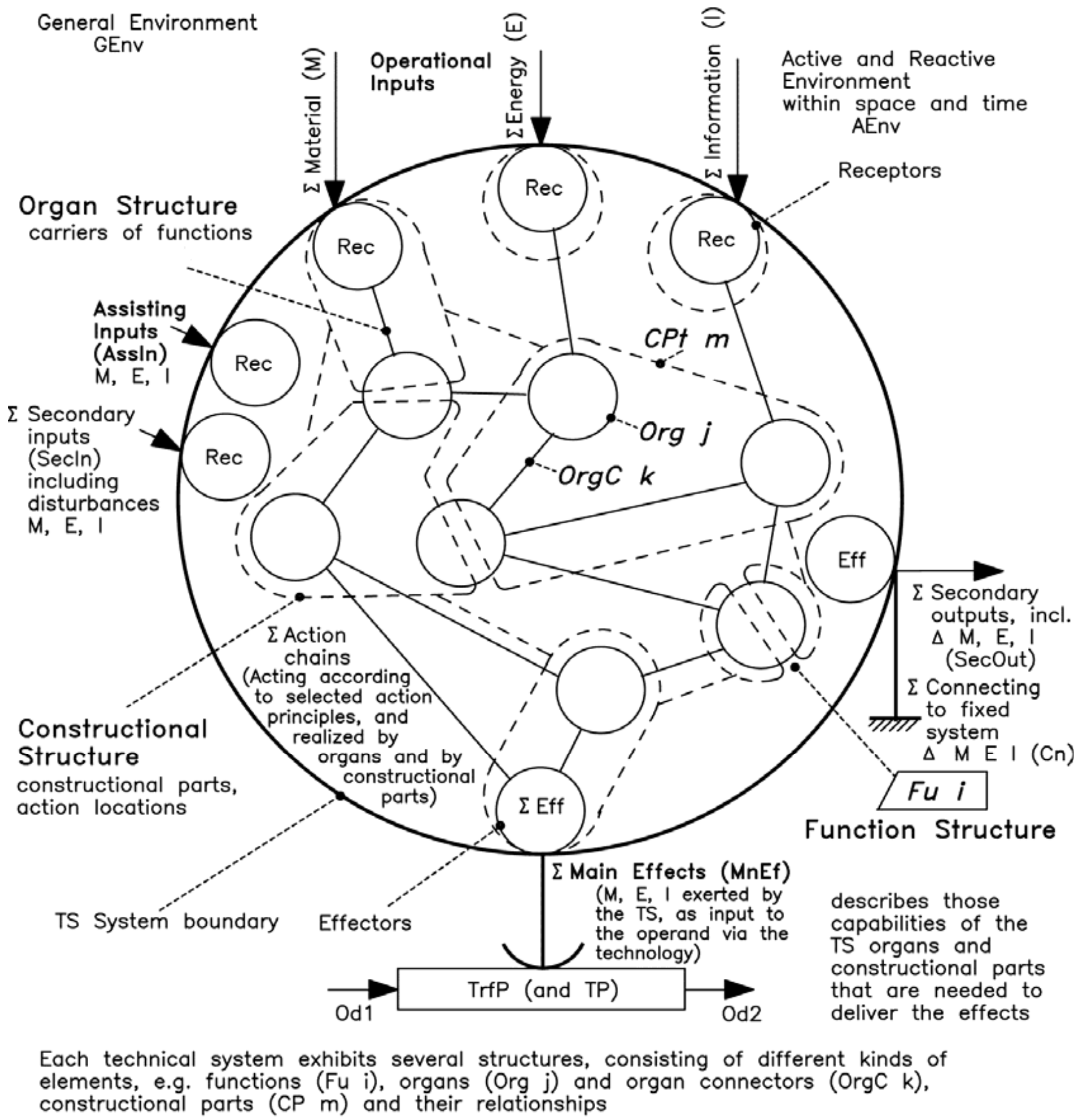



*Figure 9*. Model of a TS—structures. Source: Eder, (2009b); Eder and Hosnedl (2008).

The "states" of TS-properties exist and change among the different states of existence, e.g., various life-cycle phases of a TS(s), and under various operating states, the "duty cycle" of an operational TS: (1) at rest, no operation; (2) during start-up; (3) during normal operation—idling, full-power and part-load, overload, etc., for self-acting operation (automatic), or running and ready to be operated by another operator, e.g., human or another TS; (4) during shut-down, ending an operational state and returning to "at rest" conditions; (5) in fault conditions: (a) internal faults—overload, safe trip-out, breakage, or equivalent; and (b) external faults—damage, wrecking, etc.; (6) during maintenance, repair, testing, etc.; (7) at "life ended"; and (8) any other states. The TS(s) can thus be operational, and even operating, in the absence of the operand of the TrfP.

Further considerations include mode of action, development in time, and other items of interest for engineering design processes.

The models of Hubka's theory are closely interconnected, and have been extended into considerations of engineering education (Eder & Hosnedl, 2008), engineering management (Eder & Hosnedl, 2008; 2010), the design process itself (Eder, 2009b; Eder & Hosnedl, 2008), and others.

## Outline of Engineering Design Methodology

Using the model of Figure 7 as basis, the stages and steps of a novel design process are fully described (Eder & Hosnedl, 2008; 2010). The most important design operations (using the letter/number scheme from the full listing) are summarized as:

(1) Task defining:

(P1) establish a design specification for the required system, a list of requirements; partly clarified also in (Pahl et al. 2007);

(P2) establish a plan and timeline for design engineering;

(2) Conceptualizing:

(P3a) from the desirable and required output (operand in state Od2), establish a suitable transformation process TrfP(s);

(P3.1.1) if needed, establish the appropriate input (operand in state Od1);

(P3.1.2) decide which of the operations in the TrfP(s) will be performed by TS(s), alone or in mutual cooperation with other operators; and which TS(s) (or parts of them) need to be designed;

(P3.1.3) establish a technology, Tg, (structure, with alternatives) for that transformation operation, and therefore the effects (as outputs) needed from the TS(s);

(P3b) establish what the TS(s) needs to be able to do (its internal and cross-boundary functions, with alternatives);

(P4) establish what organs (function-carriers in principle and their structure, with alternatives) can perform these functions. These organs can be found mainly in prior art, especially the machine elements, in a revised arrangement as proposed in (Weber & Vajna, 1997; Eder, 2004, 2005);

(3) Embodying/laying out and detailing:

(P5a) establish what constructional parts and their arrangement are needed, in sketch-outline, in rough layout, with alternatives;

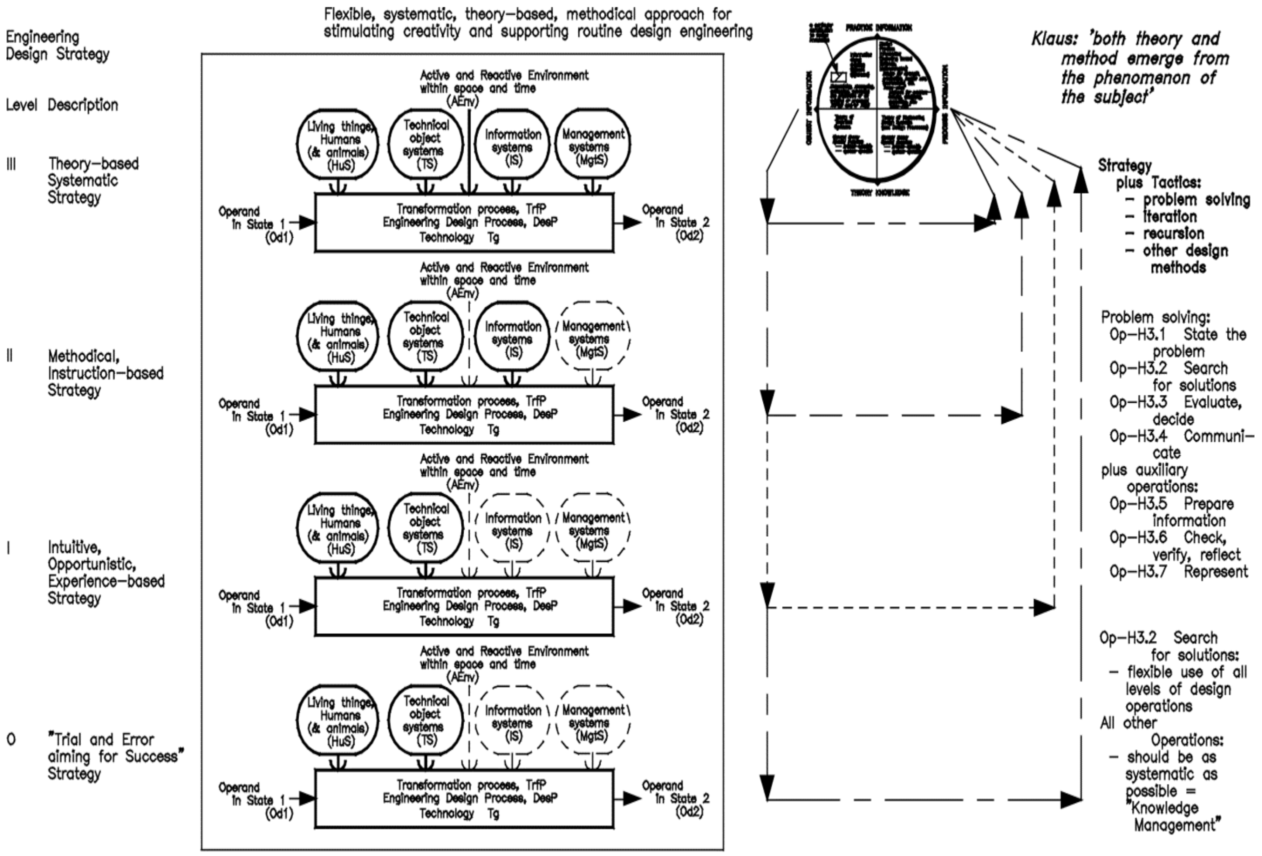
(P5b) establish what constructional parts are needed, in dimensional-definitive layout, with alternatives;

(P6) establish what constructional parts are needed, in detail and assembly drawings, with alternatives.

Adaptation for redesign problems (probably about 95% of all design engineering tasks) proceeds through stages (P1) and (P2) above, then analyzes from (P6) or (P5b) to (P4), and/or to (P3b) to reverse-engineer these structures, modify them according to the new requirements, and use the stages in the usual order to complete the redesign. These headings for novel and re-design processes are used in the case examples mentioned below.

The classes of properties of existing TrfP(s) and the TS(s), and the classes of properties related to the life-cycle phases LC1–LC3 (the manufacturing organization), lead directly to the list of primary and secondary classes of requirements that are the basis for step (P1), establishing a design specification (Eder & Hosnedl, 2010).

Hubka's engineering design methodology allows and encourages the engineering designers to generate a wider range of solution proposals at various levels of abstraction from which to select—one of the hallmarks of creativity. They should also use serendipity, opportunism, spontaneity, and pragmatic and "industry best practice" methods (see Figure 10). The apparent linearity of this procedure is only a broad approximation (Müller, 1990), parts of the TrfP(s) and/or TS(s) will inevitably be at different stages of concretization, and of different difficulty, routine to safety (Müller, 1990). 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, essential operations include iterative working—repeating a part of the design process with enhanced information to improve the solution proposals, within a stage or step of the engineering design process, and between stages and recursive working, breaking the larger problem into smaller ones, sub-problems and/or sub-systems, to recursively solve (e.g., using the same systematic design methodology) and re-combine, using analysis and synthesis (Eder, 2008). In the process, the perceived or assumed TS-boundary is frequently redefined to restrict and focus, or expand, the designer's "window" of observation (Nevala, 2005).




(Adapted from PowerPoint 5.9.2011, slides 33 & 34, copyright Stanislav Hosnedl, U. of West Bohemia)

*Figure 10*. Strategies for design engineering and problem-solving.

CAD (computer-aided design) can effectively be used in stages (P5a), (P5b), and (P6)—in earlier stages, the representations are often too abstract for computer graphic processing (including semantics and implications), but mathematical analysis and simulation in earlier stages are often useful, called CAE (computer-aided engineering).

Stage (P3b), development of a TS-function structure, reveals a special position. For instance, the TS-cross-boundary functions can include such non-obvious functions as "present a pleasing appearance to the TS(s)" or "allow easy and ergonomic operation by a human"—a direct connection to the need for involvement of industrial design. Also, the TS-internal functions can include "adjust" or "regulate and control" with respect to some TS-properties—This can be solved mechanically, electrically, fluidically, electronically (plus software), etc., and can provide a direct connection to mechatronics.

## Problem-Solving

Superimposed on the systematic approach to design engineering is a sub-process of problem-solving, frequently applied in every design stage (see Figure 11).

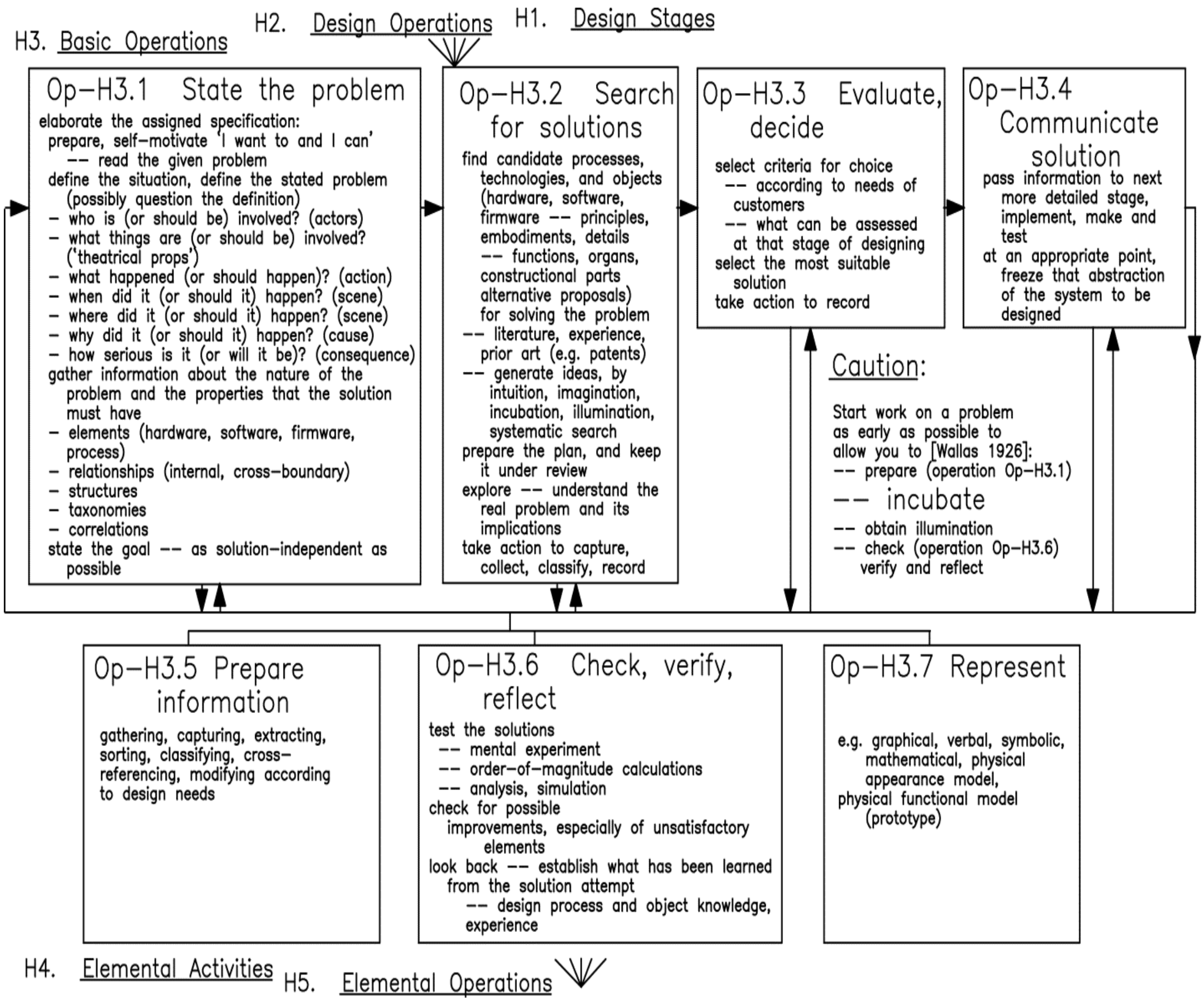



*Figure 11*. Basic operations—problem-solving in the engineering design process. Source: Gregory (1966); Koen (2003); Schön (1983; 1987); Wales et al. (1986a; 1986b); Wallas (1926); Hubka and Eder (1996); Eder and Hosnedl (2008; 2010).

Iterative working is related to TrfP/TS properties, requirements, and both heuristic and analytical use of the mediating properties, the engineering sciences, and the problem solving cycle (Eder, 2008, 2009a; Weber, 2005, 2008) (see Figures 11 & 12). Observable and mediating properties of future "existing" TrfP(s)/TS(s) can be analytically determined from the established elemental design properties, giving a reproducible result. The inversion of this procedure, synthesis, is indeterminate, each required observable property is influenced by many different elemental design properties that therefore need to be iteratively established to approach the desired state of the observable property. Analysis is in essence a one-to-one transformation, convergence to one solution. Synthesis goes far beyond a reversal of analysis, it is almost always a transformation that deals with alternative means and arrangements, involving divergence as well as convergence, a one-to-many (or few-to-many) transformation. Synthesizing, as part of Op-H3.2 "Search for Solutions", is the more difficult kind of action (Eder, 2008; 2009a). Figure 12 constitutes proof that iterative procedure is a theoretical necessity in EDS, and a practical necessity in design engineering. This insight is also of educational importance, and demonstrates the need for perseverance.

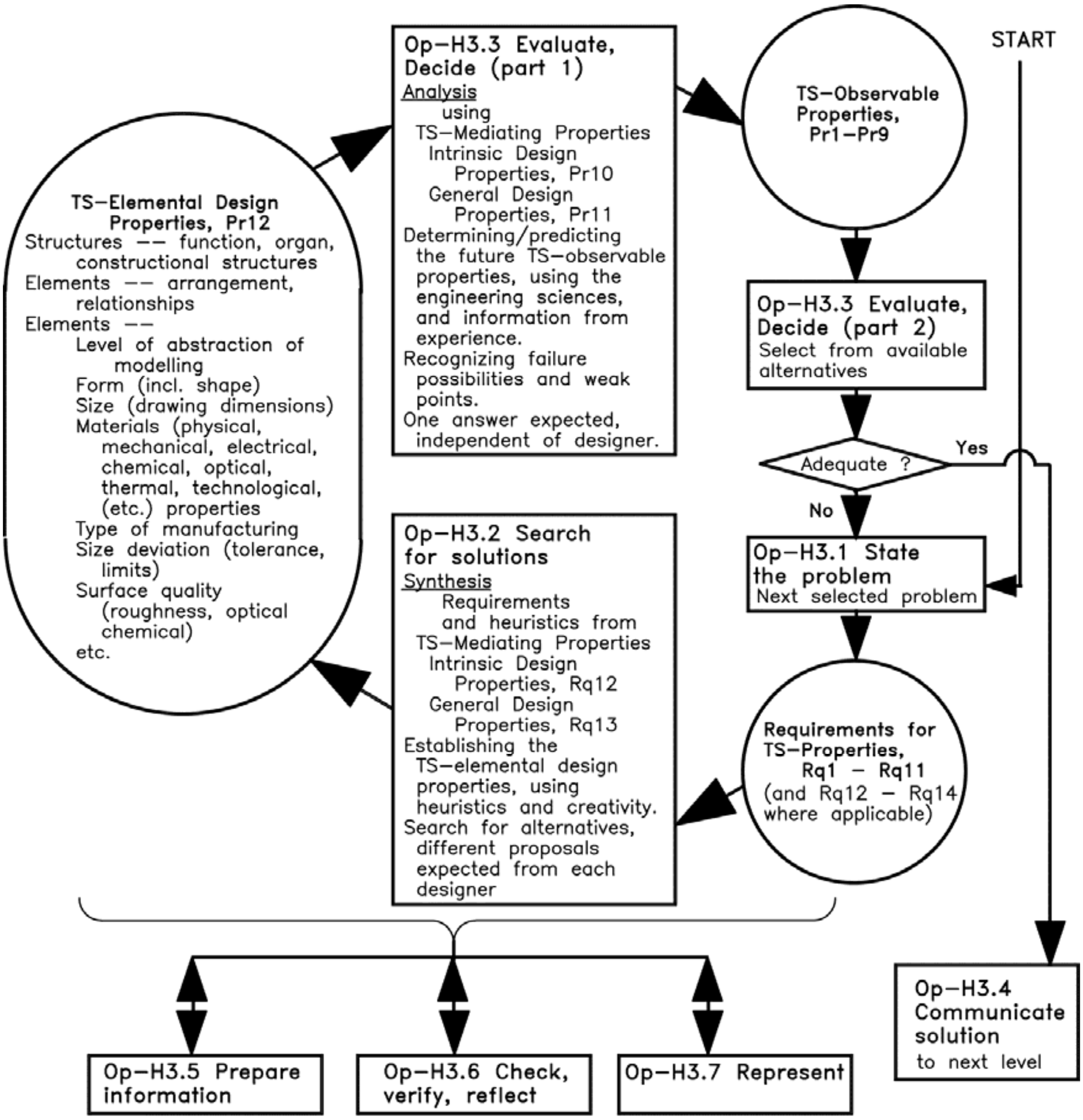



*Figure 12.* Main relationships between problem-solving, and mediating: Elemental design and observable properties. Source: Weber (2008); Eder and Hosnedl (2010).

## Application of Computers for Engineering Design

In the era known as B.C. (before computers), the process of design engineering (especially for industrial equipment) had an expected output in the form of detail drawings (see Figure 4) of all constructional parts prepared on translucent tracing paper (or cloth) to relevant national standards, including tolerances, surface finish, raw materials, etc., under consideration of likely manufacturing methods, delivered to manufacturing as "blue-prints". In addition, assembly drawings, parts lists, assembly and adjustment instructions, usage instructions, repair instructions, etc., were prepared. Checking of these documents was always performed to ensure accuracy and completeness, avoidance of undesired redundancy, conformity to standards, tolerancing, etc..

For a novel product (usage process, TrfP, and/or TS), a senior engineering designer (usually a university graduate) would conceptualize, produce sketch layouts, perform preliminary calculations of expected performance and capabilities, and produce a final layout to correct sizes. Technologists would then produce the detail drawings, and a check-assembly—in a drawing office equipped with drafting machines. Specialized checking personnel would perform the drawing check. For redesign, similar tasks needed to be completed, but with much less conceptualizing.

This was obvious at the time, but needs to be repeated for the current situation in which much of the previous information has been lost. Engineering designers can obviously still design without computers. Even when designing with computers, engineering designers often need to do some preparation work (e.g., conceptualizing) without computer assistance. Computers cannot design completely independently, generally computers are tools that can assist designing (Hubka & Andreasen, 1983). Some parts of designing may be automated. Computers help to solve problems, contribute to improvements in TrfP(s) and/or TS(s), optimize quality, improve and perfect the parameters of the design process, and record the results of designing.

Acceptance by industry of early 2D- and 3D- CAD applications (due to their limitations) caused a drastic change in detail-design procedures. CAD applications could not be used for layouts, most of them are still not suitable. Detail design of individual constructional parts tended to be allocated to different engineering designers on their “own computer seat”. Coordination among these specialists became difficult, and many errors resulted. The latest versions of some CAD applications are starting to allow “inheritance” of some properties from one constructional part to another, and automated check assembly (see Figure 13) (Eder & Hosnedl, 2008; 2010).

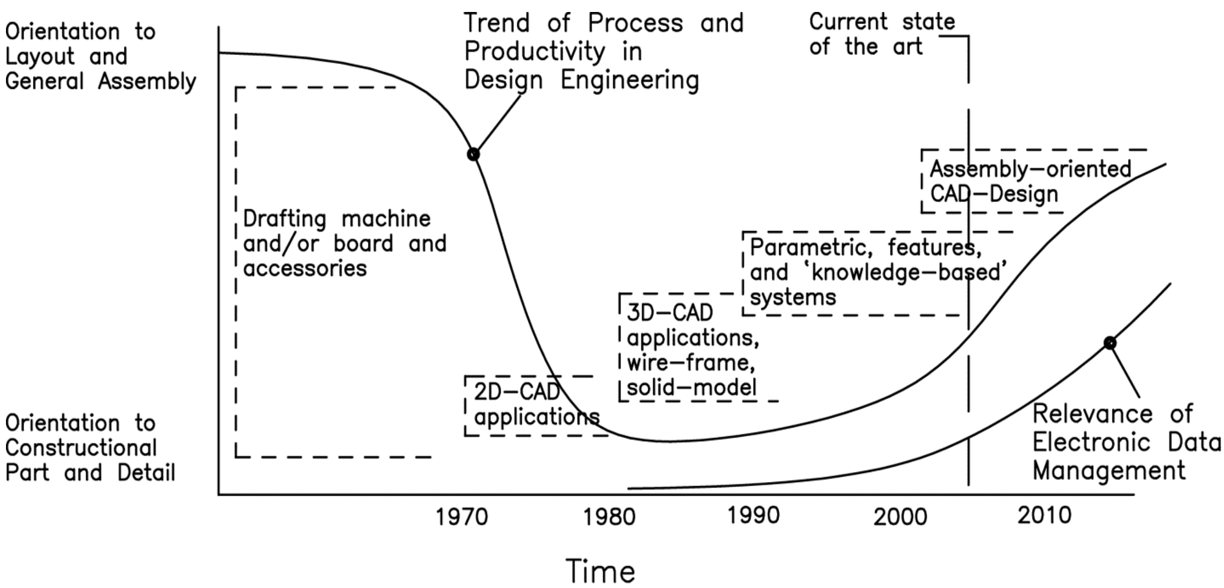



*Figure 13*. Progress of computer support of representation for design engineering. Source: Eder and Hosnedl (2008, 2010; as cited in Burr et al., 2005, with permission).

## Supporting Evidence

Evidence exists for the efficacy of the Pahl et al. (2007) and VDI (verein deutscher ingenieure—Association of german engineers) design methodologies (Birkhofer, 2011). The reason for comparing Pahl et al. (2007) is that these are the most comprehensive methodologies to date, but Pahl/Beitz do not fully articulate their theory. Hubka’s theories and methodology have been compared with several other approaches and design methods (Eder & Hosnedl, 2008, 2010; Eder, 2012c), almost all of which are expanded sub-sets of the Hubka methodology. Hubka and Eder's (1988) methodology is derived from his theory of TS(s)—Hubka and Eder strictly differentiated between the theory of (existing) TS(s), and engineering design methodology for future transformation systems for which the process (not only manufacturing) and the TT operator are to be designed (and from which appropriate methods, models, and parts can be selected). Either pragmatic and practical experience, or a theory can be a basis for proposing a method—Theory and method are not interchangeable. For instance, Pahl/Beitz (Pahl et al., 2007) used experience, Hubka and Eder (1988) used a theoretical approach based on experience.

Students' learning design engineering at times need a good example of procedure for novel design engineering. As shown in (Eder, 2009b), such a fully systematic procedure is only necessary in limited situations, when an engineering designer is faced with an unfamiliar and non-routine situation. Systematic design engineering as a procedure is the heuristic-strategic use of a theory to guide the design process—engineering design science (Eder & Hosnedl, 2008, 2010; Hubka & Eder, 1996) is recommended as guiding theory. Methodical design engineering as a procedure is the heuristic use of newly developed and established methods within the engineering design process, including theory-based and "industry best practice", strategic and tactical, formalized and intuitive methods. Systematic and methodical procedures have a substantial overlap, but are not co-incident. The full procedure should be learned, such that the student can select appropriate parts for other applications.

Creativity (Eder, 1996) is usually characterized by a wide search for solutions, especially those that are innovative. This search can be supported by the recommended systematic and methodical approach. All generated alternatives should be kept on record, to allow re-tracing and recovery from subsequent detection of a better alternative. Each step in the overall procedure should be concluded by selecting the most appropriate (one or two) solutions for further processing, in order to control a tendency towards "combinatorial complexity".

The primary purpose of the case examples that follow the Hubka's design methodology is to present teaching examples for procedural application of the recommended engineering design method, especially for the conceptualizing phases of the engineering design process, that students and practitioners can follow and study to help learn the scope of the method and its models and show that the systematic method can be made to work. This purpose has been applied in courses at the ETH (Eidgenössische Technische Hochschule) by Dr. Vladimir Hubka (1976−2000), at The Royal Military College of Canada (1981−2006) by the author, and at the University of West Bohemia (1990−present) by Professor Stanislav Hosnedl, who has applied the theory and method for all levels of higher education and for industry consultations. A secondary purpose was to verify and validate the theory and its models, check for correctness, illustrate and document the theories, procedures, methods, and models that can be used within systematic design engineering, and to show up deficiencies which were corrected in the theories, models, and methods. The emphasis in all case studies was on the engineering design procedure and use of the models, the chosen TS(s) in several case studies were not necessarily optimal.

The systematic procedure must be adapted to the problem. The cases demonstrate that an engineering designer can idiosyncratically interpret the models to suit the problem, and develop information in consultation with a sponsor. Opinions will vary about whether a requirement should be stated in a particular class of properties, or would be appropriate in a different class.

Hubka's engineering design methodology is demonstrated by the scope and variety of our case examples. Care should be exercised when reading these case examples, they were not intended to show a plausible optimal resulting proposed TS(s), and some of these cases are doubtful in that respect. The initials indicate the originator: VH (Vladimir Hubka), MMA (Mogens Myrup Andreasen), WEE (W. Ernst Eder), and SH (Stanislav Hosnedl).

The first case study, systematic design according to the state of the theory and method at that time, appeared in a machine vice (VH) (Hubka, 1976). Hubka and Eder (1992a) included the second case study—a welding positioner (VH). The next three case examples, also systematic, were published in 1981 in German—a riveting fixture (VH), a milling jig (VH), and a powder-coating machine (MMA)—the first two were systematic, the third took a more industrial-artistic design approach. Another set was published in 1983 in German—a P-V-T-experiment (WEE), a hand winding machine for tapes (VH), and a tea-brewing machine (MMA)—again, the third took an industrial-artistic design approach. An English edition of case studies was finally published in (Hubka, Andreasen, & Eder, 1988), after revisions requested by the publisher, and included the existing six case studies first published in German language, plus two new items—a wave-powered bilge pump for small boats (MMA), and an oil drain valve (VH)—and again the bilge pump only loosely followed the systematic method.

Three further case studies were published in (Eder & Hosnedl, 2008)—the tea machine revised to current systematic procedures showing enhanced engineering information (WEE); re-design of a water valve (WEE—the first demonstration of systematic re-design); and an electro-static smoke-gas-dust precipitator, with rapper for dust removal (WEE—the first demonstration of treatment for sub-problems) (Eder, 2009c). The most recent book in this sequence (Eder & Hosnedl, 2010) contains three new case studies, a portable frame for static trapeze display demonstrations (WEE) (Eder, 2010) which was built and used, re-design of an automotive oil pump (WEE—the second demonstration of re-design) (Eder & Heffernan, 2009), and a hospital intensive care bed (SH—the second demonstration of treatment for sub-problems)—the latter shows cooperation between industrial design and design engineering (Hosnedl et al., 2008), and is one of many projects operated in cooperation with Czech industry. Hosnedl et al. (2008) has also introduced the Hubka theories and methods into industrial use. Two new cases were presented at the International Design Conference DESIGN 2012, Dubrovnik (WEE) (Eder, 2012a; 2012b), both sub-systems from the Caravan Stage Barge (2010) which has been in operation in Canadian and USA coastal waters, and now in the Mediterranean, since 1995. The Canadian Engineering Education Association 3rd Annual Conference 2012 received two further case examples (WEE), a sub-system of the Caravan Stage Barge (Eder, 2012e), and an auxiliary sub-system for a wind tunnel balance (Eder, 2012f).

For engineering education, a consequence of the discussions in this paper is that students, as novices in design engineering, should be introduced to the theory of TS(s) (Eder & Hosnedl, 2008, 2010; Hubka & Eder, 1988, 1996) in suitable stages throughout the (three-, four-, or five- year undergraduate) curriculum, should be encouraged to study several worked case examples, and should practice the models and steps of the theory-based design methodology, preferably on projects close to engineering practice. In a "capstone experience", such as a final-year project, they can then apply their intuition, trial-and-error procedures, and other methods, coordinated by systematic design methods, to the specific project to learn a more independent way of approaching projects, and still be aware of systematic project management (see Figure 10).

## Closure

Depending on the nature of the (tangible or process) product, it is obvious that both engineering designers and artistic-industrial designers must in many cases work together. Their duties are partially overlapping. The theory of TS(s) (Eder & Hosnedl, 2008, 2010; Hubka & Eder, 1988, 1996) is partially applicable to industrial design (McAloone & Bey, 2010) of the five cases presented in this booklet from Technical University of Denmark, only one refers to an engineering product, but exclusively with the external observable properties. It is also partially applicable to architecture.

Nevertheless, engineering design is distinct from other forms of designing, and this needs to be acknowledged, especially for engineering education.

## References

Birkhofer, H. (2011). From design practice to design science: The evolution of a career in design methodology research. *Journal of Engineering Design, 22*(5), 333-359.

Booker, P. J. (1979). *History of engineering drawing*. London: Northgate.

Burr, H., Vielhaber, M., Deubel, T., Weber, C., & Haasis, S. (2005). Cax/engineering data management integration: Enabler for methodical benefits in the design process. *Journal of Engineering Design, 16*(4), 385-398.

*Caravan Stage Barge*. (2010). Retrieved from http://www.caravanstage.org

Eder, W. E. (1996). WDK 24—EDC—Engineering design and creativity. Proceedings of the *Workshop EDC*, Pilsen, Czech Republic, November 1995, Zürich, Heurista.

Eder, W. E. (2004). Machine elements û integration of some proposals. Proceedings of *AEDS 2004 Workshop, The Design Society—AEDS-SIG*, November 11-12, 2004, Pilsen, Czech Republic. Retrieved from http://www.kks.zcu.cz/aeds

Eder, W. E. (2005). Machine elements û revision and outlook for design education. Proceedings of *The Second CDEN International Conference*, University of Calgary, Alberta, July 18-19, 2005, Kananaskis Resort, Alberta.

Eder, W. E. (2008). Aspects of analysis and synthesis in design engineering. Proceedings of *Canadian Design Engineering Network CDEN 08*, Halifax, N. S., July 27-29, 2008.

Eder, W. E. (2009a). Analysis, synthesis and problem solving in design engineering. Proceedings of *International Conference on Engineering Design, ICED 09* (pp. 2-23), August 24-27, 2009, Stanford University, Stanford, California, USA, Session W3 SIG-AEDS.

Eder, W. E. (2009b). Why systematic design engineering? Proceedings of *the 6th Symposium on International Design and Design Education, DEC 6*, August 30-September 2, 2009, San Diego, California, USA, New York, ASME, paper number DETC2009-86067.

Eder, W. E. (2009c). Case study in systematic design engineering—Smoke gas dust precipitation paper. Proceedings of *the 6th Symposium on International Design and Design Education, DEC 6*, August 30-September 2, 2009, San Diego, California, USA, ASME DETC2009-86069.

Eder, W. E. (2010). Case study in systematic design engineering—Trapeze demonstration rig. Proceedings of *the 7th Symposium on International Design and Design Education, DEC 7*, August 15-18, 2010, Montreal, Quebec, Canada, ASME DETC2010-28065.

Eder, W. E. (2011). Engineering design science and theory of technical systems—Legacy of Vladimir Hubka. *Journal of Engineering Design, 22*(5), 361-385.

Eder, W. E. (2012a). Case example in systematic design engineering—Leeboard mounting. Proceedings of *International Design Conference, DESIGN 2012*, Dubrovnik, Croatia, May 21-24, 2012, FMENA, Zagreb.

Eder, W. E. (2012b). Case example in systematic design engineering—Propeller shaft bearing arrangement. Proceedings of *International Design Conference, DESIGN 2012*, Dubrovnik, Croatia, May 21-24, 2012, FMENA, Zagreb.

Eder, W. E. (2012c). *Comparison of several design theories and methods with the legacy of Vladimir Hubka*. Retrieved from http://www.designsociety.org

Eder, W. E. (2012d). Engineering design *vs.* artistic design—A discussion. Proceedings of *Canadian Engineering Education Association CEEA 2012 Conference*, June 17-20, 2012, University of Manitoba, Winnipeg, Manitoba.

Eder, W. E. (2012e). Case study in systematic design engineering—Bow thruster covers. Proceedings of *Canadian Engineering Education Association CEEA 2012 Conference*, June 17-20, 2012, University of Manitoba, Winnipeg, Manitoba.

Eder, W. E. (2012f). Case study in systematic design engineering—Wind tunnel balance model support. Proceedings of *Canadian Engineering Education Association CEEA 2012 Conference*, June 17-20, 2012, University of Manitoba, Winnipeg, Manitoba.

Eder, W. E., & Heffernan, P. J. (2009). A case study in systematic and methodical design engineering. Proceedings of *CDEN/C2C2 Conference 2009*, July 27-29, 2009, McMaster University, Hamilton, Ontario.

Eder, W. E., & Hosnedl, S. (2008). *Design engineering: A manual for enhanced creativity*. Boca Raton, Florida: CRC-Press.

Eder, W. E., & Hosnedl, S. (2010). *Introduction to design engineering—Systematic creativity and management*. Leiden, Netherlands: CRC-Press/Balkema.

Flurscheim, C. H. (1983). *Industrial design in engineering: A marriage of techniques*. London: The Design Council and Berlin/Heidelberg: Springer-Verlag.

Green, W. S., & Jordan, P. W. (2002). *Pleasure with products: Beyond usability*. Boca Raton: CRC-Press.

Gregory, S. A. (1966). Design science. In S. A. Gregory (Ed.), *The design method* (pp. 323-330). London: Butterworths.

Hales, C. (1991). *Analysis of the engineering design process in an industrial context*. Winetka, Illinois: Gants Hill Publ.

Hosnedl, S., Srp, Z., & Dvorak, J. (2008). Cooperation of engineering and industrial designers on industrial projects. Proceedings of *the 10th International Design Conference* (pp. 1227-1234), FMENA, Zagreb, DESIGN 2008.

Howard, T. (2011). *The design society newsletter*. Lyngby, Denmark: Technical University of Denmark.

Hubka, V. (1976). *Theory of design processes* (in German). Berlin: Springer-Verlag.

Hubka, V. (1982). *Principles of engineering design—General procedural model of designing* (W.E. Eder trans.)**.** Zürich: Heurista.

Hubka, V., & Andreasen, M. M. (1983). WDK 10: CAD, design methods—Konstruktionsmethoden. Proceedings of *ICED 83 Copenhagen* (Vols. 2). Zürich: Heurista.

Hubka, V., Andreasen, M. M., & Eder, W. E. (1988). *Practical studies in systematic design*. London: Butterworths.

Hubka, V., & Eder, W. E. (1988). *Theory of technical systems: A total concept theory for engineering design*. New York: Springer- Verlag.

Hubka, V., & Eder, W. E. (1992a). *Engineering design*. Zürich: Heurista.

Hubka, V., & Eder, W. E. (1992b). *Introduction to design science*. Berlin, Springer-Verlag.

Hubka, V., & Eder, W. E. (1996). *Design science: Introduction to the needs, scope and organization of engineering design knowledge*. London: Springer-Verlag.

Julier, G. (2000). *The culture of design*. London: Sage Publ.

Klaus, G. (1965). *Cybernetics in philosophical view* (4th ed.). Berlin: Dietz Verlag.

Klaus, G. (1969). *Dictionary of cybernetics*. Frankfurt: Fischer. (in German)

Koen, B. V. (2003). *Discussion of the method: Conducting the engineer's approach to problem solving*. New York: Oxford University Press

McAloone, T., & Bey, N. (2010). *Environmental improvement through product development, DTU management engineering, engineering design and product development*. Technical University of Denmark, Lyngby, Denmark.

McMasters, J. H. (2004). The biomechanics of flight: Many possible solutions looking for problems. *International Journal of Engineering Education, 20*(3), 398-404.

Müller, J. (1990). *Working methods of engineering sciences B systematics, heuristics, creativity* (in German). Berlin: Springer-Verlag.

Nevala, K. (2005). Content-based design engineering thinking (Academic dissertation, University of Jyväskalä). Finland, Jyväskalä: University Printing House. Retrieved from http://cc.oulu.fi/~nevala

Pahl, G., Beitz, W., Feldhusen, J., & Grote, H. K. (2007). *Engineering design* (3 ed., K. Wallace, & L. Blessing Ed. and trans.). London: Springer-Verlag.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. Basic Books, New York.

Schön, D. A. (1987). *Educating the reflective practitioner: Towards a new design for teaching and learning in the professions*. San Francisco: Jossey-Bass.

Tjalve, E. (1979). *A short course in industrial design*. London: Newnes-Butterworths.

Tjalve, E., Andreasen, M. M., & Schmidt, F. F. (1979). *Engineering graphic modelling*. London: Newnes-Butterworths.

Wales, C. E., Nardi, A. H., & Stager, R. A. (1986a). *Professional decision-making*. Morgantown, West Virginia: Center for Guided Design (West Virginia University).

Wales, C. E., Nardi, A., & Stager, R. (1986b). *Thinking skills: Making a choice*. Morgantown, West Virginia: Center for Guided Design (West Virginia University).

Wallas, G. (1926). *The art of thought.* London: Cape.

Weber, C. (2005). *CPM/PDD—An extended theoretical approach to modelling products and product development processes* (pp. 11-28). In Proc. Ph.D., November 7-9, 2005, Srni, Czech Republic.

Weber, C. (2008). How to derive application-specific design methodologies. In D. Marjanovic (Ed.), *Proceeding of 10th International Design Conference—DESIGN* (pp. 69-80). FMENA, Zagreb, 2008.

Weber, C., & Vajna, S. (1997). A new approach to design elements (machine elements). In A. Riitahuhta (Ed.), *WDK 25—Proceeding of ICED 97* (Vol. 3, pp. 685-690). Tampere: Tampere University.