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ANALYSIS, SYNTHESIS AND PROBLEM SOLVING IN DESIGN ENGINEERING

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ABSTRACT

Design engineering aims to provide transformation processes (TrfP) and technical systems (TS), preferably as complete transformation systems (TrfS), to solve a specific task. A theory-based systematic method for design engineering is outlined, which contains a cycle of problem solving. Some main elements of design engineering are discussed, with emphasis on two processes of analysis and synthesis. A relationship based on these processes of analysis and synthesis is developed between properties of existing TrfP and TS, and requirements for future TrfP and TS, and is supported by combining the properties and requirements with the steps in the cycle of problem solving. Vladimir Hubka's postulate of 1974 is thus confirmed that properties and requirements can usefully be separated into three main sections: observable, mediating and elemental.

Keywords: Design engineering, product properties, requirements, problem solving

1 INTRODUCTION

Engineering aims to provide processes and technical systems to solve a specific task, to help in performing a desired transformation process, independent of the degree to which the applied phenomena are understood, especially in their interactions. The main regions of activity for engineering are designing, manufacturing/implementing, operating, procuring and supervising. Among these, design engineering as an activity is probably least understood, its investigation only reaches back about 70 years.

A life ambition of Professor Dr. Vladimir Hubka (29 March 1924 – 29 October 2006) was to develop a comprehensive theory and related method for design engineering. During his 25 years of industrial experience, and especially in the early to mid 1960's, he and colleagues in Czechoslovakia (as it then was) started to develop such a theory, first reported in [1]. After departing from Czechoslovakia in 1968, he continued his reflective research with several other colleagues, to produce many papers in conferences and journals, and a significant series of books in German and English [2,3,4,5,6,7,8,9], until the onset of his medical difficulties in 2002. Since then, further progress has been made [10], and continues with some of the changes reported in AEDS 2007 [11], proposals reported in AEDS 2008 [12,13], and this paper.

Hubka's theories have been tested in practical and industry applications in recent years (e.g. [14]). This has resulted in some significant changes in terminology and in interpretation, mostly as results of using and explaining the theory and its recommended methodology. For instance, a duplicate usage of the term 'TS-internal' has forced a change in the name of a group of two classes of TS-properties from 'TS-internal' to 'TS-mediating', as justified in this paper. Duplicate use of 'TS-external' forced a change to 'TS-observable properties'. Inconsistent usage of the word 'characteristics' in English-language engineering has induced a change of name for the property class 'design characteristics' to 'intrinsic design properties'. Hubka in his active lifetime concentrated on the TS and its design process; the treatment of properties and design processes for TrfP within the theory, and the explicit treatment of requirements, as distinct from properties of existing systems, are newer developments.

2 SYSTEMATIC ENGINEERING DESIGN PROCESS

The need for a systematic approach to design engineering is demonstrated in [15]. A comparison of Hubka's theory to other design theories was presented in [16]. A brief survey of the history of investigations into design engineering is given in [9, chapter 3].

As shown in [5,8,9], the recommended theory-based engineering design process is founded in the model of the transformation system, figure 1. The model 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* (in the form of materials, energy and/or information – M, E, I) exerted continuously, intermittently or instantaneously by the *operators* (human systems, technical systems, active and reactive environment, information systems, and management systems, as outputs from their internal processes), by applying a suitable *technology* Tg (which mediates the exchange of M, E, I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.

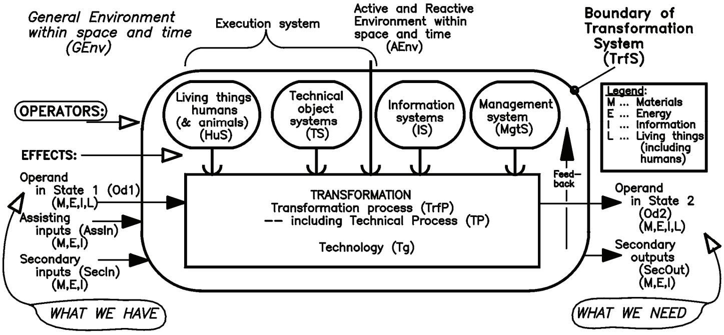


Figure 1. General Model of a Transformation System [10]

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 figure 1 is understood, designers can develop a theory-based systematic method for a novel system – TrfP(s) and/or TS(s), the addition of '(s)' signifies that the TrfP and/or TS is the subject of the design process – to be designed [7,8,9,10], 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 of transformation processes and technical system as guideline;

(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 with other operators;

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

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

(P7) establish what the technical system needs to be able to do (its internal and cross-boundary functions, with possible alternatives) to produce the 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 [17,18,19];

(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.

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.

These model processes cannot be performed in a linear progression, they need iterative and recursive processing, see below.

At each stage and step, a sub-process of problem solving takes place – many times and in rapid iterative repetition in the main cycle, with frequent calls as needed to the three auxiliary processes, see figure 2. In practice, the individual steps may not be recognizable, they can occur at such high speed and essentially in the mind of the designer.

It is almost impossible (except in the most routine situations) to jump from requirements (P1) to a final solution (P9). An essential procedure is to estimate possible candidate solutions, explore their anticipated properties, and correct them towards meeting the requirements – a process of iteration.

The main difference between design engineering and other forms of designing are (a) that design engineering is always constrained by the engineering sciences and by considerations of economics, but (b) it has available the structures of the transformation process (TrfP), technologies (Tg), TS-internal and cross-boundary functions (Fu), and TS-internal and cross-boundary organs (Org), to achieve the TS-constructional structure (CStr) – and other design disciplines are mainly concerned with the TS-observable properties.

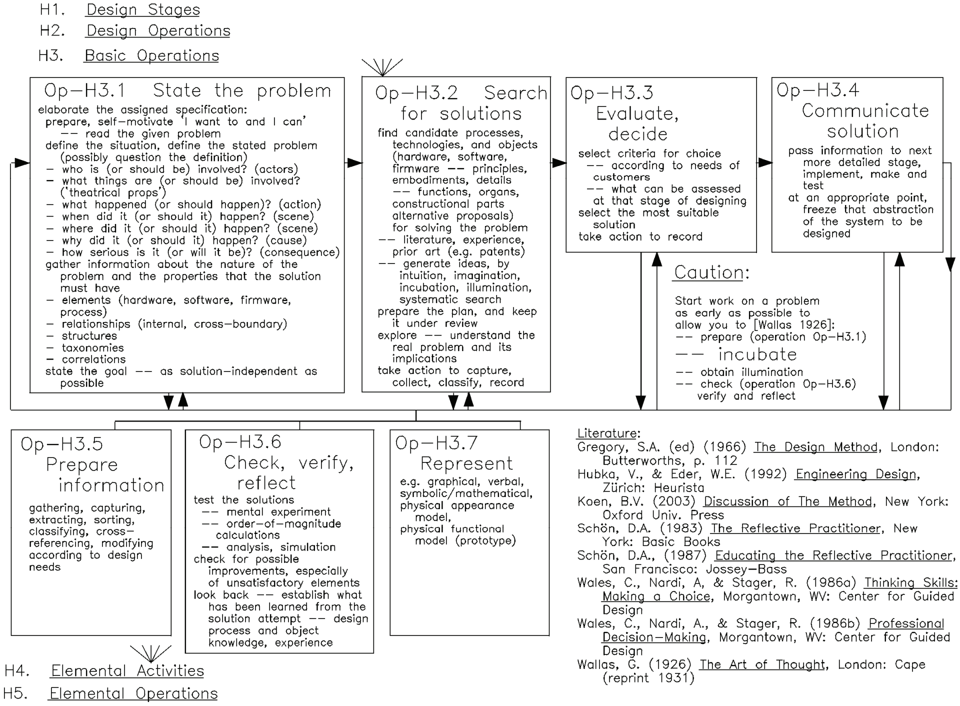


Figure 2. Problem solving (modified from [10])

3 DESIGN PROCESS -- GENERAL

Designing involves planning and executing (or having executed) an envisaged task, including writing, graphical work, products, etc. Design engineering involves *predicting* and *synthesizing* a TrfP(s)/TS(s), which needs compromise and avoidance of conflicts or contradictions in the relationships among individual parts. A new entity is created, with optimal TS-mediating and TS-observable properties for the envisioned transformation process, for which generating alternatives and variants of goals and means, principles and embodiments, is important.

Vladimir Hubka in 1974 [2] recognized that the properties of technical systems (TS) were important for design engineering. He also recognized an important distinction between TS-observable properties, TS-mediating properties, TS-mediating properties (in his terminology 'TS-mediating properties'), and a sub-division of the TS-mediating properties into TS-intrinsic properties (in his terminology 'Design Characteristics') and TS-general design properties, and TS-elemental design properties. The engineering designer works with the TS-elemental design properties to generate all other TS-properties.

The primary classes of properties for an existing transformation process (TrfP) are shown in figure 3, and for an existing technical system (TS) in figure 4. Important classes for the purpose of this paper are the Intrinsic Design Properties (Trf-Pr6 and TS-Pr12), representing the experience information that may be obtained from a TrfP and/or TS, and the General Design Properties (Trf-Pr7 and TS-Pr11), representing the applicable engineering sciences.

Actual properties of an existing TrfP can be completely arranged into the classes shown in this table.

	Class	Description
TrfP– OBSERVABLE PROPERTIES	TrfP–Pr1	Operand in state Od1, Od2, and in each intermediate state
	TrfP–Pr2	Assisting and secondary inputs
	TrfP–Pr3	Secondary outputs
	TrfP–Pr4	Technology for each transformation or operation
	TrfP–Pr5	Active and reactive effects received from the operators by means of the applied technology
TrfP– MEDIATING PROPERTIES	TrfP–Pr6	TrfP–Intrinsic design properties –– experience information, etc.
	TrfP–Pr7	TrfP–General design properties –– engineering sciences, etc.
	TrfP–Pr8	TrfP–Elemental design properties –– Types of transformation or operation performed on the operand, and their relationships

Figure 3. Primary Classes of Properties of Existing Transformation Processes

Actual properties of an existing TS can be completely arranged into the classes shown in this table.

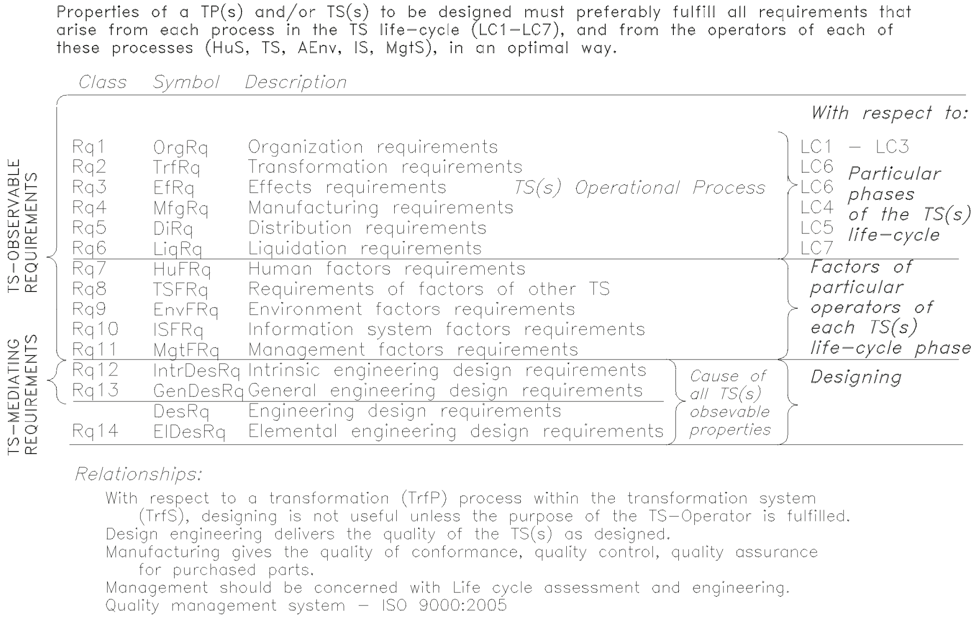
	Class	Symbol	Description			
TS–OBSERVABLE PROPERTIES	Pr1	EfPr	Effects properties	TS(s) Operational Process		With respect to: LC6 Particular LC4 phases LC5 of the TS(s) LC7 life–cycle
	Pr2	MfgPr	Manufacturing properties			
	Pr3	DiPr	Distribution properties			
	Pr4	LiqPr	Liquidation properties			
	Pr5	HuFPr	Human factors properties			Factors of particular operators of each TS(s) life–cycle phase
	Pr6	TSFPr	Properties of factors of other TS (in their operational process)			
	Pr7	EnvFPr	Environment factors properties			
	Pr8	ISFPr	Information system factors properties			
	Pr9	MgtFPr	Management factors properties			
TS–MEDIATING PROPERTIES	Pr10	IntDesPr	Intrinsic engineering design properties		Cause of all TS(s) observable properties	TS(s) as designed
	Pr11	GenDesPr	General engineering design properties			
		DesPr	Engineering design properties			
	Pr12	ElDesPr	Elemental engineering design properties			

Figure 4. Primary Classes Properties of Existing Technical Systems

Designing in engineering has the purpose of creating future *operating* artifacts, TS(s), and the operational processes, TrfP(s), for which they can be used, to satisfy the needs of customers, stakeholders and users, i.e. to fulfill the requirements. This purpose is accomplished by designing suitable technical means (TrfP and/or TS), and producing the information needed to realize and implement a product. **Designing something useful with a substantial engineering content, usually within market constraints, distinguishes engineering from scientific or artistic activity.** Therefore

***design engineering*, combining art, craft and science, is the activity and subject of this paper**. The products may be able to actively operate, or to be operated as a tool by a human being.

The primary classes of *requirements* are shown in figure 5. This listing is theoretically complete according to the axioms adopted for the theory. It provides a good basis for writing a design specification (list of requirements) for any engineering design problem. Note that usually a design specification, whether as given to the designer(s) by management, or developed by designers for their own use, contains mainly statements about the observable properties. It is relatively rare to find requirements for the mediating properties, Rq12 and Raq13, they contain mainly the technological information and engineering science that is available to allow synthesis in design engineering, including standards, codes of practice, etc. It is even more unlikely that requirements for elemental design properties, Rq14, are explicitly stated, such requirements are usually included in the observable properties. A fuller listing of requirements, including theoretically complete secondary classes of requirements, is available.


Properties of a TP(s) and/or TS(s) to be designed must preferably fulfill all requirements that arise from each process in the TS life-cycle (LC1–LC7), and from the operators of each of these processes (HuS, TS, AEnv, IS, MgtS), in an optimal way.

Class	Symbol	Description	With respect to:
Rq1	OrgRq	Organization requirements	LC1 – LC3
Rq2	TrfRq	Transformation requirements	LC6
Rq3	EfRq	Effects requirements	LC6
Rq4	MfgRq	Manufacturing requirements	LC4
Rq5	DiRq	Distribution requirements	LC5
Rq6	LiqRq	Liquidation requirements	LC7
Rq7	HuFRq	Human factors requirements	Factors of particular operators of each TS(s) life-cycle phase
Rq8	TSFRq	Requirements of factors of other TS	
Rq9	EnvFRq	Environment factors requirements	
Rq10	ISFRq	Information system factors requirements	
Rq11	MgtFRq	Management factors requirements	
Rq12	IntrDesRq	Intrinsic engineering design requirements	Designing
Rq13	GenDesRq	General engineering design requirements	
	DesRq	Engineering design requirements	
Rq14	ElDesRq	Elemental engineering design requirements	

Relationships:

With respect to a transformation (TrfP) process within the transformation system (TrfS), designing is not useful unless the purpose of the TS-Operator is fulfilled.
Design engineering delivers the quality of the TS(s) as designed.
Manufacturing gives the quality of conformance, quality control, quality assurance for purchased parts.
Management should be concerned with Life cycle assessment and engineering.
Quality management system – ISO 9000:2005

Figure 5. Primary Classes of Requirements for Transformation Systems

Design engineering explores alternative solution proposals, and delivers proposals for appearance and presence, and/or implementation and manufacturing specifications for a designed product. The output of *Design engineering* is conventionally a set of manufacturing drawings for TS-constructional parts (or their computer-resident equivalents), assembly drawings, parts lists, and documentation for assembly, adjustment, transport, usage, and other life-cycle processes. Documentation is also needed to demonstrate that performance, strength and durability have been considered, usually by engineering science analysis. For novel design engineering, more abstract elements and structures are usable – transformation processes, technologies, functions, and organs [5,7,8,9,10]. Creativity has a role [20], systematic and methodical designing is preferred [8,9,10], but see the companion paper [15]. Industrial design and design engineering must frequently be coordinated.

Designing (both artistic and engineering) is a set of tasks that involve cognitive-conceptual processing of information, that also contains routine work, and can be supported by prescribed methods. Typical activities include:

(a) *analysis*, given a structure, find its behavior (self-behavior and emotional reactions of humans) and other properties; an entity (a whole) is decomposed and explored using *causality* as a premiss, and mathematical models – e.g. the engineering sciences;

(b) *synthesis*, given the desired behavior and other requirements, find a structure that satisfies the behavior and requirements – usually one of several possible structures; explore, select and unite the (often opposing or contradictory) units, and moderate and overcome any contradictions, using *finality* as the aim, including creativity, to find and select among candidate solutions for a TrfP(s) and/or TS(s);

(c) *management* to formulate, direct and control activities towards the goals;

(d) *decision making*, and formulating the criteria for decisions, *analyzing*, *evaluating*, *selecting and deciding*;

(e) *problem solving* as a detail procedure within designing, searching for information, verifying, checking, reflecting [21,22,23], and making the results of designing useful, *representing* (e.g. graphically, verbally and/or digitally) and *communicating*;

(f) *Black box problem*, Identification: given a system, of which the structure is unknown or only partly known, find its behavior (and its inputs and outputs), and possibly its structure.

The contrast to *causality* is the concept of *finality* (purpose determinacy). The goal for finality is to establish a suitable *causa finalis*, as a future ('as should be' state) TrfP and/or TS intended for that purpose. The goal for the design process is therefore to establish a suitable TS(s)-constructional structure (and other structures). Finality plays the role of a compass to show a direction towards an envisaged goal. The relationship *{intended effect —> possible cause —> optimal cause}* according to finality is the relationship *{goal —> means —> optimal means}*.

Designing is always directed towards envisaged *goals*. Engineering designers look for mainly technical *means* with which the (intermediate) goal can be reached, problems (inadequacies, defects) can be eliminated, and/or needs fulfilled. The relationship of goals to means expresses the 'finality nexus' (linkage of finality) and represents the process of *synthesis* – starting from the goal, a search for suitable means is performed. Design engineering consists of a sequence of *{goals —> means}* transitions, a state of *finality*. Consequently the leading question for design engineering is 'With what means can one achieve the necessary effect?'

4 ANALYSIS AND SYNTHESIS

Both synthesis and the black box problem must be accompanied by analysis.

Analysis (analyzing) involves finding the causes and parameters of the actual or anticipated behavior of an existing or planned structure, and/or its (detail) values. This can be a verbal and graphical analysis, e.g. to formulate TS-internal and cross-boundary functions, or a mathematical analysis to find a value of a dependent variable from given or assumed independent variables. In reality, analysis is in essence a one-to-one transformation. Analysis involves mainly convergent thinking, aiming to produce one 'solution' in the form of expected data, e.g. about performance of the envisaged TrfP(s) and TS(s).

Synthesis (synthesizing) involves finding suitable means to achieve a goal, e.g. a proposed (function-, organ- and/or constructional) structure that will show a required behavior – this is not a simple inversion of analysis, it goes far beyond a reversal, it is almost always a transformation that deals with alternative means and arrangements, a one-to-many (or few-to-many) transformation. Synthesizing is the more difficult kind of action, it involves divergent thinking, searching for alternative solutions.

Synthesis and product development consists of establishing and assigning the product's elemental design properties from the *required* observable properties. The mediating properties show a complex relationship to the observable properties, compare figure 6.

A generally held conviction wrongly claims that all synthesis is 'creative' and 'intuitive' – yet many methods can help in synthesis. The term 'creative synthesis' should be used only for new and previously unknown results of synthesis, e.g. radical patents, or a synergistic formation.

5 TRANSFORMATION SYSTEM - DESIGN PROCESS

An essential feature of a systematic and methodical engineering design process will be illustrated for technical systems, starting from step (P6) of the scheme listed in section 2.

In analysis, the relationships between elemental, mediating and observable properties are known and can be determined, with one answer (subject to a range of error), see figure 7, part A. In synthesis, 'inverting the relationships' can and usually does result in a search for alternative solutions, and conflicts which must be resolved, many of which are not predictable in advance, see figure 7, part B.

Solving the synthesis problem therefore requires an iterative procedure, whether consciously or intuitively applied, as illustrated in figures 7 and 8. This process selects appropriate requirements for observable properties from classes Rq1-Rq11, uses the requirements and heuristics of the intrinsic design properties, Rq12, and the general design properties (for an heuristic use of the engineering sciences, see also [24]), Rq13, to generate (synthesize) proposals for the elemental design properties, Pr12. These can then be used to analytically estimate some or all of the expected TS-properties Pr1-Pr9, using the intrinsic design properties, Pr10, and the general design properties, Pr11 as tools. Comparing these ‘as is’ estimates with the requirements, the recognized differences can then drive the design process towards correction and convergence – Property-Driven Design (PDD) [12].

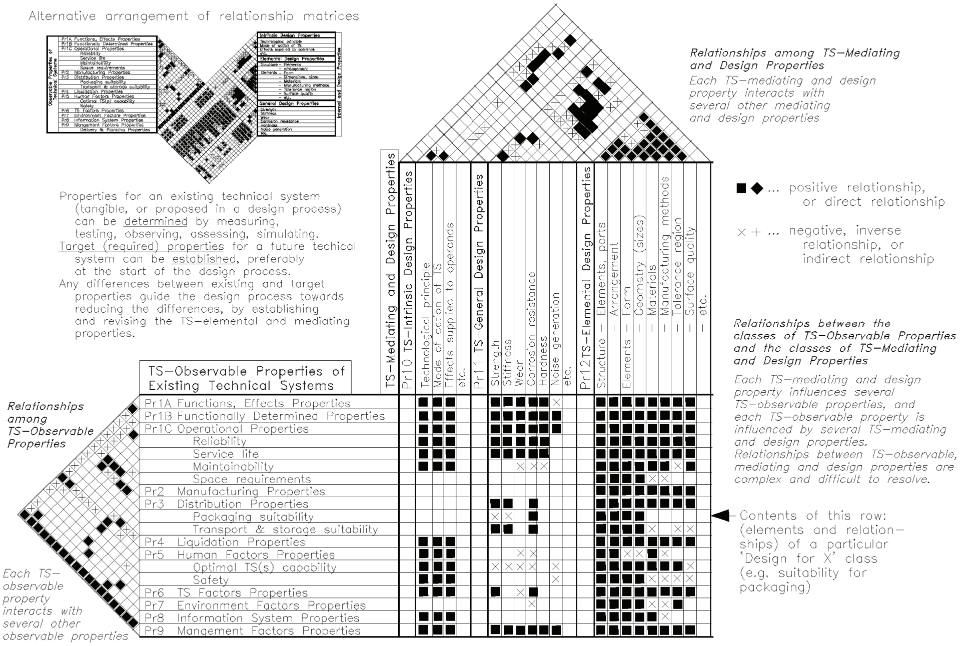


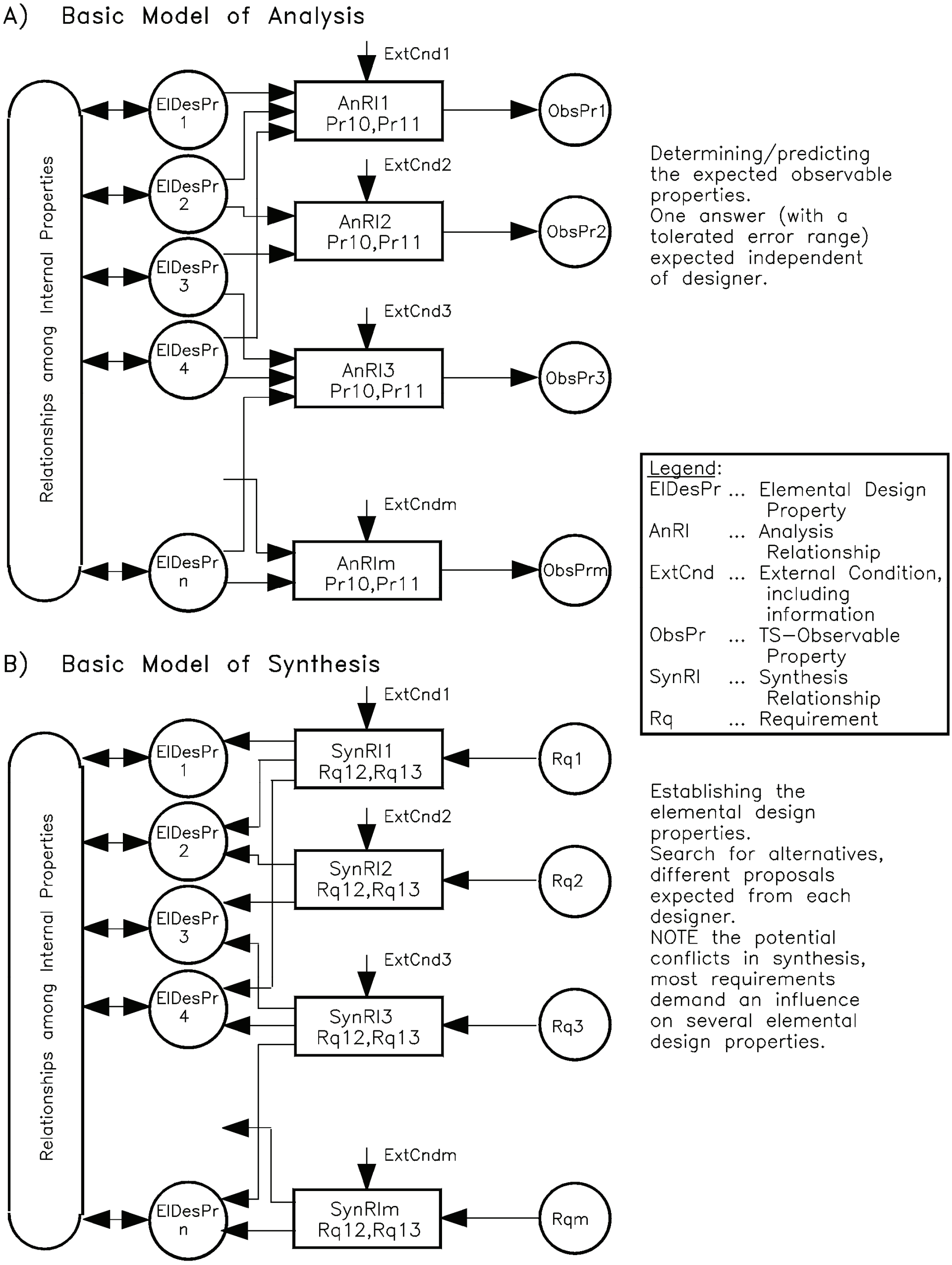
Figure 6. Relationships Among Classes of Properties of Existing Technical Systems (modified from [10])

The observable TS-properties can in general only be established indirectly through the elemental design properties – the exception is the overall appearance, the human interface, and the anticipated emotional reaction (a task of industrial design and/or architecture), which can be established directly.

The TS-structures indicated in the elemental design properties may be used to provide several stages of mappings with recommended methods to generate solution proposals and establish the accepted solution, the TS(s), see section 2 – the ‘(s)’ designates that this is the subject of designing. This systematic and methodical procedure is illustrated in the case studies [6,7,10]. These case study also make clear that only a suitable selection of requirements from the design specification can be realized at any one time, that recursive and iterative working is necessary, and that an ideal aim should be that all properties (as requirements) should be fulfilled in the final solution.

All mediating and observable properties of existing TrfP and TS are caused by the elemental design properties, class Pr12, see figures 3 and 4. During design engineering, the elemental design properties (including all TS-structures) are gradually established from the requirements, in a process of finality involving the basic operations of problem solving, with multiple iterations, see section 2 of this paper. A relationship of these operations with the TS-properties and requirements is shown in figure 9 [13].

The main processes are located in the basic operations of problem solving, Op-H3.3 (part 1) and Op-H3.2, see section 2 of this paper. Synthesis, Op-H3.2, appears to be a direct inversion of analysis, Op-H3.3 (part 1), but this cannot be the case [25], see section 4. The same relationships apply for transformation processes, using the appropriate classes of properties from figure 3.



Determining/predicting the expected observable properties.
One answer (with a tolerated error range) expected independent of designer.

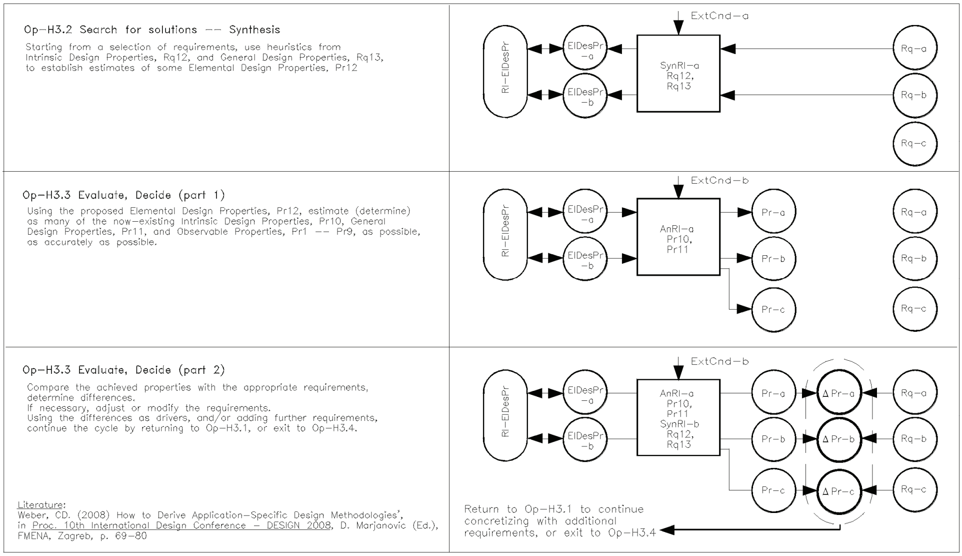
Legend:

ElDesPr	...	Elemental Design Property
AnRl	...	Analysis Relationship
ExtCnd	...	External Condition, including information
ObsPr	...	TS–Observable Property
SynRl	...	Synthesis Relationship
Rq	...	Requirement

Establishing the elemental design properties.
Search for alternatives, different proposals expected from each designer.
NOTE the potential conflicts in synthesis, most requirements demand an influence on several elemental design properties.

Literature:
Weber, CD. (2008) How to Derive Application–Specific Design Methodologies',
in Proc. 10th International Design Conference – DESIGN 2008, D. Marjanovic (Ed.),
FMENA, Zagreb, p. 69–80

Figure 7. Basic Model of Analysis and Synthesis (adapted from [12])



Op–H3.2 Search for solutions –– Synthesis

Starting from a selection of requirements, use heuristics from Intrinsic Design Properties, Rq12, and General Design Properties, Rq13, to establish estimates of some Elemental Design Properties, Pr12

Op–H3.3 Evaluate, Decide (part 1)

Using the proposed Elemental Design Properties, Pr12, estimate (determine) as many of the now–existing Intrinsic Design Properties, Pr10, General Design Properties, Pr11, and Observable Properties, Pr1 –– Pr9, as possible, as accurately as possible.

Op–H3.3 Evaluate, Decide (part 2)

Compare the achieved properties with the appropriate requirements, determine differences.
If necessary, adjust or modify the requirements.
Using the differences as drivers, and/or adding further requirements, continue the cycle by returning to Op–H3.1, or exit to Op–H3.4.

Literature:
Weber, CD. (2008) How to Derive Application–Specific Design Methodologies', in Proc. 10th International Design Conference – DESIGN 2008, D. Marjanovic (Ed.), FMENA, Zagreb, p. 69–80

Return to Op–H3.1 to continue concretizing with additional requirements, or exit to Op–H3.4

Figure 8. Iterative Scheme of Synthesis, Analysis and Evaluation (adapted from [12])

Noteworthy is the specific role for the Intrinsic and General Design Properties (TrfP-Pr5, TrfP-Pr6, TS-Pr10, TS-Pr11) and Requirements (Rq12, Rq13), they *mediate* between the Elemental and Observable properties. In particular, the mode of action of a TS is the direct link from the TS-structures to the TS-behavior.

6 CLOSURE

Iterative working is an essential feature of all non-routine design engineering. The discussion of this paper provides a clear justification based on Engineering Design Science as theory, and a clear method for applying the theory as method for problem solving. The work of Vladimir Hubka is still alive, and under further development.

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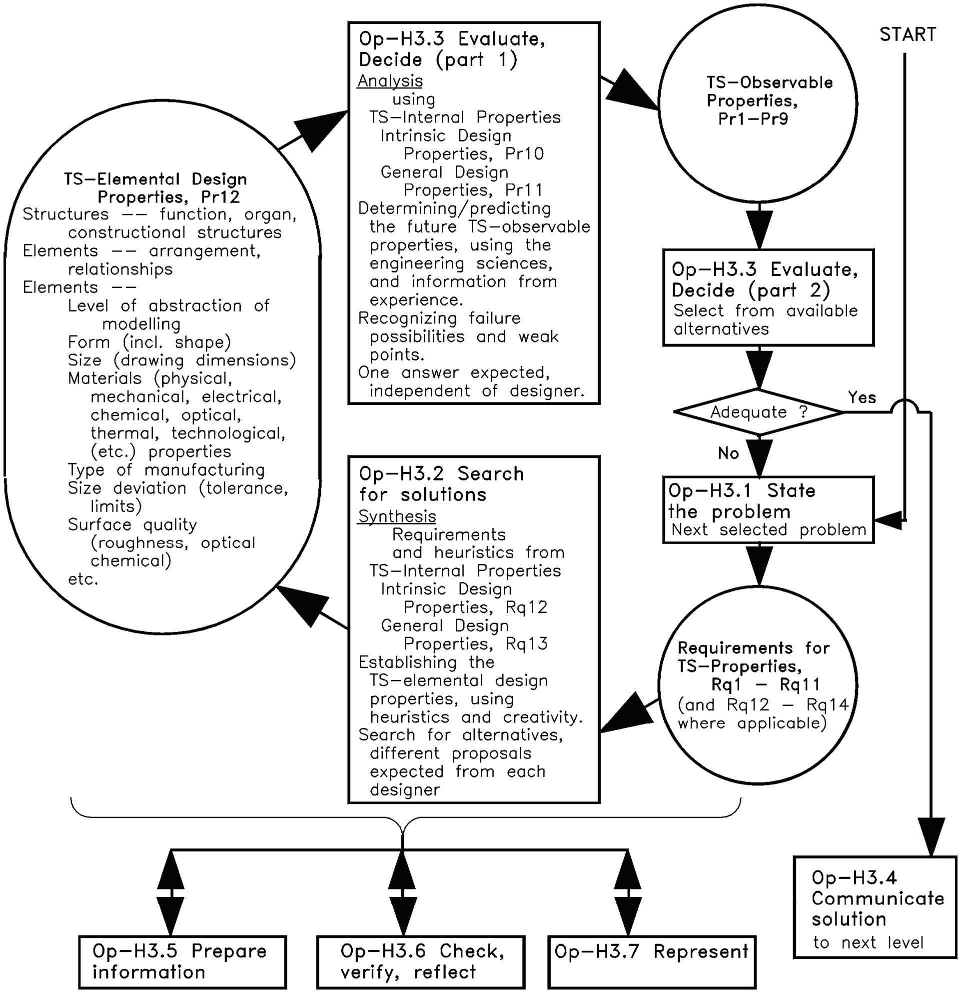

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Figure 9. Main relationship Between Problem Solving, and TS-Mediating and TS-Observable Properties (adapted from [13])

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