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REQUIREMENTS TO PROPERTIES – ITERATIVE PROBLEM SOLVING

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1. Introduction

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 [12], and this paper.

2. Design Engineering and Problem Solving

The procedural model of design engineering as proposed by Hubka [3,6,7,8,9,10] follows from the general model of a transformation system, figure 1, and is laid out in several hierarchical groupings. The whole design process is divided into five administrative phases: product planning, task defining, conceptualizing, embodying/laying out, and detailing. At the next level, the stages and steps of a novel design process are summarized as:

(P1) establish a design specification for the required system, a list of requirements;
(P2) establish the required output (operand in state Od2) of the transformation;
(P3) establish a suitable transformation process;
(P4) decide which of the operations in the transformation process will be performed by technical systems, alone or in mutual cooperation with other operators;
(P5) which technical systems (or parts of them) need to be designed;
(P6) establish a technology (structure, with alternatives) for that transformation operation, and therefore the effects (as outputs) needed from the technical system;
(P7) establish what the technical system needs to be able to do (its internal and cross-boundary functions, with alternatives);
(P8) 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, the machine elements, revised as proposed by Weber [13,14,15];
(P9) establish with what constructional parts (in sketch-outline, in rough layout, in dimensional-definitive layout, then in detail and assembly drawings, with alternatives) are needed.

Only those parts of this engineering design process that are thought to be useful are employed. Such an 'idealized' procedure cannot be accomplished in a linear fashion. Iterative working is essential, as is shown in section 6 of this paper.

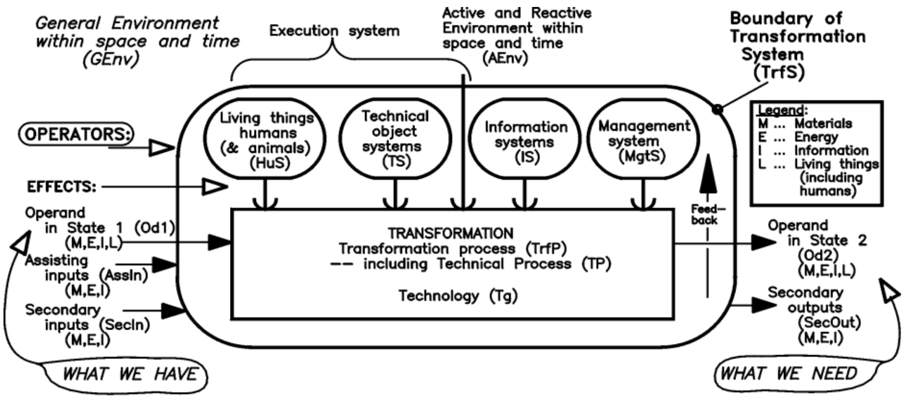

Figure 1. General Model of a Transformation System [1]

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 for a novel system.

Superimposed on the set of design operations, at the next level of the hierarchy, is a cycle of basic operations of problem solving, see figure 2, which consists of:
Op-H3.1 State the problem;
Op-H3.2 Search for solutions;
Op-H3.3 Evaluate, decide;
Op-H3.4 Communicate solution.
These are supported by auxiliary operations of:
Op-H3.5 Prepare information;
Op-H3.6 Check, verify, reflect;
Op-H3.7 Represent.
These last three were recognized by Hubka as essential, but are hardly ever found in other schemes of problem solving.
The utility of this procedure was demonstrated in various case studies [6,7,10], including industrial projects involving collaboration between engineering and industrial design [16].

3. Some Consequences

The further development to date has been found necessary, because of insights gained from applications in engineering design practice, e.g. [16].
We acknowledge a difference between 'determining' and 'establishing' a property. Once a tangible TS(s) exists ('*as is*'), either fully or partially realized and/or implemented, or in an intermediate or final stage of proposal (design), various properties can be *determined* by measuring, simulating or assessing. Before a tangible TS(s) exists ('*as should be*'), as its requirements are stated, in anticipation of a future state, we need to *establish* the needed internal and design properties, to predict in advance what alternatives can be generated, what manifestations and values may be possible and useful, and how to achieve the external properties by specifying the internal and elemental design properties. Engineering designers establish (with the help of the internal properties) and deliver the proposed elemental design properties, e.g. for mechanical engineering (and other branches) as engineering detail and assembly drawings and parts lists, or their computer file equivalents.
The two distinct states of TS can be illustrated by, (1) existing, '*as is*', with all properties measurable, assessable or latent, e.g. 'diameter 15.9836 mm', and (2) future, '*as should be*',

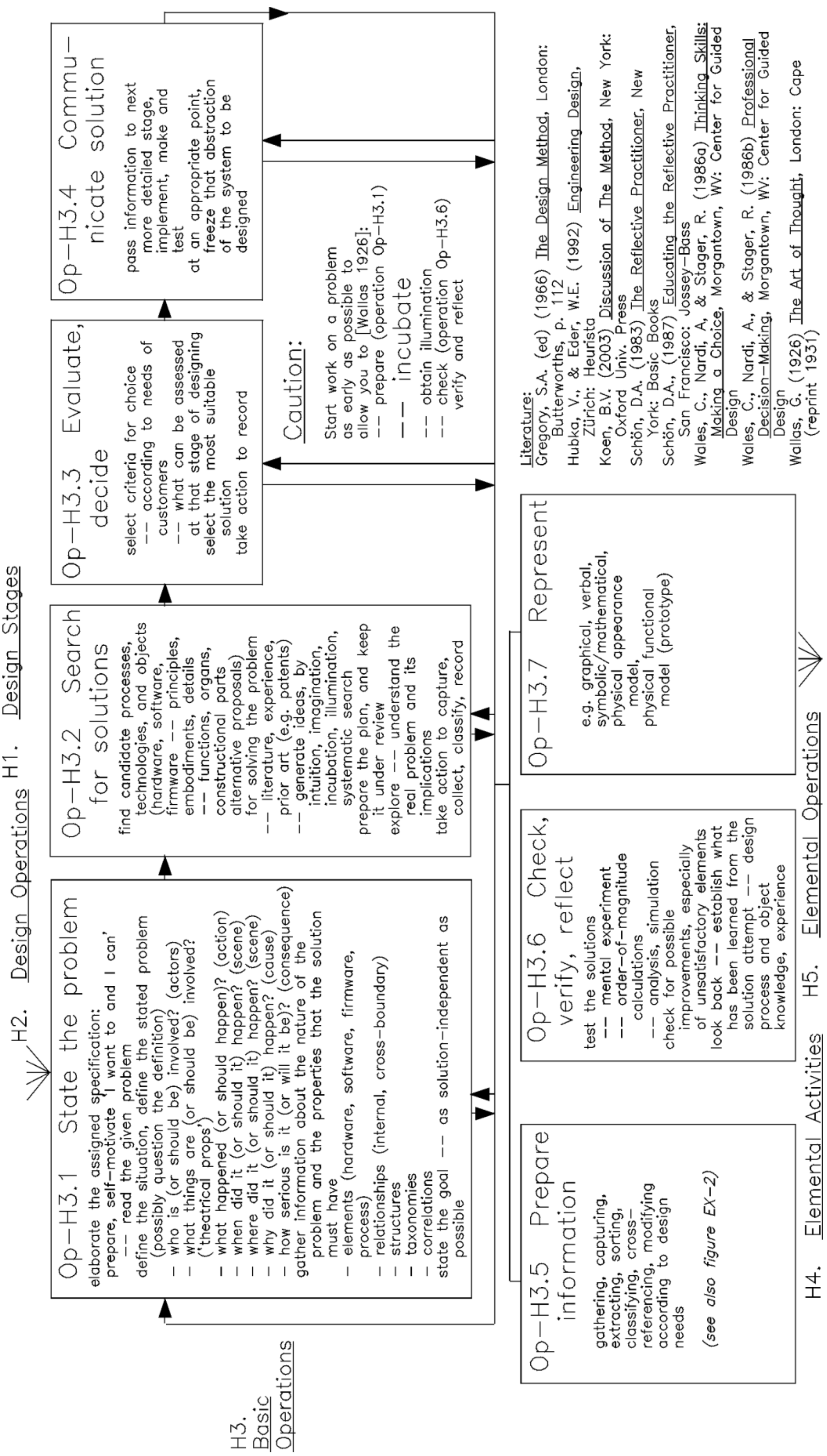

Figure 2. Problem Solving (modified from [10])

with only requirements to demand or limit the properties, e.g. 'a diameter requirement of 16 mm' with tolerance grade 'h7' and heuristics to guide designers in establishing and selecting the properties. The 'as is' state normally does not allow conclusions about the 'as should be' requirements – e.g. the diameter 'as is' is presumed from inspection to conform to the requirement, which may be for a tolerance of 'h7', 'h8' or 'h11'.

The 'as is' TS(s) cannot carry information about any other alternatives that were considered during life-cycle phases LC1 – LC3. The TS(s) also cannot carry full information about any requirements or constraints from the life-cycle phases – the TS(s) must remain within these constraints. Normally, it is not possible to identify any requirements or constraints used in LC1 – LC3 from an 'as is' TS(s).

As a consequence, the properties of TrfP and TS in the 'as is' state must be conceptually different from the requirements for a future TrfP and TS(s) – partly because actual measurements are possible *vs*. specification of required tolerance ranges, and partly because certain life-cycle phases cannot be reconstructed from an 'as is' system, but must be considered as requirements for an 'as should be' system.

The TS(s) passes through a life cycle, which typically consists of transformation systems: LC1 – product planning; LC2 – designing of the TrfP(s) and the TS(s); LC3 – manufacturing planning; LC4 – manufacturing and assembly; LC5 – distribution; LC6 – operation of the TS(s) and performance of the TrfP(s); LC6a – servicing, maintaining, repairing the TS(s); and LC7 – liquidation. The nature of the procedures for phases LC1 – LC3 is that the TS(s) exists as information. This information is progressively concretised (synthesized) in the engineering design process (LC2), until a full description of the TS(s) exists that is anticipated to comply with all requirements and constraints of all life-cycle phases, LC1 – LC7, to fulfil all requirements, and thus to be ready for manufacture and/or implementation. This description represents the requirements for manufacture, and acts as one of the five operators of phases LC4 onwards, and therefore already contains the effects of operators of LC1 – LC3, as considered during those origination phases. This engineering design process can progress intuitively or systematically and methodically – reflecting the work of engineering designers.

The documentation of LC1 – LC3 should contain records of all alternative solution proposals considered. The final full description of the TS(s) (information input for LC4 onwards) contains only the information about the TS(s) to be manufactured and/or implemented.

Nevertheless, this final description should contain all necessary considerations about needs and influences from the operators in the tangible life-cycle processes for future TS(s), LC4 – LC7. A complete classification scheme for this information is shown in figure 3, which can also be used to record the heuristic and scientific 'Design for X' information that can assist designers in searching for, selecting and developing solutions for the design problem.

4. Theory of Properties

The theory of TS-properties is a sub-section of the Theory of Technical Systems [5], which is a sub-section of Engineering Design Science [8,9,10]. Each 'as is' transformation process TrfP(s) and each 'as is' technical system TS(s) carries all properties, whether they have been designed (considered) or not.

Classes of properties for a *transformation process* (TrfP) (see figure 1) consist of (a) the properties of the operand, in state Od1, Od2, and in each intermediate state, (b) the properties of any assisting and secondary inputs, (c) the properties of secondary outputs, (d) the active and reactive effects exerted by the operators that cause the transformation of the operand by means of an applied technology, and (e) the types of transformations or operations, and their relationships, that are or can be performed on an operand – this last class constitutes the elemental design properties of a TrfP..

The list of primary TS-properties resulting from figure 3 is shown in figure 4. The primary class of properties of *technical systems* should relate to the TS(s) as operator of its operational process (LC6), i.e. its usage for its intended purpose – we will label this as class Pr1. Further classes of TS-properties are needed for the other life-cycle processes where a tangible TS(s) exists – classes Pr2, Pr3 and Pr4. From figure 3, the considerations for those

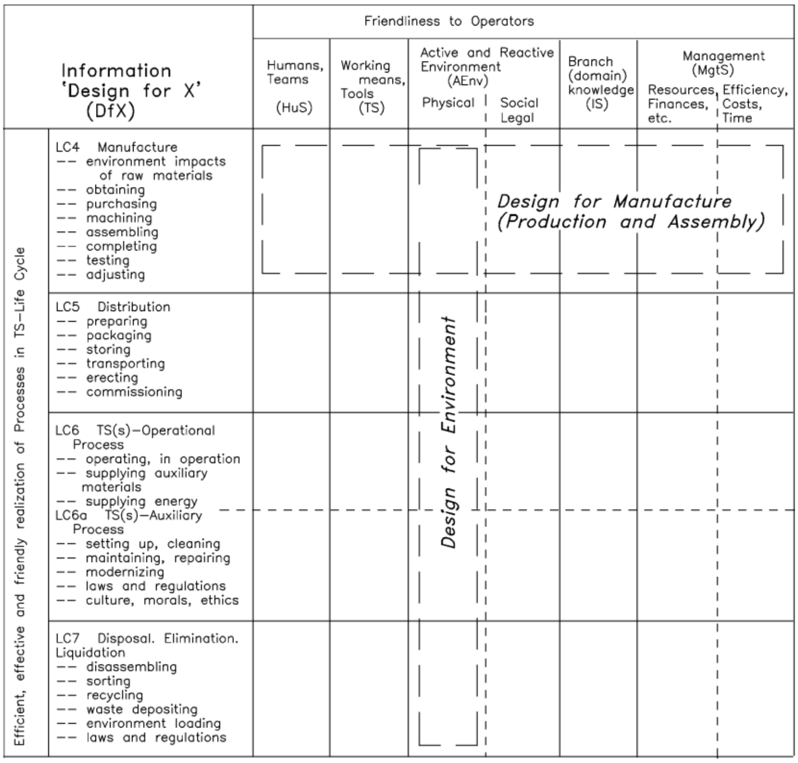

Figure 3 General Systematics of 'Design for X' (DfX) Classes [10]

life-cycle processes results in classes Pr5 – Pr9 to take into account the operators of the relevant life-cycle phases. Property class Pr5 relates directly with industrial design.

In addition, three classes are proposed as axioms: Pr10 and Pr11 of internal properties, sub-divided into Pr10 intrinsic design properties and Pr11 general design properties, and Pr12 of elemental design properties, as was already indicated in [3,5,7,8,9,10]. These are the properties for an existing TrfP/TS that were generated (established) by engineering designers, and were under their direct control.

Each technical system carries all its structures, whether they have been deliberately designed or not, they are included in Pr12. These structures have been found useful in the full systematic design process, see section 2, stages (P7), (P8) and (P(9) – function structure, organ structure and constructional structure. Each structure consists of appropriate elements and their relationships. For the constructional structure, the elements are: *form* – including gas, liquid and solid, and for solids their shapes; *size* – especially drawing dimensions, but also surface and cross-sectional areas, second moment of area, etc.; *material* – mass, mass moment of inertia, and chemical, technological, electrical, optical, magnetic and other physical properties; *type of manufacture* – any observable consequences of manufacturing methods; *size deviation* – difference to a stated nominal; *surface* – roughness, optical reflectivity, electrical, etc.

The actual properties ('as is'), their manifestations, values and units (where applicable) depend also on the state of the TrfP(s)/TS(s): (a) as designed – output of LC2, (b) as organizationally and technologically planned – output of LC3, (c) as manufactured – output of LC4, (d) as distributed – output of LC5, (e) in operational use – in LC6, (f) ready for disposal – input to LC7, and any other relevant state of existence.

As shown in figure 5, the intrinsic design properties, Pr10, the general design properties, Pr11, and the elemental design properties, Pr12, are *causally* responsible for the manifestations and values of all other properties.

The relationships among properties (including their manifestations and values) are complex. Most of the external properties interact with each other, as shown in figure 6, the 'roof' over the left section. Most internal properties interact with each other, as shown in figure 6, the upper 'roof'. There are also complex interactions between external and internal properties,

Advanta-geous, Suitable for:		Symbol	Class of Properties		Typical Questions about the Class	Groups or Examples of Property Class -- Emergent Properties of TS(s)
TS-External Properties	Particular Phases -- Processes of TS(s)-Life Cycle	FuPr EfPr (Pr1A) - LC6	Functions Properties Effect Properties	TS(s)-Purpose Properties (Pr1) for TS-Operational Process	What does the TS(s) do? What capability does the TS(s) have?	Main function Assisting functions: auxiliary function propelling function regulating/controlling fu. connecting function
		FuDtPr (Pr1B) - LC6	Functionally Determined Properties		What conditions are characteristic of the function?	Power, Speed, Size Functional dimensions Load capacity
		OppPr (Pr1C) - LC6	Operational Properties		How suitable is the TS(s) for its operational process (usage, working)?	Operational safety Reliability, Life Energy consumption Space occupation Maintainability Adjustability Modularization
		MfgPr (Pr2) - LC4	Manufacturing and other Origination Properties		How suitable is the TS(s) for manufacture?	Manufacturability Assemblability Manufacturing quality
		DiPr (Pr3) - LC5	Distribution Properties		How suitable is the TS(s) for transport, storage, packaging, etc.?	Transportability Storage suitability Packaging suitability
		LiqPr (Pr4) - LC7	Liquidation Properties		How easy is the TS(s) to liquidate, dispose of, recycle, re-use?	Re-cycling
	Particular Operators of Each Phase -- Process of TS(s)-Life Cycle	HuFPr (Pr5)	Human System Factors related TS(s)-Properties		How is the TS(s) operated, what influence does the TS(s) have (directly or indirectly) on human beings (esthetic, emotions, senses, comfort, danger, endurance, etc.)?	Operator safety Way of operating Secondary outputs Requirements for human attention to TS(s) Form, color, surface
		TSFPr (Pr6)	Technical Systems Factors related TS(s)-Properties		What TS were used for the TS(s)-life cycle process? What other TS cooperated?	Manufacturing equipment, office machinery, etc.
		EnvFPr (Pr7)	Environment Factors related TS(s)-Properties		Do harmful outputs exist? What cultural and societal effects occur? What laws (etc.) were followed?	Cultural norms, societal expectations, pollution, ecological loads, etc. Danger of wastes
		ISFPr (Pr8)	Information System Factors, 'Know-how' related TS(s)-Properties		What information and know-how was available? Are instructions sufficient? What laws, codes of practice, standards exist?	Library, publications, standards, patent clearance, legal requirements
		MgtFPr (Pr9)	Management, Economics, Societal, Goals, Organization, Personnel related TS(s)-Properties		What organizational, planning, management influence exist? How economic is the working and manufacturing process? When was the TS(s) delivered? Manufacturing quantity?	Management procedure, Operating and Manufacturing costs, effectiveness Manufacturer recommended price Delivery capability, time Quantity production
TS-Internal and Design Properties	For all External Properties of TS(s) -- causes of all TS-external properties	Pr10	Intrinsic Design Properties		What technological principles, action sites, etc. are employed?	Legend: TS ... TS as Operator of (partial) process TS(s) ... TS(s) as Product of organization
		Pr11	General Design Properties		Which engineering sciences, etc. are applicable?	
		DesPr	Design Properties		With what means are the external properties (classes Pr1--Pr9) realized?	Structures (Fu, Org, C) Relationships/Elements Form, Shape Geometry (size) Materials Type of manufacturing Tolerances Surface quality etc.
		Pr12	Elemental Design Properties		What structures, arrangements, elements/parts are used?	

Figure 4. Classes of Properties of Existing Technical Systems (modified from [10])

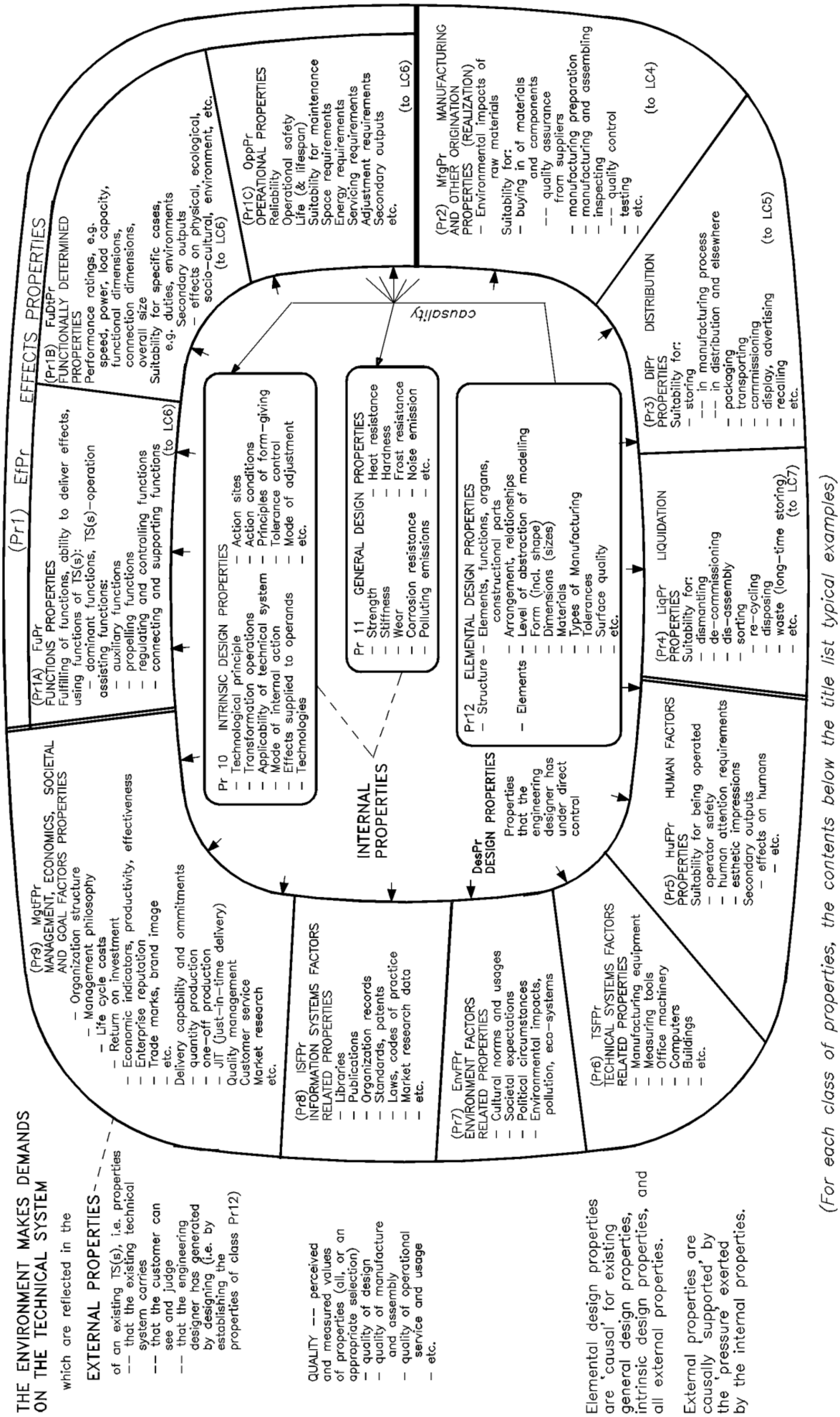

Figure 5. Relationships Among Classes of Properties of Existing Technical Systems (modified from [10])

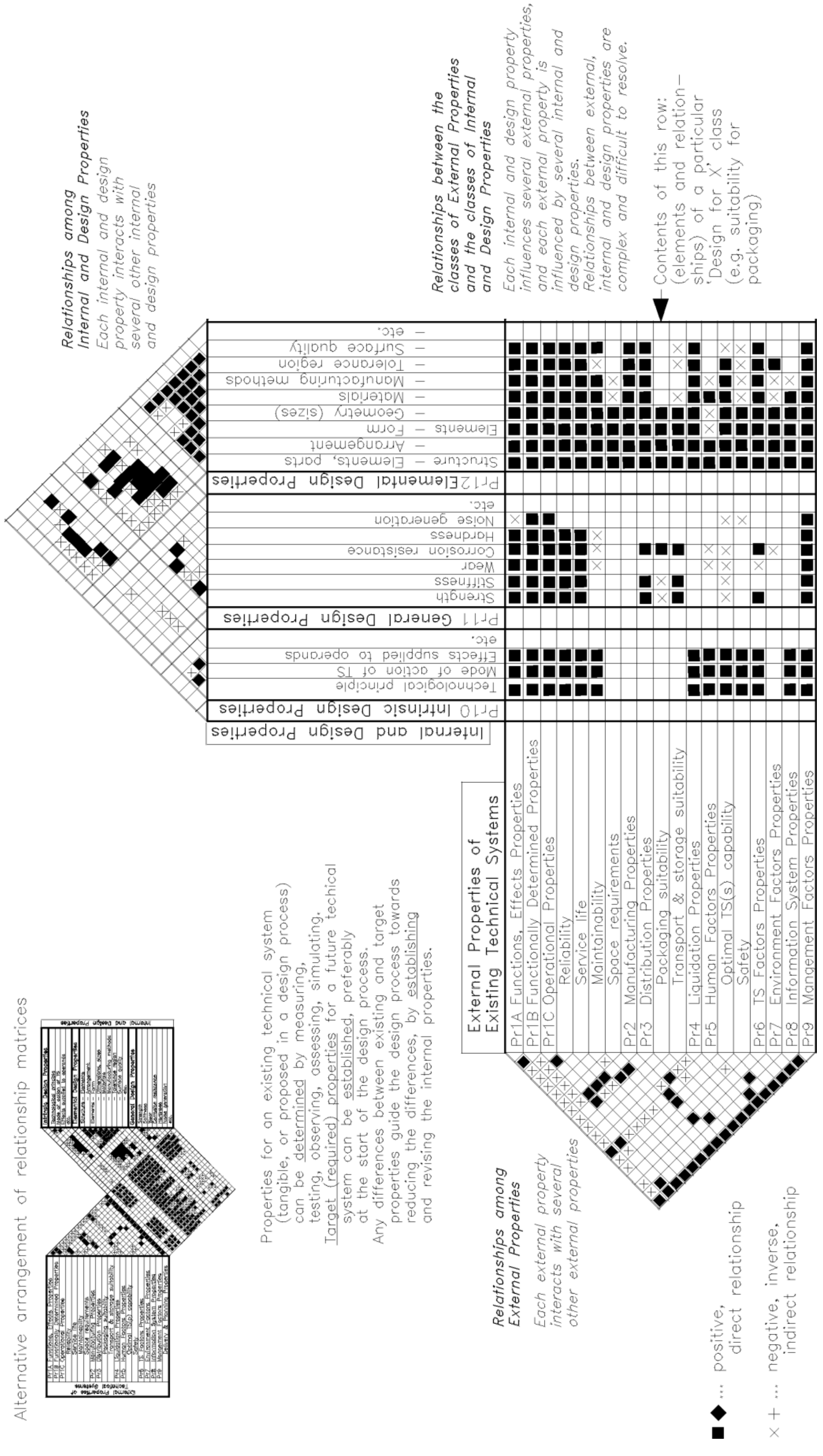

Figure 6. Relationships Among Classes of Properties of Existing Technical Systems (modified from [10])

the inner rectangular matrix. Each property influences several other properties. It is therefore possible to allocate any one property to one or more classes, a unique allocation is in most cases not possible. The ‘alternative arrangement’ shown in figure 6 (top left) is familiar to anyone who has read references [2,5,7,8,9].

5. TrfS-Requirements

Technical systems are always created and manufactured for a specific purpose. A need exists (or is created by advertising), and is usually expressed as a set of requirements to satisfy a purpose and a selection of external properties. Such requirements may be ‘stated’, ‘generally implied’, or ‘obligatory’ [17], where the generally implied category should normally be held to a reasonable minimum. Even in early developments about design thinking [18], it was found useful to recommend that the engineering designer (design team) should prepare a design specification (a list of requirements) to guide their work, and that this list should be agreed with management, and kept under frequent review.

In general, the external properties of a future TrfP(s)/TS(s) cannot be designed directly, except for aesthetic, ergonomic and emotional properties, which are generally covered by industrial design. For all other external properties (especially class Pr1), the designers directly (but iteratively and recursively) establish suitable internal and design properties (classes Pr10, Pr11 and Pr12) – the properties with which engineering designers should realize the future TS(s) – anticipating that suitable external properties will result.

As a basic principle, the primary and secondary classes of *requirements* for a future (not yet existing, ‘as should be’) new or re-designed TrfP(s)/TS(s) should be complete and comprehensive, with no gaps. They should therefore include (a) requirements and constraints of the organization, (b) requirements and constraints for the properties of the transformation process TrfP(s), and (c) requirements and constraints for the properties of the operators – especially for the TS(s) which needs to be designed.

The requirements and constraints for an organization with respect to a future TrfP(s)/TS(s) must be recognized and/or developed from the life-cycle phases LC1 – LC3, especially the processes and their operators, similar to the procedures in figure 3. Classes of requirements for a *transformation process,* TrfP(s) are similar to the classes of properties of transformation processes. Classes of requirements for a *technical system*, TS(s) operator, are directly analogous to its properties. The primary classes of requirements, Rq1 – Rq14, derived in this way are shown in figure 7.

Class Rq1 requirements for properties with respect to a specific organization are mostly unchanged from one design project to the next, they may be standardized as ‘boiler-plate’. Classes Rq12 – Rq14 are not usually specified. Requirements class Rq7 relates directly to industrial design.

Sub-classes, with suffixes of capital letters (e.g. Rq1A), are needed or useful in several of these TS-property classes to clarify the context of the life cycle, its operators, and especially its active and reactive environment, and its management. These should also be theoretically complete. Sub-classes for classes Rq1 and Rq2 (A – E) relate to the operators of the relevant transformation processes. Sub-classes for classes Rq7 and Rq8 (A– G) relate to the life cycle phases for the TS(s). Sub-classes for Rq9 (A, B) are complete in themselves. Sub-classes for Rq3, Rq10 and Rq11 are developed pragmatically and axiomatically, and are therefore augmented by a sub-class of ‘other’ to provide space for any special properties for a particular TS-‘sort’, or unanticipated properties, see figure 7.

Compared to figure 6, relationships among these classes of requirements can be illustrated as in figure 8. The relationships drawn for the internal and design requirements now show the directions for the processes of *finality*, i.e. during designing the requirements for external properties are translated into requirements for internal properties, whilst searching for alternative means to fulfill them, and selecting among them to find an optimal solution. The link to the properties of figure 6 is from the requirements for elemental design properties, class Rq14, to the established design properties of class Pr12.

Properties of a TS(s) to be designed must preferably fulfill all requirements that arise from each process in the TS life-cycle, and from the operators of each of these processes, in an optimal way.

TS-EXTERNAL PROPERTIES

Class	*Symbol*	*Description*		***With respect to:***
Rq1		Organization properties		LC1 -- LC3
	Rq1A	of human operators of LC1 -- LC3		
	Rq1B	of TS operators of LC1 -- LC3		
	Rq1C	of environment operators of LC1 -- LC3		
	Rq1D	of information operators of LC1 -- LC3		
	Rq1E	of management operators of LC1 -- LC3		
Rq2		Properties of the Transformation	*Purpose of TS(s) Operational Process -- the TP(s)*	LC6
	Rq2A	of human operators		
	Rq2B	of TS operators (Rq3 -- Rq14)		***Particular phases of the TS(s) life-cycle***
	Rq2C	of environment operators		
	Rq2D	of information operators		
	Rq2E	of management operators		
Rq3		Effects properties of the TS		LC6
	Rq3A	Function properties – behavior		
	Rq3B	Functionally determined properties – parameters, properties conditional on functioning (operating)		
	Rq3C	Operational properties		LC6a
Rq4		Manufacturing properties, planning and preparation – realization properties, manufacture, assembly, adjustment, packaging, etc.		LC4
Rq5		Distribution properties, maintenance and service organization, warranty, consulting		LC5
Rq6		Liquidation properties		LC7
Rq7		Human factors properties – ergonomics, esthetics, psychology and emotions, cultural acceptability		***Factors of particular operators of each TS(s) life-cycle phase***
	Rq7A	In product planning, LC1		
	Rq7B	In design engineering, LC2		
	Rq7C	In organizational preparation, LC3		
	Rq7D	In manufacturing, LC4		
	Rq7E	In distribution, LC5		
	Rq7F	In operation, LC6		
	Rq7G	In liquidation, LC7		
Rq8		Properties of factors of other TS (in their operational process)		
	Rq8A	In product planning, LC1		
	Rq8B	In design engineering, LC2		
	Rq8C	In organizational preparation, LC3		
	Rq8D	In manufacturing, LC4		
	Rq8E	In distribution, LC5		
	Rq8F	In operation, LC6		
	Rq8G	In liquidation, LC7		
Rq9		Environment factors properties		
	Rq9A	Social, cultural, geographic, political and other societal factors		
	Rq9B	Materials, energy and information – TP/TS inputs – effects of and on environment – TS-material – effects of and on environment – TP/TS secondary outputs and TS disposal		
Rq10		Information system factors properties -- including law and societal conformity, cultural, political, and economic considerations, information availability, etc.		
	Rq10A	Scientific information		
	Rq10B	Technological information		
	Rq10C	Societal information		
	Rq10D	Legal information		
	Rq10E	Cultural information		
	Rq10F	Other information		
Rq11		Management factors properties		
	Rq11A	Management planning – product range		
	Rq11B	Management of design process		
	Rq11C	Design documentation – design report, version control		
	Rq11D	Situation – management climate, personnel relationships, etc.		

Figure 7, Part 1. Primary and Secondary Classes of Requirements for a Transformation System

Properties	Class	Symbol	Description	With respect to:
TS–EXTERNAL PROPERTIES		MgtFPr		Factors of particular operators of each TS(s) life–cycle phase (cont.)
	Rq11E (cont.)		Quality system – quality of design, quality control, quality assurance	
	Rq11F		Information properties – licensing, intellectual property, etc.	
	Rq11G		Economic properties – costs, pricing, returns, financing, etc.	
	Rq11H		Time properties – delivery, planning, process durations, repair, maintenance, etc.	
	Rq11J		Tangible resources – availability, accessibility, etc.	
	Rq11K		Organization – goals, personnel, etc.	
	Rq11L		Supply chain properties – availability, delivery time, reputation, reliability, etc.	
	Rq11M		Other management aspects	
TS–INTERNAL PROPERTIES		DesPr	Engineering design properties	Designing
	Rq12		Intrinsic engineering design properties Technological principle Mode of action Technologies Action sites Mode of adjustment etc.	
	Rq13		General engineering design properties Application of engineering sciences: strength, stiffness, wear, corrosion, hardness, etc., physical. mechanical, thermal, chemical, electrical, optical, technological, biological, etc. properties	
TS–DESIGN PROPERTIES	Rq14	Cause of all TS(s) external properties	Elemental engineering design properties Structures –– function, organ, constructional structures Elements –– arrangement, relationships Elements –– Level of abstraction of modeling Form (incl. shape) Size (drawing dimensions) Materials (physical, mechanical, electrical, chemical, optical, thermal, technological, etc. properties Type of manufacturing Size deviation (tolerance, limits) Surface quality (roughness, chemical) etc.	

Relationships:

With respect to a transformation process within the transformation system, designing is not useful unless the purpose of the TrfP and the TS(s) 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 7, Part 2. Primary and Secondary Classes of Requirements for a Transformation System

For the engineering designers, there is therefore a need to set targets, to list all requirements with allowable deviations [18]. This should occur from the point of view of management, taking all legal aspects into account. It should also occur from the viewpoint of the engineering designers – a design specification, which can best be established by using the classes and sub-classes of requirements as shown in figure 7. This is the recommended *method* based on the *theory* that describes the *subject* of TS-properties. Further levels of sub-classes can be added to adapt these schemes to the needs of a particular industry and/or a specific TS-'sort'.

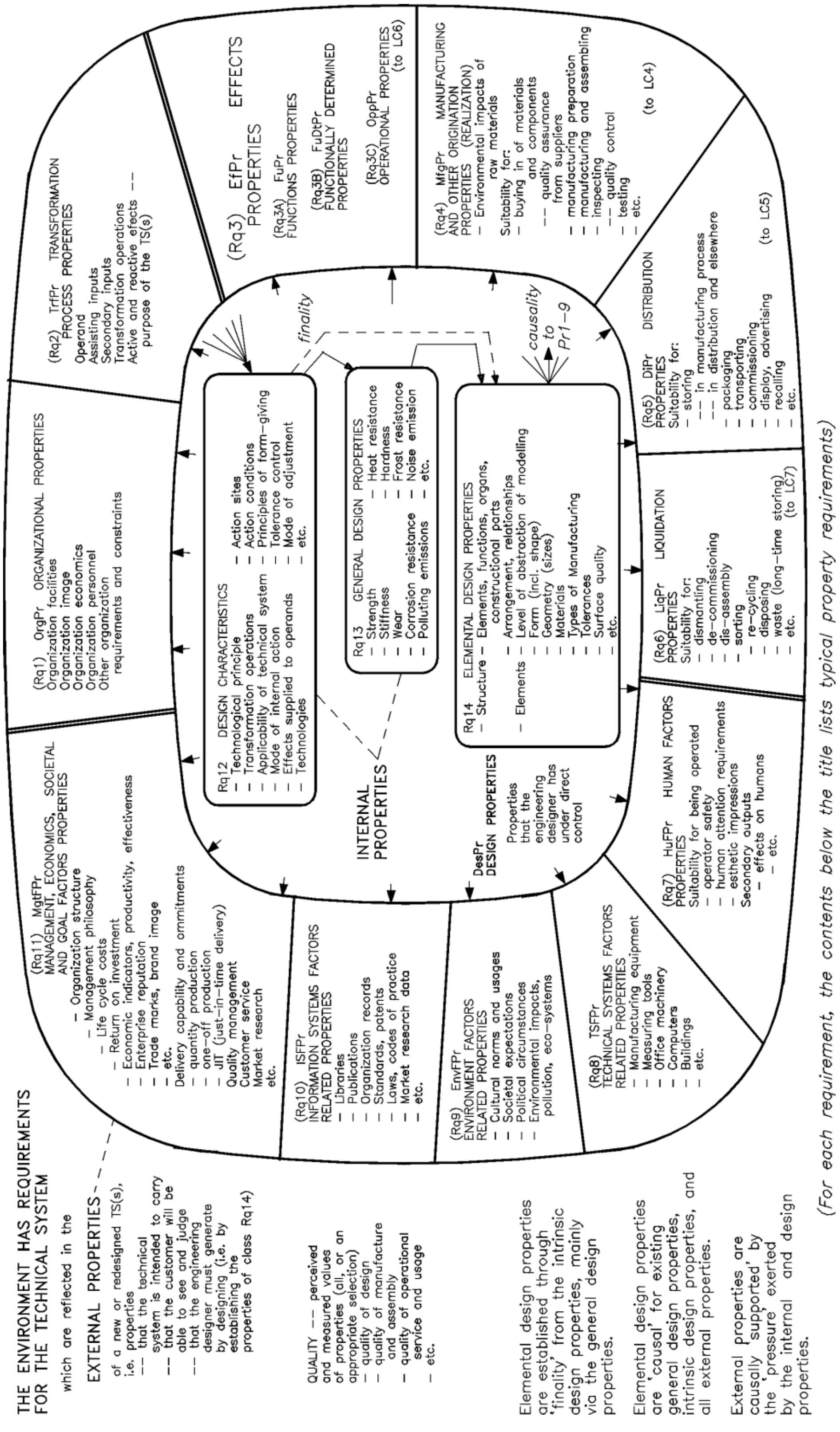

Figure 8. Relationships Among Classes of Requirements for a Technical System

5. TrfS-Requirements

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.

All internal and external properties of existing TS are caused by the elemental design properties, class Pr12, see figures 4 and 5. 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 [12].

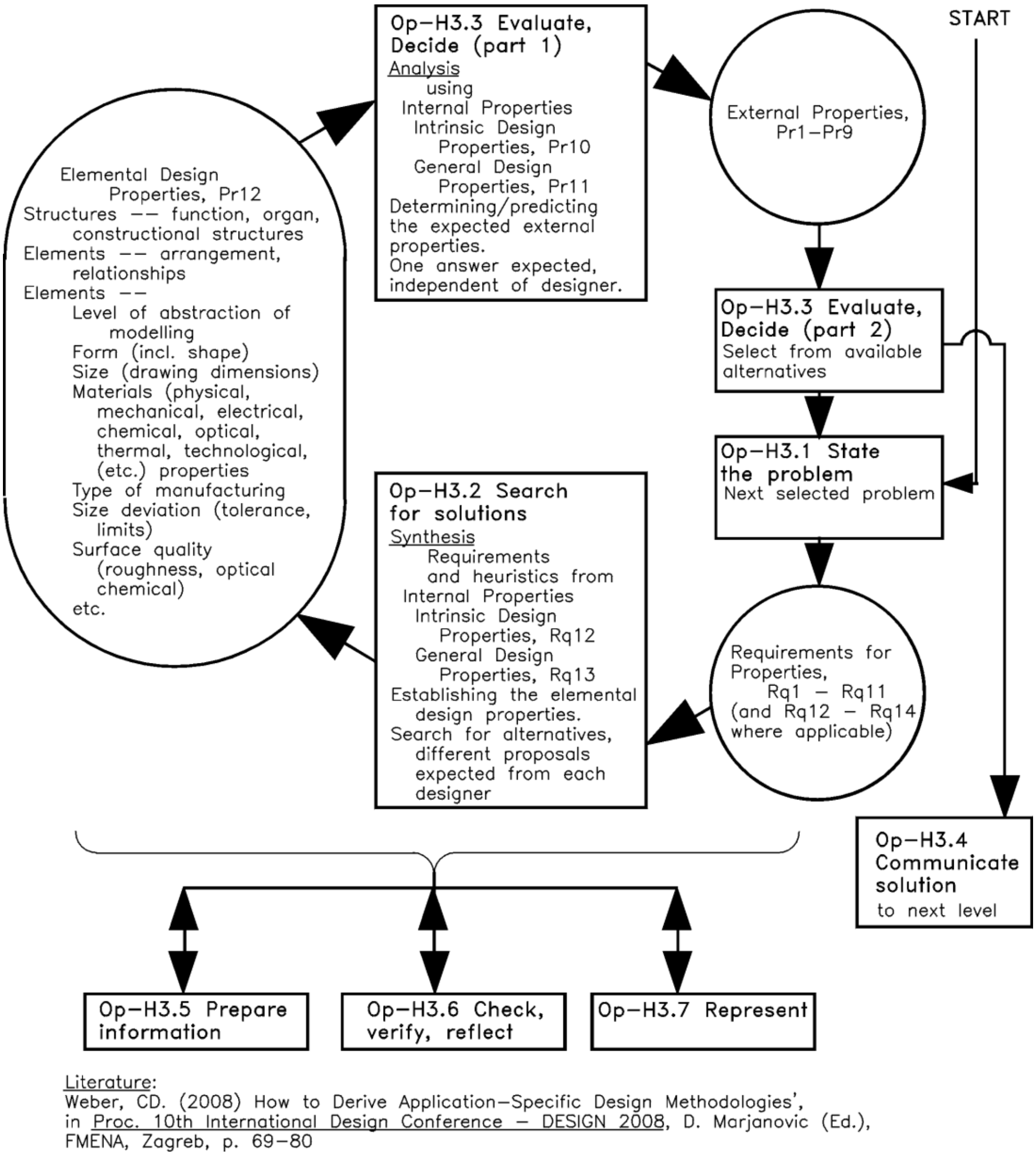

Figure 9. Main relationship Between Problem Solving, and Internal and External Properties (adapted from [12])

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 [19].

Analysis (analyzing) involves finding the causes and parameters of the actual or anticipated behaviour 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. It produces statements about (currently) existing ('as is') properties, and allows (a) a review of each 'as is' proposal to discover deficiencies in themselves (formulated by Pahl [20] as 'Fehleranalyse', fault analysis), and (b) a comparison of 'as is' properties with requirements.

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 behaviour – 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.

Synthesis and product development consists of establishing and assigning the product's internal properties from the *required* external properties. The internal properties show a complex relationship to the external properties, compare figure 6. In analysis, these relationships are known and can be determined, with one answer (subject to a range of error), see figure 10, 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 10, part B.

Solving the synthesis problem therefore requires an iterative procedure, whether consciously or intuitively applied, as illustrated in figures 10 and 11. This process selects appropriate requirements for external 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 [21]), 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].

The external TS-properties can in general only be established indirectly through the elemental design properties – the noteworthy 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. 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.

The need for planning at various levels of the life cycle of technical systems (see figure 6), especially in phases LC1 – LC3, should now be obvious. This is the reason for developing 'integrated product development' as the most suitable procedure.

6. Closure

The complexity of design engineering resides in the relationships among properties of technical systems. Engineering designers directly establish the internal properties of a technical system to be designed, in order to indirectly establish its external properties. Therefore there is a need for design engineering personnel to know (a) about TS-properties, both in their theory, and in their application as requirements, (b) about the essential nature of the engineering design process, and (c) a systematic and methodical procedure for design engineering as a fall-back position when intuition and experience is found deficient. Such knowing is best transmitted in an educational institution, before the designer needs to apply it in a serious and time-restricted situation.

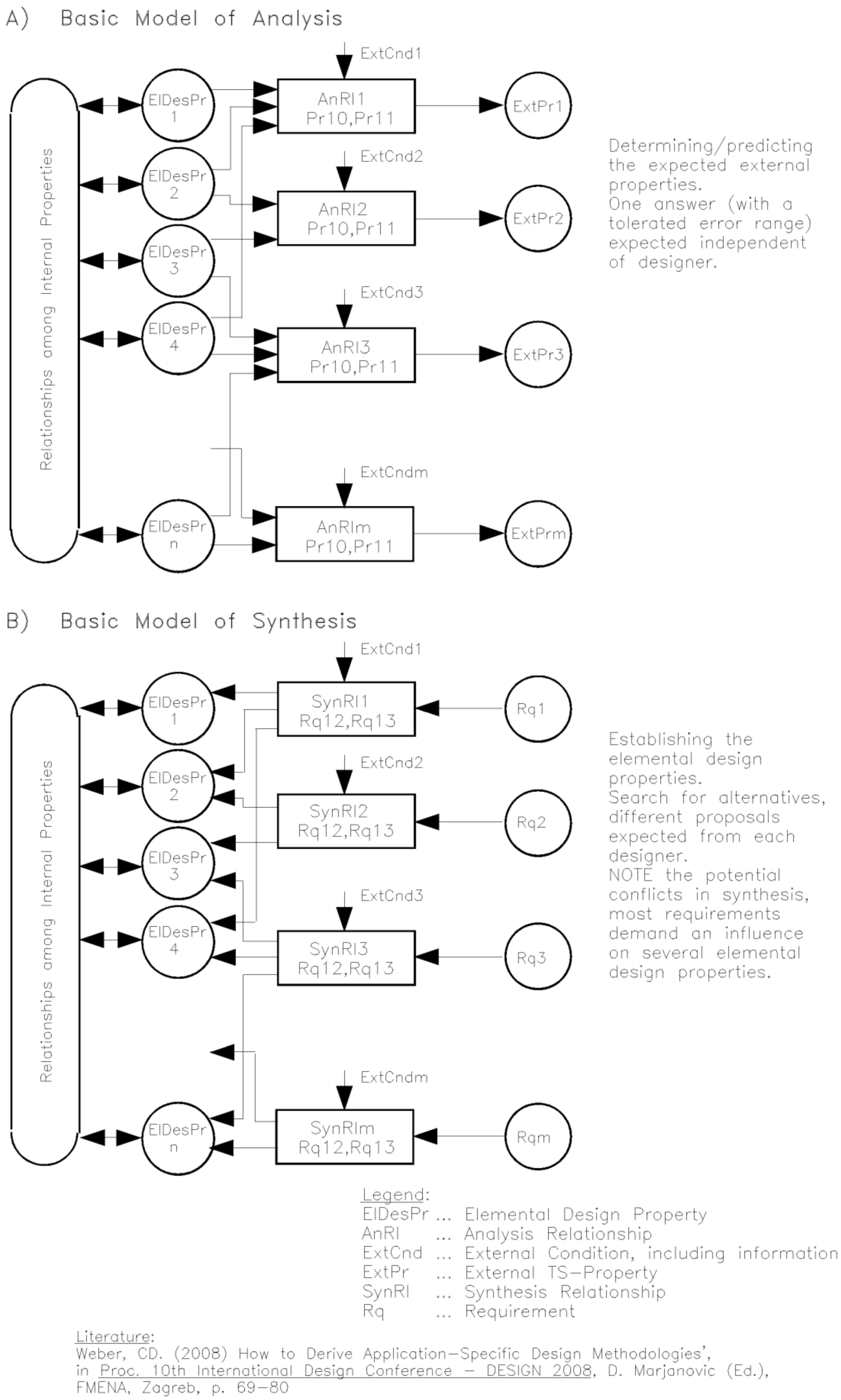

Figure 10. Basic Model of Analysis and Synthesis (adapted from [12])

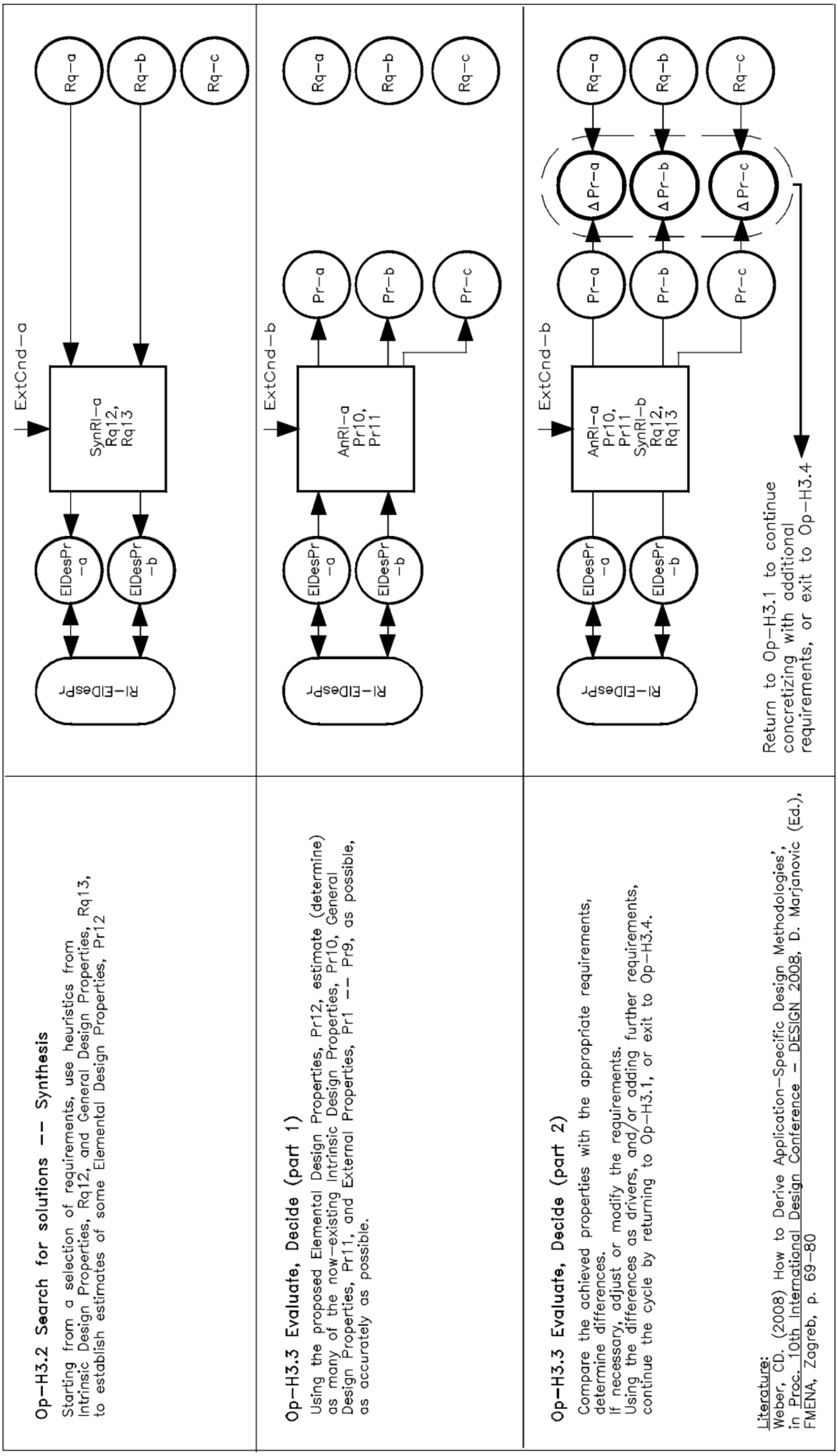

Figure 11. Iterative Scheme of Synthesis, Analysis and Evaluation (adapted from [12])

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