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Theory of Technical Systems – Educational Tool for Engineering

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Abstract Hubka's theory of technical systems (TTS) is briefly outlined. It describes commonalities in all engineering devices, whatever their physical principles of action. This theory is based on a general transformation system (TrfS), which can be used to show engineering in the contexts of society, economics and historic developments. The life cycle of technical systems consists of seven major TrfS, each consisting of further product-specific TrfS. From this TTS, Hubka derived a methodology as voluntary guide to systematic design engineering, for application when an intuitive approach based on experience proves to be ineffective. This approach to engineering design is distinct from more artistic designing. The methodology applies to novel design problems, and to re-design. Some educational aspects are developed to show the range of knowledge needed for engineering designing. Operators of a TrfS are also TrfS – illustrated by observing the management systems in the TS-life cycle. Connections to the general economy, and its financial consequences, are shown on TS-life cycle LC4 with its supply chain, and on LC6 and LC6A, with the need to service the operating product, and to establish supply and distribution chains. Transformation systems are hierarchical, each TrfS is a sub-system to a more complex system – each sub-system can be viewed as a TrfS, leading to a repeating use of the same design methodology for sub-systems. Invention and innovation in TrfS can be shown (historically) to alter the state of society, beneficially and adversely. A comparison with a different methodology is mentioned.

Keywords Engineering Product, Economy, Society

1. Introduction

Both Dr Vladimir Hubka and the author have spent several years (25 and 10 respectively) in engineering industry, designing technical equipment, before joining the teaching staff of a University engineering department. Having collaborated with Dr Hubka since 1980, and retired several years ago, the author has reached the conclusion that the theory of technical systems as developed by Hubka has a much wider scope than originally envisaged by him. As a result, this paper sets out to explore some aspects of this wider scope, and show use of TTS as a pedagogical tool for engineering education, and for general education.

Hubka's development of a (non-mathematical) theory of technical systems (TTS) [1-4] started around 1965, and has continued to date. It describes in summary and detail what is common to all engineering devices (products with a substantial engineering content, technical systems, TS), independent of their physical principles of action. This theory is based on the concept of a general transformation system (TrfS), figure 1. This TrfS includes a transformation process (TrfP), the intended purpose for its manufacture and use, and its five typical active and reactive operators – human systems (HuS), technical systems (TS), environment (AEnv), information systems (IS), and management systems (MgtS), all five interacting to delivering effects to the TrfP, to transform an operand (Od) within that TrfP external to the operators. The operand may consist of material, energy, information or living matter (e.g animals or humans), and can be transformed in its (internal) structure, its (external) form, its location, and/or its time dimension. For humans as operand, these transformations may be interpreted as an internal operation, an amputation, travel, and/or rest in bed.

TTS includes a typical TS-life cycle, consisting of seven typical stages, see figure 2 – each life-cycle stage is a transformation system in its own right. In reality, each of these life-cycle TrfS actually consists of several to many TrfS that are product-specific. That technical system that is intended as the tangible product of a manufacturing organization is labelled TS(s) – the subject of interest, the product of that organization – to distinguish it from all other TS. Generally, during life cycle stages LC6 (and LC6A-and LC7) the TS(s) is in the hands of the user, performing (when needed) its intended tasks for that user.

TTS also includes several other propositions that are less interesting for this paper, e.g. properties (observable, and design properties that are generated in the design/drawing office) and structures of transformation processes (TrfP) and technical systems (TS), inputs and outputs of TrfP (Od) and its operators (material, energy and information), developments in time, etc.

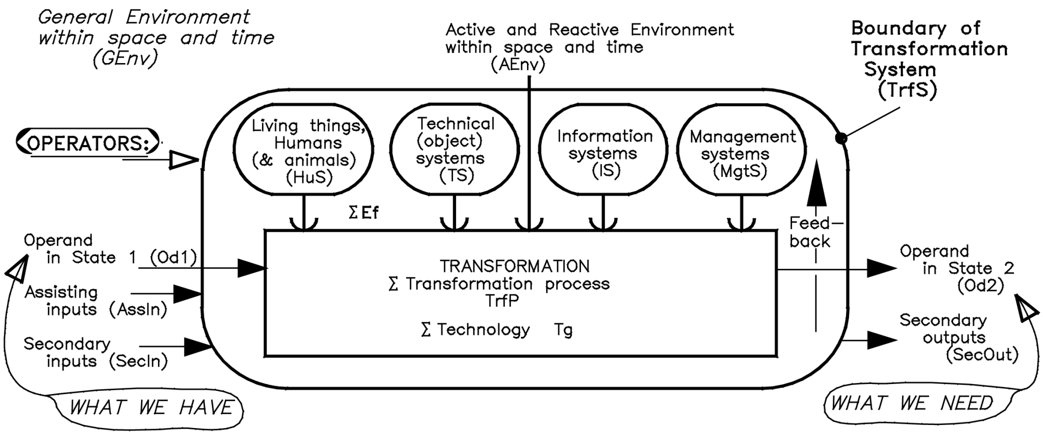

Figure 1. General Model of a Transformation System [1-4]

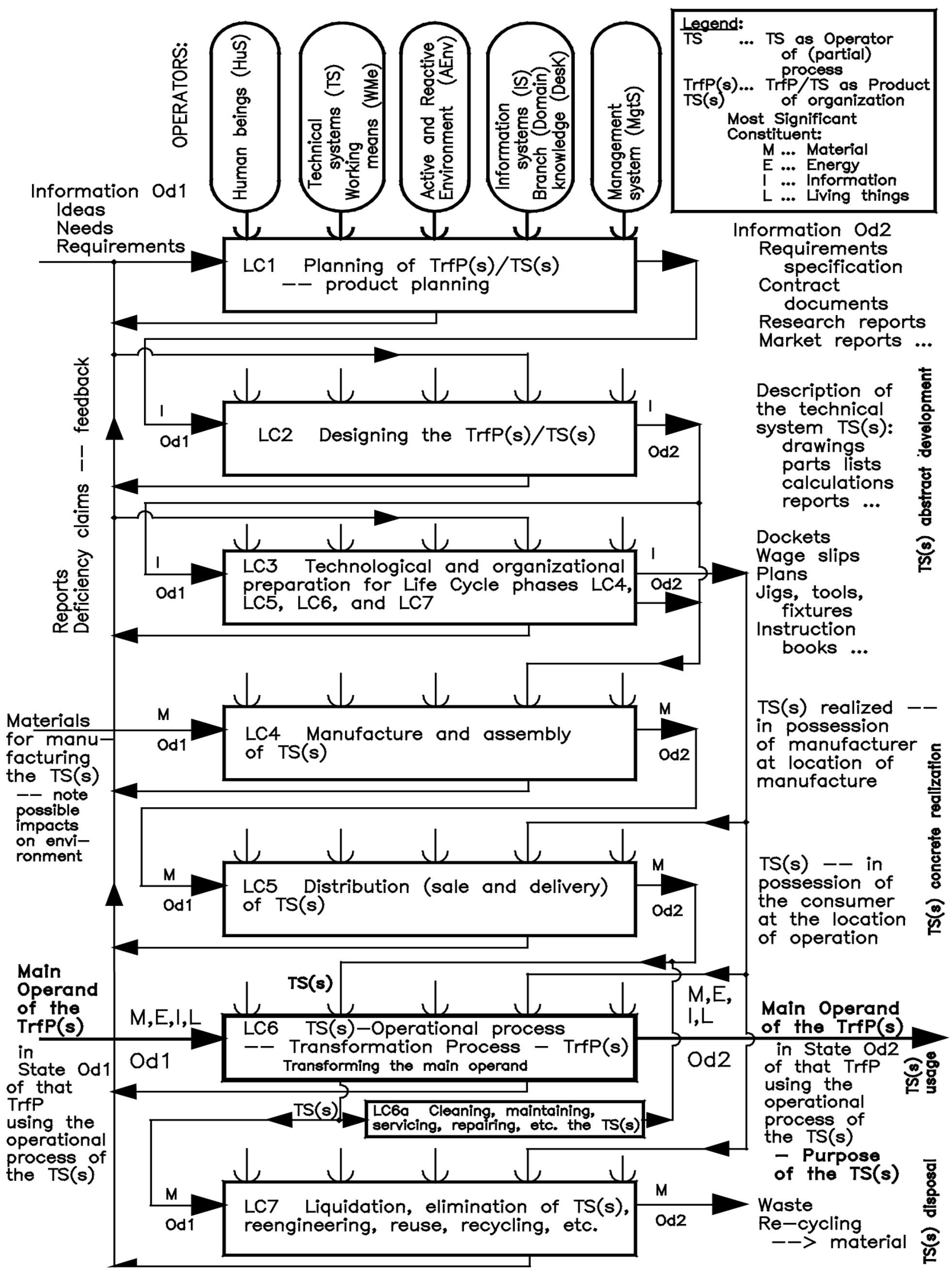

Figure 2. General Model of the Life Cycle of a Technical System [1-4]

Table 1. Characteristics of Designing [11,12]

Objectives, Design Conditions	Design Engineering	Artistic – Industrial / Architectural
The object to be designed, or the existing object	Transformation Process and/or Technical System *Primary: function* *Performing a task*	Tangible product *Primary: appearance, functionality*
Representation and analysis of the object as designed – the "captured design intent"	Preparing for TS(s) manufac- ture, assembly, distribution, etc., AI, CAD/CAM	Rendering for presentation and display, product range decisions
Design Process (for the object), Methodology, generating the "design intent"	Theories of designing, Eng. Design Science, formal design methods	Intuitive, collaborative, interactive designing
Properties of the object as output of designing	Design properties on engineering drawings to make observable object	Observable properties to achieve customer satisfaction
Design phenomenology	Empirical, experimental and implementation studies	Protocol studies on designers designing
Responsibilities	Professional, ethics, reliability, safety, enterprise, stakeholders	Organization, stakeholders (contract responsibility)
Location	Design/Drawing office	Studio
Team size	Small to very large	Individual to small
Design direction	"Inside outwards"	"Outside (to in)"

2. Designing

From this TTS, Hubka derived a fully systematic methodology as voluntary guide to design engineering [2-4]. This methodology includes recommendations for application to novel design problems, and to re-design, see section 4. It is augmented by case examples (24 to date), mainly involving simple engineering products (technical systems), but also more complex ones, novel and re-design problems, and problems which can be sub-divided into a hierarchy of sub-problems e.g. [5-10]. This approach to engineering design is specific to engineering designing, and is distinct from more artistic designing, see table 1.

If a product is intended to be visually attractive and user-friendly [12], its form (especially its observable shape) is important – a task of *artistic designing* for industrial designers, architects and similar professionals. Industrial design [13-20] (in the English interpretation) tends to be primary for consumer products and durables, emphasizes the artistic elements, appearance, ergonomics, marketing, customer appeal [12], satisfaction, and other observable properties of a product. This includes color, line, shape, form, pattern, texture, proportion, juxtaposition, emotional reactions [12], etc. The task given to or chosen by industrial designers is usually specified in rough terms. The mainly *intuitive* design process with emphasis on 'creativity' and judgment, is used in industrial design (artistic product design), architecture, typographic design, fine art, etc.

If a tangible product should work and fulfill a purpose by helping to perform a transformation process (e.g. mechanical, electrical, chemical, etc.), its *functioning and operation* are important – a task for *design engineering (designing)* within or across the engineering disciplines. Anticipating and analyzing this capability for operation is a role of the engineering sciences. If a product is to be made (especially in quantity), its design for manufacturability is important – a task which often involves production engineering – designing and making production equipment, jigs and tools, work-stations, assembly lines, etc. Other aspects of the life of a tangible product may require involvement of different specialists, e.g. for industrial design, human factors, disposal and liquidation at the end of its life.

The outcome of design engineering is a full set of *manufacturing instructions* – detail and assembly drawings to scale, including tolerances and raw material specifications [21] for each constructional part, including instructions for assembly, adjustment, testing, use, spare parts, etc. These instructions were traditionally produced manually in a design/drawing office, using drafting machines. These drawings, in more recent times, are likely to be computer resident. 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 using the engineering sciences – coordinated with physics and the other "pure" sciences.

Both types of designers must usually work together, preferably as a team, to create an attractive and economically viable product for human society. If during the design phase the artistic designer of a product decides to alter the appearance, the engineering design team must often re-design the working interior to fit into the available space.

3. Some Educational Aspects

The model of a transformation system can be used effectively within (engineering) education to show engineering in the wider contexts of society, economics and historic developments. Design engineering is a central factor in the context of social, cultural, economic, organizational, and technical activity, see figure 3. This also illustrates the range of topics with which an engineer should be familiar, at least in outline.

Each operator of a TrfS is itself a TrfS. This is verified especially by observing the operator management system (MgtS) in the TS-life cycle, see figure 4 right side. Each of the management systems performs its management (transformation) process (TrfP), under the effects of its operators – management human system, management technical systems, active and reactive environment, management information system, and higher-level management system.

The connection to the general economy, and its financial consequences, is shown in figure 4 (left side). Considering TS-life cycle LC4, any manufacturing performed by this organization needs to establish its supply chain, the TrfS to the left of LC4, to obtain raw materials, part-finished goods (e.g. rolled steel sections), COTS (commercial off-the-shelf products), OEM parts (products for original equipment manufacturers), components subject to (national or international) standards, (e.g. rolling contact bearings) etc. – these classes of supplies are not exclusive, e.g. a standard part may also be a COTS or OEM item. Such components are somewhat specialized, they need expertise not generally available, or are obtained cheaper by allowing outside suppliers to design, manufacture and deliver them. Engineering designers need to understand how such individual COTS operate and behave, what limitations they exhibit, how they should be handled (in manufacture, assembly and adjustment, maintenance, use), etc. They are generally thought of as simple to complex machine elements, in a revised arrangement as proposed by Weber [23-25], including modes of action such as hydraulic, compressible fluid dynamic, electrical, electronic, chemical (e.g. combustion), etc. Although analysis by applying established theories of the engineering sciences (and costing, etc,) is important, designing these technical artifacts also need synthesis [26], judgment and creativity. The outside suppliers of such components may be financially and corporately tied to the subject manufacturer, or be independent and deliver similar products to competing manufacturers.

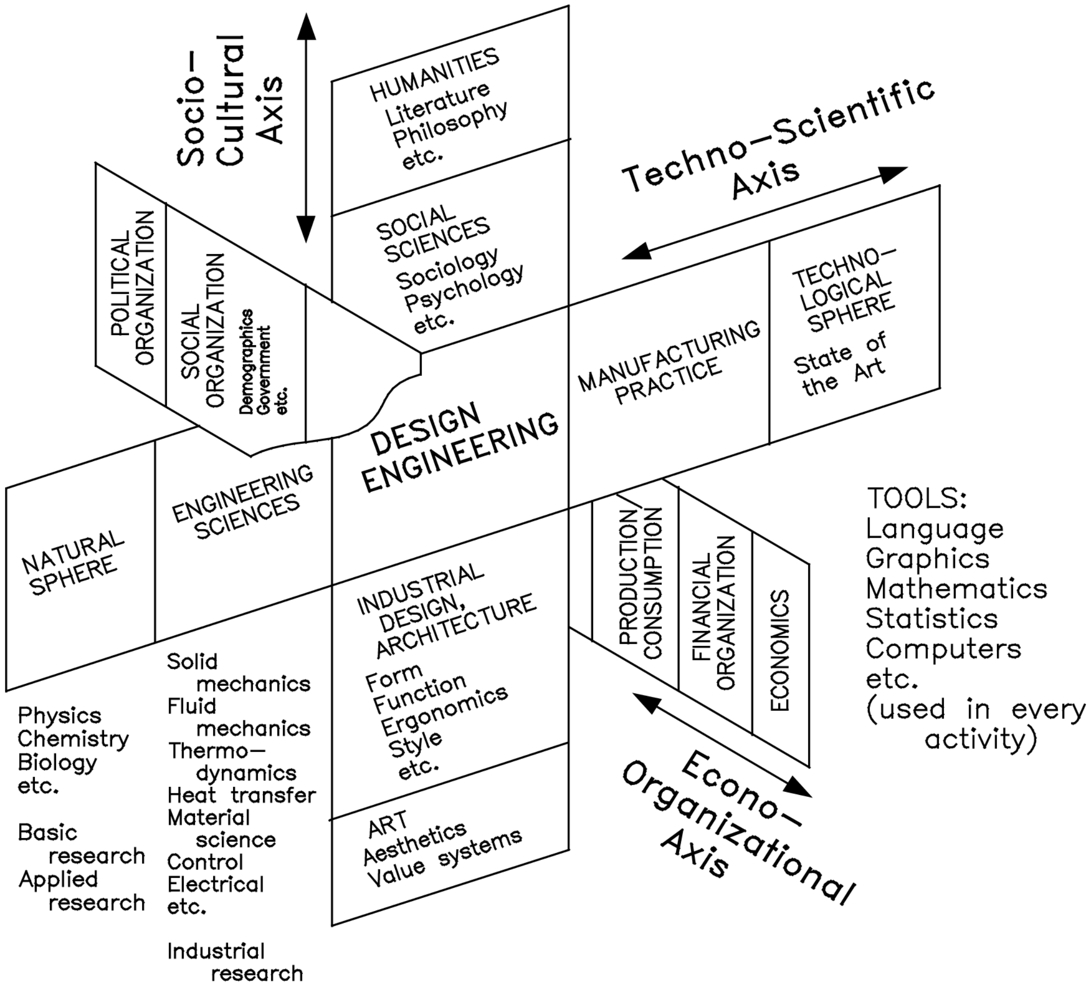

Figure 3. Role of Design Engineering in Context (Adapted from [22])

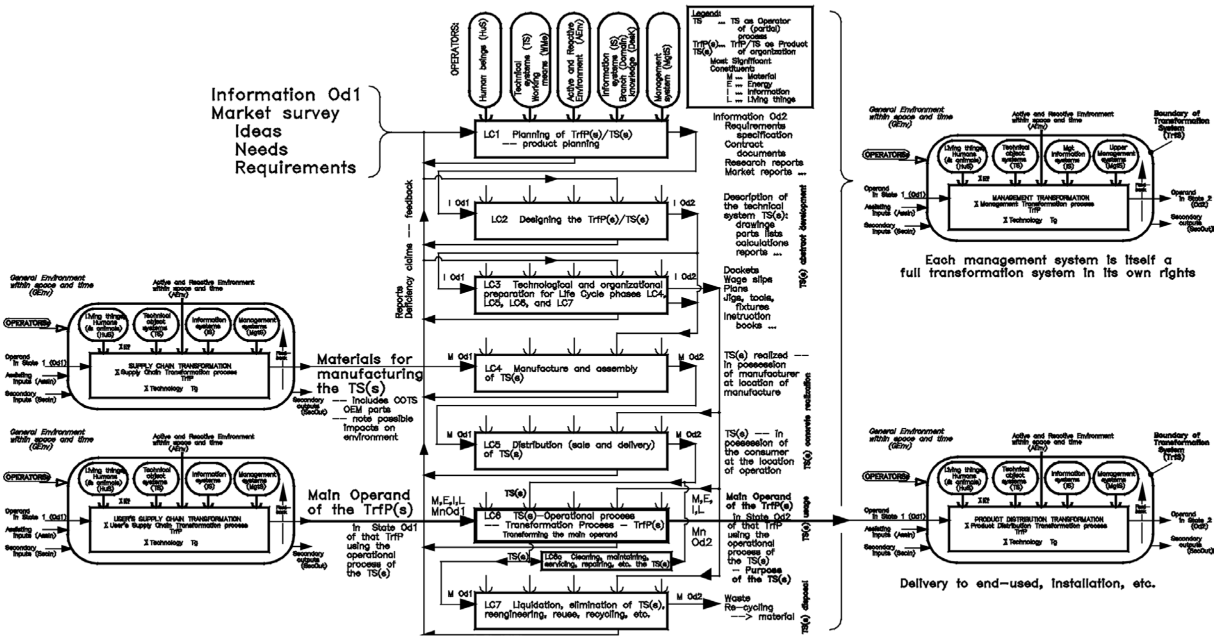

Figure 4. Extended Model of the Life Cycle of a Technical System

Life cycle stages LC6 and LC6A show the need to service the operating product. This includes regular maintenance (e.g. oil change), repairs, upgrading additions or modifications to the TS(s) in the hands of the user. These tasks can be performed by the user of the TS(s), by the owner, by a specialized service organization, or by the subject manufacturer in a Product-Service-System relationship – e.g. the subject manufacturer can retain ownership, perform the LC6A tasks, and lease the TS(s) to the user.

TS-life cycle stage LC6 indicates a need to establish a supply chain for inputs to the user's transformation process, and a distribution chain for the user's products – each shown in figure 4 as a TrfS left and right of the TS-life cycle. These auxiliary user TrfS are, of course, specific to the product that the user of the TS(s) makes (note: this may be trivial, e.g for an 'electric shaver' in the hands of its user, the supply chain is a male chin, the distribution chain is a waste bin for the shavings).

Transformation systems are hierarchical. Each sub-system can be viewed as a TrfS in its own right, leading to a repeating use of the same design methodology for sub-systems. Each TrfS is a sub-system to a more complex system. Invention and innovation in TrfS (and especially in TS) can be shown (historically) to alter the state of society, beneficially and adversely, more or less. Inventions and innovations produce improvements in existing TS, or occasionally result in novel TS. They represent progress for human society, historical observation that is useful for education.

The formalization available in TTS [1] has been found useful as insight for reorganizing the product management a of large-scale IT (information technology) organization [27].

All this is general knowledge to many people, although they probably are not aware of this level of formalization. It cannot normally be assumed as general knowledge, it is probably new to engineering and other students in education, especially in the wider contexts. This exposition also highlights a noteworthy difference between engineering and science: (a) in their aims – research to obtain knowledge *vs* designing of new products, (b) in their procedures – search for novelty *vs* achieving acceptable performance, safety and reliability, (c) in their required range of knowing and awareness – depth in the subject region *vs* wide-ranging awareness, see also [28-31].

4. Systematic Design Engineering

One of the distinguishing features between science and engineering design is that engineers are often involved in designing engineering products (technical systems) that should operate to the satisfaction of the user, be economical, be environmentally acceptable, be socially and politically acceptable, safe, etc. (Scientists at times need to design technical systems for their own research, but usually not under time and financial constraints, and without a need to satisfy customers, as for industry.) In the past, designing for engineering artifacts has been learned by an apprenticeship approach. Little guidance was available for those critical situations when experience and heuristic guidelines led to an impasse. Since the 1960's, various design methods have been proposed, either from experience (e.g. Pahl and Beitz 1977 [32]), or on the basis of experience and a descriptive (non-mathematical) theory (e.g. Hubka [1-4].

Engineering design can range from routine (e.g. a large power transformer within an organization manufacturing such power transformers to order as their commercial product) to very novel (e.g. the first nuclear reactor for a power station, the first in-cylinder gasoline fuel injector).

Innovations in most products usually occur within a smaller sub-system of the product (e.g. the change from carburation to fuel injection for gasoline engines).

In routine engineering design, the human mind has the experience and knowing available to perform the design work without thinking (consciously) about the process and procedures to be used. When the design work becomes non-routine (e.g. in a critical situation), the designer needs (immediate) advice on how to proceed to increase his/her probability of resolving the existing situation.

During innovations, a critical situation may arise, when the engineering designer has no guidelines about the methods or procedures that may help him/her to overcome that situation. This is when a well-founded a systematic methodology can help [33], by providing models, tools, methods and procedures to assist understanding and creativity, especially in times of need – but these should preferably be learned in a benign environment before any attempt to use them in a critical situation, a suitable task for education.

Returning to figure 1, for an existing engineering artifact, each of the elements in the general model of the TrfS can be recognized and analyzed (determined, although one or more may have the quantity and/or value of zero – an automatic transmission for a car has no direct effects delivered by the human system).

Synthesis, a component of engineering designing, is not a simple reversal of analysis [26]. Yet a logical progression of steps can be derived from figure 1 to assist novel designing:

(a) establish a design specification, a structured list of requirements for the future system,

(b) establish a time-line for the task,

(c) establish a suitable transformation process (TrfP) and its structure of operations – with alternatives,

(d) establish what effects (Ef) are needed to drive the technologies of each operation – with alternatives,

(e) establish the TS-internal and cross-boundary functions (capabilities of organs and organ groups – and their structure) capable of delivering the effects – with alternatives, see figure 5,

(f) establish which TS-organs (contact locations between constructional parts – and their structure) can realize these functions – with alternatives, usually helped by a morphological matrix,

(g) establish what constructional parts can realize the chosen organ structure – with alternatives,

(h) establish the details of these constructional parts.

Noteworthy is the difference in terminology between analysis and synthesis. In analysis we typically determine and recognize what exists – a convergent mental activity [34]. In synthesis we work towards establishing alternative solution proposals, and selecting the ones thought to be the most likely to succeed, to develop a proposal that we think is likely to perform the future task – a divergent mental activity. This procedure is illustrated in our case examples, e.g. [5-10]

Redesign also starts with (a) establish a design specification, a structured list of requirements for the future system, including the desired alterations. It then typically continues: (Rg) analyze the organs and organ groups from the constructional structure, (Re) formulate the TS-functions and their structure, (e) change the TS-function structure to accord with the new requirements, and continue with the steps (f), (g), and (h) as for novel design.

This sequence for novel designing or for re-designing cannot be performed in this apparently linear fashion – both iterative working, and sub-dividing the problem and recombining (recursive working) are essential operations. In each step of the design process, additional activities need to be performed, described by the model of problem-solving in Hubka's approach [1-4], augmented by recent insights by Weber [35].

5. Problem Solving

A group of frequently repeated basic operations is contained in each and all these activities of section 3. Mostly they are implicitly contained in the whole procedure and also in individual steps. Four basic operations – defining the (sub-)problem, searching for solutions, evaluating and deciding, and communicating the proposed solution – are an invariable sequence (but not rigidly in that order). They are supported by the results of the subsidiary operations of providing and preparing information, verifying, and representing. This cycle of four operations forms a repetitive set of activities, and usually starts from the search for solutions or from the definition of the problem. Figure 6 shows these operations with added suggestions for procedure, taken from various sources.

The usual term for such a procedure for problem solving, in this general and unequivocal formulation, is an 'algorithm' – although for problem solving the algorithm must be prescriptive, i.e. voluntary, adaptable and flexible. In practice, such procedures are mostly not visible, they run sub-consciously (in the mind) in a routine fashion at low mental energy [42]. Such a formalized process should be introduced in general (and engineering) education, as soon as the students are sufficiently mature, to clarify and reinforce the informal and intuitive problem solving to which they have been induced, thus providing a fall-back procedure for when they reach a critical situation of potential failure. Problem solving can be recognized as an iterative approach to a solution, by repeated application of the step-sequence. Quoting Samuel Beckett (1906-1989): "No matter. Try again. Fail again. Fail better" ("Worstward Ho", Richmond: Calder Publ., 1984).

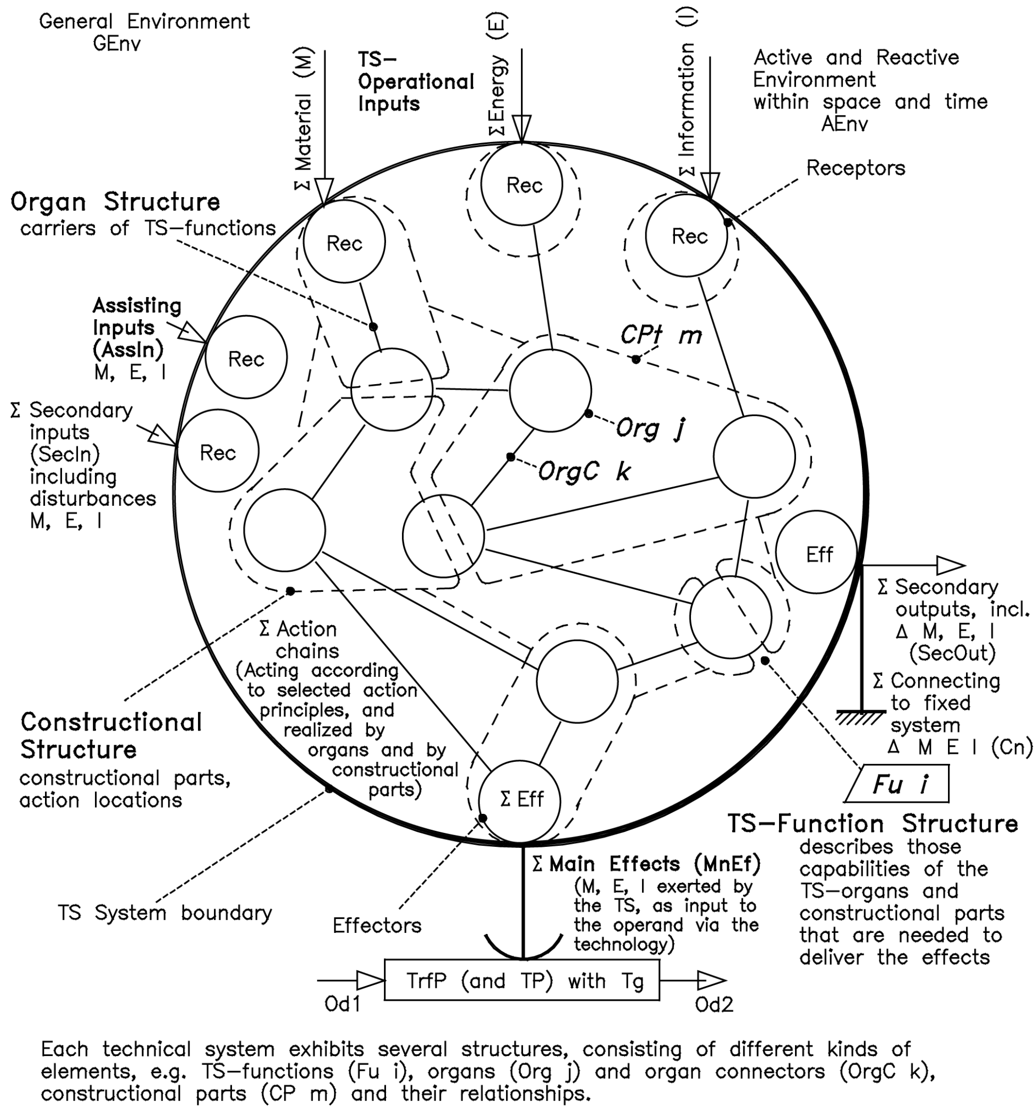

Figure 5. Structures of Technical Systems [1-4]

6. Comparison Hubka – Pahl/Beitz

The methodology developed by Pahl and Beitz [32] (and largely adopted by VDI – Verein deutscher Ingenieure, Association of German Engineers), first edition published four year after the first book by Hubka, was derived directly (as a design methodology) and pragmatically from the engineering design experience of the authors, and is firmly based in Mechanical Engineering. This engineering design methodology is well described for the later embodiment detailed stages, with ample advice for many aspects of layout and detail. The descriptive (non-mathematical) theory underpinning this Pahl-Beitz design methodology is not spelled out, and tends to be somewhat rudimentary, with little attempt at completeness and comprehensive applicability for all engineering products – technical systems. The methodology needs enhancement in the early stages of conceptualizing and embodiment-in-principle, especially for a novel product or a radical innovation .

The highest abstraction recognized by Pahl-Beitz is the 'function structure', a structure consisting of inter-related functions. A 'function' is defined as the capability for doing something (simple to complex), and is formulated in a verb or verb phrase combined with a noun or noun phrase (as in Hubka). In Pahl and Beitz, there is no differentiation between a TrfP and a TS-internal or cross-boundary function, and no mention of a necessary technology (Tg), as shown by Hubka [1-4]. A main purpose function (as defined by Pahl and Beitz) needs to be recognized, which is subjected to 'function decomposition' to recognize the sub-functions and (eventually) elemental functions which cannot be further decomposed, see figure 7. Few methodical tools or guidelines are offered for this decomposition.

The overall design process is illustrated as in figure 8. It is noteworthy that sub-processes such as 'evaluating' and 'deciding' are only implied, and that 'searching for solutions' is specifically mentioned as step 3, but only in the context of 'solutions in principle' – Hubka [2-4] includes these activities in the problem solving cycle, see section 4 and figure 6.

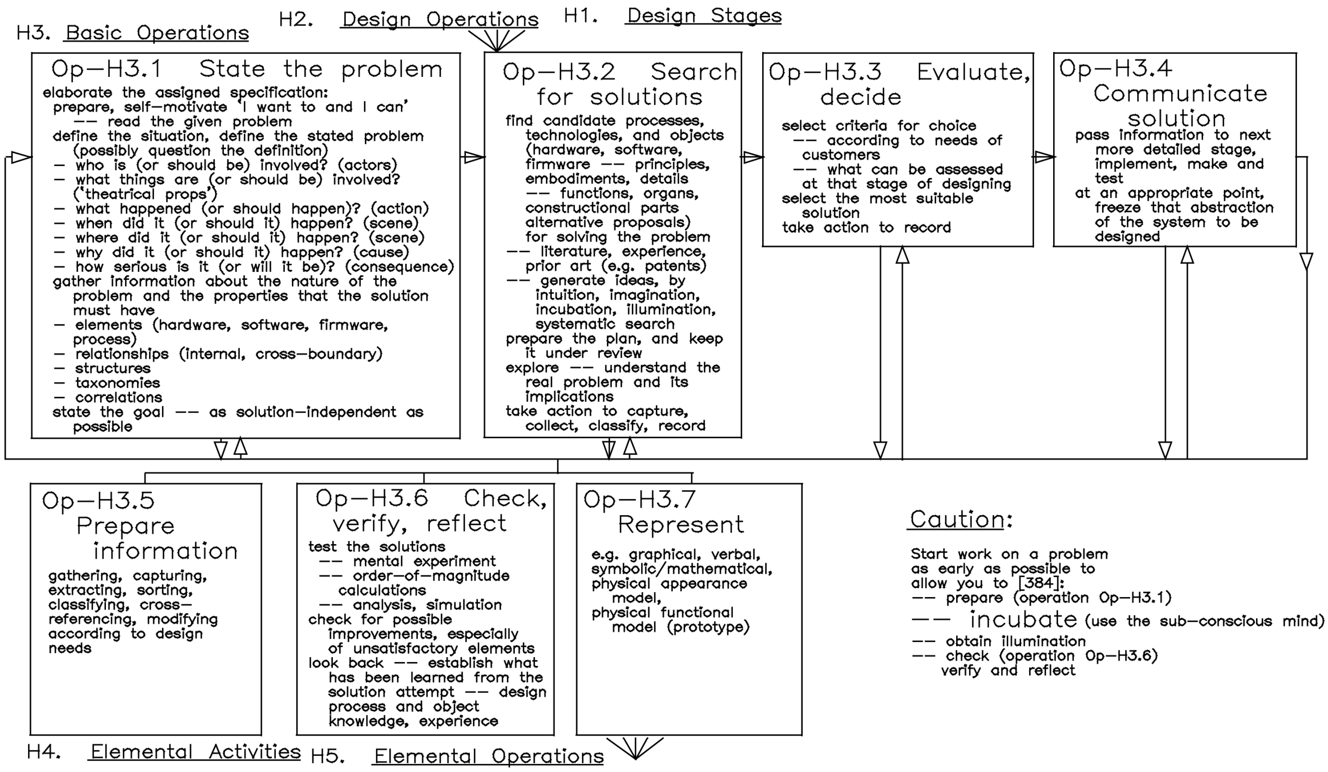

Figure 6. Basic Operations – Problem Solving in the Design Process [36-41]

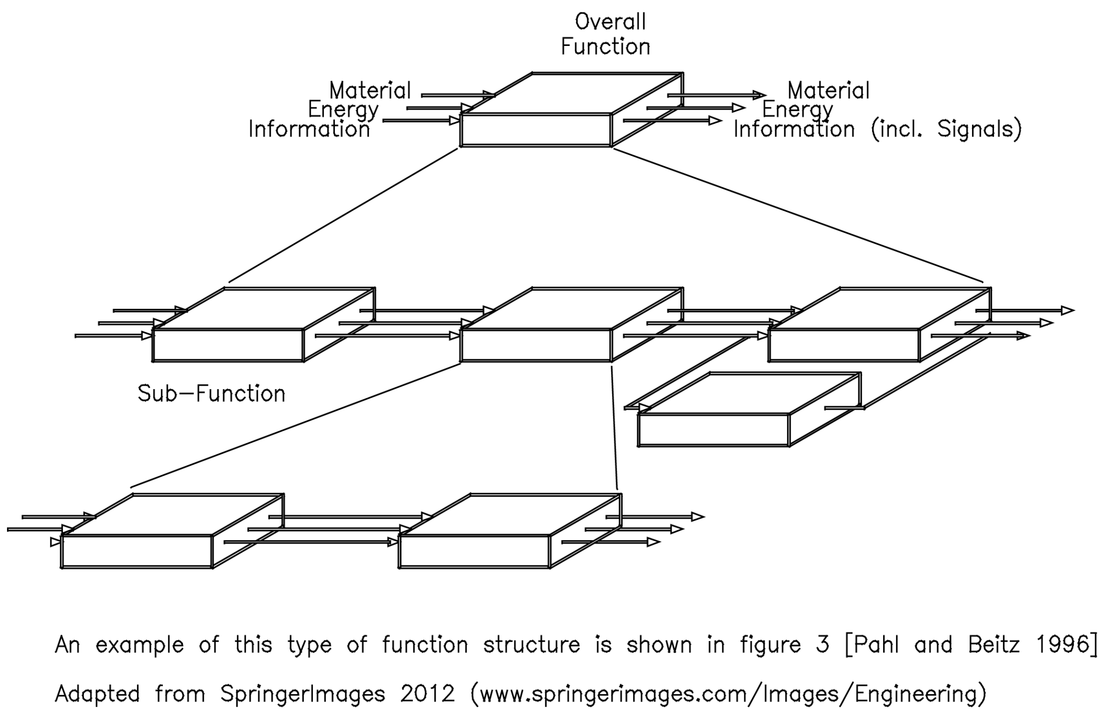

Figure 7. Function Decomposition according to Pahl and Beitz [32]

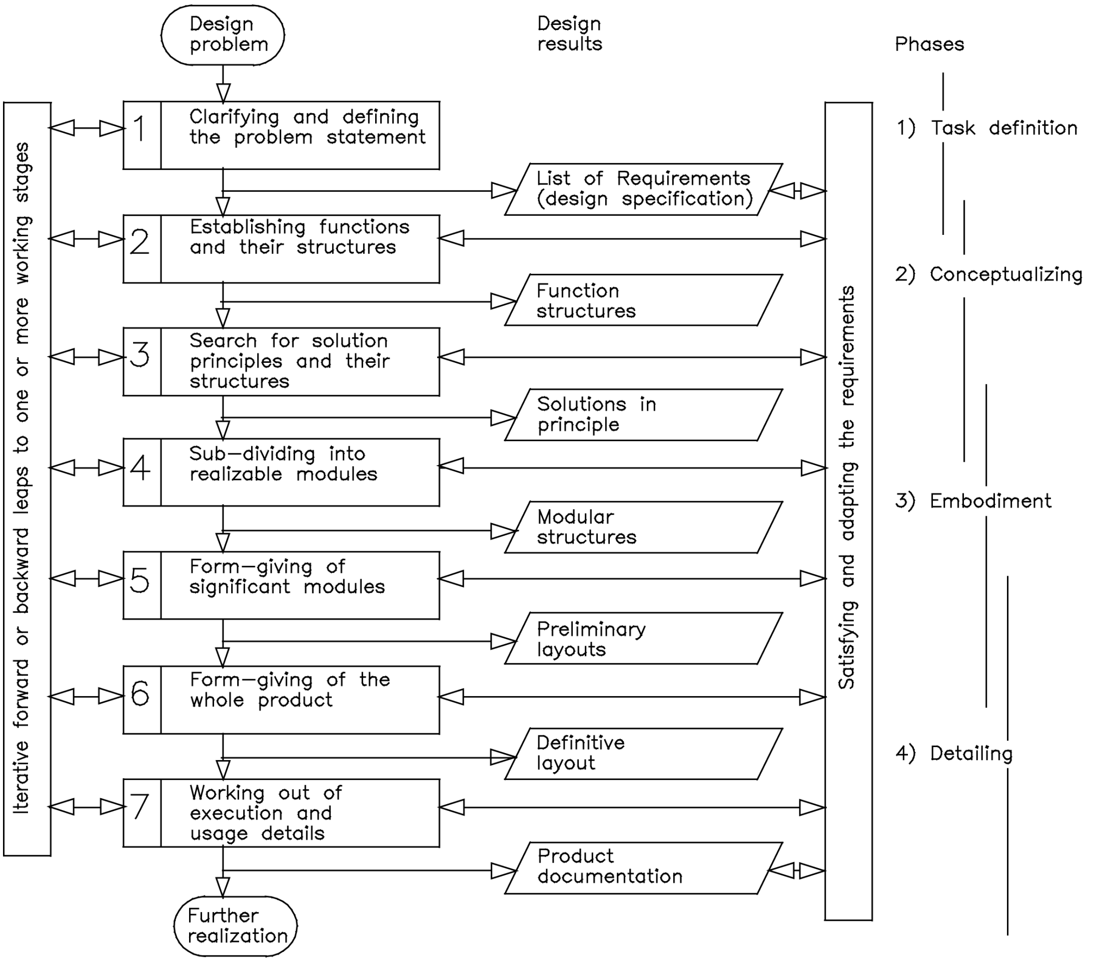

Figure 8. Design Methodology according to VDI 2221 [43,44 ,~~45~~]

The transition from the function structure towards the components (constructional parts) is achieved by applying 'physics' (covering all modes of action) – Hubka [2-4] places application of the engineering sciences into the properties and requirements, and into problem solving, section 4.

In contrast to Hubka [1-4], Pahl and Beitz [32] do not cover: (1) a formalized life cycle, (2) formalized lists of classes of properties of TS and TrfP, (3) formalized list of classes of requirements, (4) a problem solving cycle, (5) case examples of the design approach to designing technical systems, (6) consideration of other design methods, and several other contributing items. On the positive side, the vast array of advice given by Pahl and Beitz [32] about the constructional structure makes this a very valuable work for mechanical engineering designers

7. Closure

The theory of technical systems is shown to be a valuable tool for expanding the horizons of engineering (and other) students, and bringing engineering into societal and industrial context. In addition, it leads to a systematic design and problem solving methodology that is suitable for novice engineering designers (especially students in engineering courses). Such a systematic methodology provides good insights for their future activities, and assists them whenever they tend to exceed their (currently) highest level of competence, i.e. when they reach a critical situation of apparent failure.

The presented theory (of technical systems, of systematic engineering design, of problem solving method, etc.) needs to be presented at a level appropriate to the maturity of the students. Presentation of elements of these theories should be accompanied by suitable exercises, e.g. recognizing existing TrfS, applying elements of the systematic engineering design process, problem solving – this last part for instance using Wimbey pairs with students monitoring their peers.

The Hubka theories and methods [1-4] have not been widely adopted in industry [42-46], too few engineering students have been exposed to them. In contrast, the Pahl and Beitz [32] and VDI [43,44] methods have been widely accepted in Germany, because they have been taught in the academic institutions, but the improvements in engineering design performed by industry have only been noticed and reported after more than 20 years delay.

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