Requirements to Properties – Iterative Problem Solving

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Abstract

Following papers by this author in recent CDEN conferences, the concept of a complete theory-based classification is presented for the properties of existing transformation processes TrfP, and of their existing driving technical systems TS. Requirements for future TrfP and TS must include requirements set by the designing and manufacturing organization(s), the first three life-cycle phases in the theory-based model. An engineering design process intends to translate these requirements in several stages to the desired properties of TrfP and TS, using conscious or sub-conscious procedures for creative and routine steps.

For novel systems, this translation progresses via models of structures of TrfP, technologies, TS-internal and cross-boundary functions, organs and constructional parts. For redesign, mainly the more concrete structures are useful. Superimposed on this progress is a frequent cycle of problem-solving, including search for alternative solution proposals. Recent insights have shown that the requirements can be iteratively translated into properties. The difference between achieved (anticipated) properties and the relevant requirements dictated the necessary iteration behaviour, and drive the process of establishing the final proposed solution.

Such a formalized experience of staged and iterative designing is a good methodical basis for novices, and for design applications in which the process must substantially depart from routine procedures. Some case studies are referenced to demonstrate the application of this systematic and methodical approach.

1 Introduction

Previous papers by this author have appeared in the recent CDEN conferences. In general, they advocate the application of Engineering Design Science (EDS) [1,2,3,4] as basis for engineering education in all branches [5,6,7]. The Theory of Technical Systems [1], delivers the logic and explanation of those features

that all technical systems have in common, especially their place and role within society [8]. In order to fulfill the aim of generality for all branches of engineering, the subject of machine elements has received a revision to include all modes of action, including chemical, electrical, electronic, and others [9]

Design engineering is one of the major differences between engineering and the sciences – and it constitutes the difficulty for recent graduates when entering the profession. A systematic and methodical approach to designing based on Engineering Design Science has been proposed as best teaching tool for novices, and can prove useful for all engineering designers when they face a non-routine situation [10].

2 Properties And Requirements

The basic model of EDS [1,2,3,4] is that of the transformation system, figure 1, which 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 and cross-boundary 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.

From figure 1, seven stages of TS-life cycle can be defined: LC1 - product planning, LC2 - product designing, LC3 - manufacturing planning, LC4 – manufacturing, LC5 - product distributing, LC6 - product in use, LC7 - product liquidation. Real TS(s) life cycles consist of many such transformation systems, seven stages are a necessary minimum, and a maximum that preserves generality for all TS. The subscript ‘(s)’ is added to designate that TS as the subject of interest.

Figure 1. General Model of the Transformation System [3,4]

All products carry their properties, whether they have been deliberately designed, or occur as by-product of existence [11]. Many of these properties provide the purpose of the technical system, TS(s), its physical presence, and the outputs that can drive the processes we wish to perform, TrfP.

A complete theory-based classification for the properties of existing 'as is' transformation processes, TrfP for LC4 - LC7, can be derived from figure 1, see figure 2 [4], with addition of three axiomatic classes of intrinsic, general (these two are the mediating properties), and elemental design properties. This classification is complete, no other classes are needed.

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

Class	Description
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-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 2. Primary Classes of Properties for Existing Transformation Processes [4]

A complete theory-based classification for the properties of existing 'as is' technical systems, TS(s), can be derived from the life-cycle processes LC4 - LC7, and the operators of each of these life-cycle stages, see figure 3 [1,2,3,4], with addition of three axiomatic classes of intrinsic, general (these two are the mediating properties), and elemental design properties. This classification is complete, no other classes are needed.

Requirements for future 'as should be' TrfP and TS must include requirements set by the designing and manufacturing organization(s), the first three life-cycle phases in the theory-based model, LC1 - LC3. Otherwise, requirements follow the same pattern as the properties of TrfP and of TS. A complete classification, with sub-classes (each set complete in itself) is shown in figure 4. This scheme can readily be adapted to formalizing an arrangement for setting up a design specification, the recommended first activity for any design problem.

Advantages, Suitable for:	Symbol	Class of Properties	Typical Questions about the Class	Groups or Examples of Property Class -- Emergent Properties of TS(s)
Particular Phases -- Processes of TS(s)-Life Cycle	FuPr (Pr1A) - LC6	Functions Properties	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
	FuDP (Pr1B) - LC6	Functionally Determined Properties	What conditions are characteristic of the function?	Power, Speed, Size Functional dimensions Load capacity
	OpPr (Pr1C) - LC6	Operational Properties	How suitable is the TS(s) for its operational process TrfP(s)?	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
	DisPr (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
	HuPr (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 Form, color, surface
	TSPr (Pr6)	Technical System 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.
	EnvPr (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
	ISPr (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
TS-Observable Properties -- Particular Operators of Each Phase -- Process of TS(s)-Life Cycle	MgtPr (Pr9)	Management, Economics, Social, 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
	IntDesPr (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
	GDesPr (Pr11)	General Design Properties	Which engineering sciences, etc. are applicable?	
	DesPr (Pr12)	Design Properties	With what means are the observable properties (classes Pr1--Pr9) realized?	Structures (Fu, Org, C) Relationships/Elements Form, Shape, Geometry (size) Materials Type of manufacturing Surface quality State of assembly etc.
TS-Mediating and Design Properties		Causes of all Observable Properties of TS(s)		
TrfP-Mediating Properties				

Figure 3. Classes of Properties of Existing Technical Systems [4]

3 Design Process And Problem Solving

An engineering design process intends to translate these requirements in several stages to the desired properties of TrfP and TS, using conscious or sub-conscious procedures for creative, routine or systematic steps. In systematic and methodical design as recommended, progress uses the models of structures of TrfP, technologies, TS-internal and cross-boundary functions, organs and constructional parts.

Superimposed on this progress is a frequent cycle of problem-solving, including search for alternative solution proposals. Some models of problem solving are for analytical problems [12,13,14,15,16], self-motivation, and overcoming panic/fear [17,18, 19,20]. Figure 5 shows the basic operations, and additional questions, hints and operations taken from published models, as heuristic prescriptions.

The cycle of basic operations proceeds in four operational steps:

Op-H3.1 – determining, defining and clarifying the task ('framing' the problem),

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.				
TRIP-OBSERVABLE REQUIREMENTS	Class	Symbol	Description	With respect to:
	Rq1	OrgRq	Organization requirements of human operators of LC1 – LC3	LC1 – LC3
	Rq1A		of TS operators of LC1 – LC3	
	Rq1B		of environment operators of LC1 – LC3	
	Rq1D		of information operators of LC1 – LC3	
	Rq1E		of management operators of LC1 – LC3	
	Rq2	TrfRq	Requirements of the Transformation of operand in state Od1, Od2 and intermediate	LC6
	Rq2A		of assisting and secondary inputs	
	Rq2B		of secondary outputs	
	Rq2C		of technology Tg for each operation	
	Rq2E		of active and reactive effects exerted by operators that cause the TrfP(s)	
	Rq3	EfrRq	Effects requirements of the TS	LC6a
	Rq3A	FuRq	Function requirements – behavior	
	Rq3B	FuDRq	Functionally determined requirements – parameters, requirements conditional on the TS(s) operating	
Rq3C	OppRq	Operational requirements		
Rq4	MfgRq	Manufacturing requirements, planning and preparation – realization requirements, manufacture, assembly, adjustment, packaging, etc.		
Rq5	DirRq	Distribution requirements, maintenance and service organization, warranty, consulting	LC5	
Rq6	LiqRq	Liquidation requirements	LC7	
Rq7	HuFRq	Human factors requirements – 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 TS(s) operation, LC6		
Rq7G		In liquidation, LC7		
Rq8	TSFRq	Requirements 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 TS(s) operation, LC6		
Rq8G		In liquidation, LC7		
Rq9	EnvFRq	Environment factors requirements, LC1 – LC7	LC7	
Rq9A		Social, cultural, geographic, political and other societal factors		
Rq9B		Materials, energy and information		
Rq9C		– TrfP/TS inputs – effects of/on environment		
Rq9D		– TS-material – effects of and on environment		
Rq9E		– TrfP/TS secondary outputs and TS disposal		
Rq10	ISFRq	Information system factors requirements, LC1 – LC7		
Rq10A		including law and societal conformity, cultural, political, and economic considerations, information availability, etc.		
Rq10B		Scientific information		
Rq10C		Technological information		
Rq10D		Societal information		
Rq10E		Legal information		
Rq10F		Cultural information		
Rq10G		Other information		
Rq11	MgtFRq	Management factors requirements	LC7	
Rq11A		Management planning – product range, LC1		
Rq11B		Management of design process, LC2		
Rq11C		Design documentation – design report, version control, LC2		
Rq11D		Situation – management climate, personnel relationships, etc., LC2		

Part 1 of 2

Class	Symbol	Description	With respect to:
TS-OBSERVABLE REQUIREMENTS	Rq11E (cont.)	Quality system – quality of design, quality control, quality assurance	Factors of particular operators of each TS(s) life-cycle phase (cont.)
	Rq11F	Information requirements – licensing, intellectual property, etc.	
	Rq11G	Economic requirements – costs, pricing, returns, financing, etc.	
	Rq11H	Time requirements – delivery, planning, process durations, repair, maintenance, etc.	
	Rq11I	Tangible resources – availability, accessibility, etc.	
	Rq11J	Organization – goals, personnel, etc.	
	Rq11K	Supply chain requirements – availability, delivery time, reputation, reliability, etc.	
	Rq11L	Other management aspects	
	Rq11M		
	Rq12	Intrinsic engineering design requirements	
TRIP-OBSERVABLE REQUIREMENTS	Rq13	General engineering design requirements	Designing
	Rq13A	Application of engineering sciences: strength, stiffness, wear, corrosion, hardness, etc., physical, mechanical, thermal, chemical, electrical, optical, technological, biological, etc. requirements	
	Rq13B	Transformation principle	
	Rq13C	Mode of action	
	Rq13D	Technologies	
	Rq13E	Action sites	
	Rq13F	Mode of adjustment	
	Rq13G	etc.	
	Rq13H	General engineering design requirements	
	Rq13I	Application of engineering sciences: strength, stiffness, wear, corrosion, hardness, etc., physical, mechanical, thermal, chemical, electrical, optical, technological, biological, etc. requirements	
TRIP-OBSERVABLE REQUIREMENTS	Rq14	Engineering design requirements for TrfP(s) and TS(s)	Designing
	Rq14A	Elemental engineering design requirements	
	Rq14B	TrfP-Structure – operations structure	
	Rq14C	TS-Structures – function, organ, constructional structures	
	Rq14D	TrfP- and TS-Elements – arrangement, relationships	
	Rq14E	TS-Elements –	
	Rq14F	Level of abstraction of modeling	
	Rq14G	Form (incl. shape)	
	Rq14H	Size (drawing dimensions)	
	Rq14I	Materials (physical, mechanical, electrical, chemical, optical, thermal, technological, etc. properties)	
TRIP-OBSERVABLE REQUIREMENTS	Rq14J	Type of manufacturing	Designing
	Rq14K	Size deviation (tolerance, limits)	
	Rq14L	Surface quality (roughness, chemical) etc.	
	Rq14M		
	Rq14N		
	Rq14O		
	Rq14P		
	Rq14Q		
	Rq14R		
	Rq14S		

Relationships:

With respect to a transformation process within the transformation system, designing is not useful unless the purpose of the TrfP(s) 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 manufactured and purchased parts.

Management should be concerned with Life cycle assessment and engineering.

Quality management system – ISO 9000:2005

Part 2 of 2

Figure 4. Classes and Sub-Classes of Requirements for Transformation Systems [4]

Op-H3.2 – searching creatively and routinely for likely (and alternative) solutions, principles and means at differing levels of abstraction,

Op-H3.3 – evaluating, optimizing, improving, making decisions, and selecting the preferred or most promising solution(s), and

Op-H3.4 – fixing, describing, capturing the ‘design intent’, communicating the solution, transmitting to the records, the next phase, stage, step, or organization function.

These operations use three supporting operations:

Op-H3.5 – providing and preparing information,

Op-H3.6 – checking, including auditing, verifying, validating and reflecting, and

Op-H3.7 – representing, with solution proposals, etc.

These supporting operations appear only in the model of problem-solving attached to EDS, no other model of problem-solving makes specific mention of them.

Implications embedded in this scheme of problem-solving include: (a) all of the steps and operations depend on each other, and must consider the later or earlier steps or operations; (b) iterative and recursive working is essential, usually in several rounds of concretization; (c) the sequencing of these operations can be altered; (d) the operations can be performed ‘on paper’ (recorded) and/or in the human mind (tacit) – preferably in an interaction between these, in view of the mental limitations of 7+/- 2 chunks of information in short-term memory [21,22,23,24,25] or less [26,27]. The general procedure should consist of a ‘quick and dirty’ [28] first run through the steps and operations, and then a more detailed treatment in several rounds. Especially before attempting step Op-H3.2, at least a rough and preliminary consideration of Op-H3.1 should have been made. Steps Op-H3.2 and Op-H3.3 should be kept separate, psychology indicates that judgmental attitudes tend to suppress idea-generation. Normal human behaviour is to mix these steps. Better control and consideration of alternatives uses the steps in the given order, or at least keeps the documented records in that order. The problem-solver should be familiar with the use of the component steps and operations, and be aware of this usage.

Each engineering design operation is usually processed in an interchange among the basic operations. Investigating or assuming a part of the problem in another operation (making a *conjecture*) can explain and clarify the task, and lead by iteration and reflection to a more concrete result. The tasks can and should be decomposed (recursively) into subordinate problems, treated in (similar) cycles of basic operations to achieve partial solutions, and

Figure 5. Basic Operations – Problem Solving in the Design Process [3,4,15,18,19]

incorporated into the main cycle and its results. Conflicts between partial solutions occur, to be treated as problems to be solved in a cycle of basic operations

These basic operations of level H3 are also recognizable in subconscious (preconscious) forms in intuitive modes of operation. They should be learned, become internalized, 'second nature' or intuitive.

Simpler and more routine engineering design operations are more readily performed subconsciously, intuitively. More complex and difficult engineering design operations may demand a conscious procedure, level H3 guides the procedure. These basic operations represent fundamental design activities, but are not exclusive to designing. The usual engineering working principles should be respected.

4 Relationships

More recent insights [4] have demonstrated that the requirements must be iteratively translated into properties. All mediating (intrinsic and general) and observable properties of existing TrfP/TS are caused by the elemental design properties. During design engineering, the elemental design properties (including all structures) are gradually established from the requirements, in a process involving the basic operations of problem solving, with multiple

iterations. Figure 6 [29] shows a relationship of these operations with the TS-properties and requirements, the main processes are basic operations of problem solving. The difference between achieved (anticipated) properties and the relevant requirements dictate the necessary iteration behaviour, and drive the progress of establishing the final proposed solution [16].

Three types of task may be asked with respect to engineering products (systems) [30]:

Analysis: given a structure, find its behaviour and other properties – an entity is decomposed and explored, using *causality*, and mathematical models, engineering sciences – yielding one established manifestation and value for an existing system, or one (best) estimate in anticipation of a future system;

Synthesis: given the desired behaviour and other requirements, find a structure that satisfies the behaviour 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*, including creativity, to find and select among candidate solutions for a TrfP(s) and/or TS(s), including manifestations and values of properties – design engineering – any action of synthesis usually influences several anticipated properties of a future system;

Figure 6. Main Relationships Between Problem Solving, and Mediating. Elemental Design and Observable Properties [4] (adapted from [16])

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

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

5 Discussion

Such a formalized experience of staged and iterative designing is a good methodical basis for novices, and for design applications in which the process must substantially depart from routine procedures [10].

One of the difficulties of designing is the heuristic use of engineering sciences and of other information. Currently, engineering curricula are based on the analytical applications of engineering sciences. This allows convenient written examination, generally one answer is acceptable, and marking is relatively easy. In contrast, designing generally delivers a different result for each examinee, in action principles, in conceptualizing, and in detail execution. Acceptability of the proposed solution must be checked individually, marking is difficult and tends to be more subjective. Mentoring on design projects requires at least some industrial-type experience from the instructor. The added substantial teaching load must be acknowledged by the Department, Faculty and College.

Some case studies were developed, to verify, to check for deficiencies and to propose improvements to

the theory and its applied methods. The second more important aim is to demonstrate the application of this systematic and methodical approach, and to show the information contained in the structure models.

The first case study appeared in 1976 [31] – a machine vice. The second appeared in 1980 [32] – a welding positioner. The next eight were published in 1988 [33] – a riveting fixture, a milling jig, a powder-coating machine, a P-V-T-experiment, a hand winding machine for tapes, a tea brewing machine, a wave-powered bilge pump, and an oil drain valve – six were systematic, the tea machine and the bilge pump only loosely followed the systematic method, it took an industrial-artistic design approach. Three further case studies were published in 2008 [3] – the tea machine (from [33]) revised to current systematic procedures showing enhanced engineering information; re-design of a water valve [34]; and an electro-static smoke gas dust precipitator, with rapper for dust removal. The most recent book [4] contains three more cases – a portable trapeze demonstration frame [35], re-design of an automotive oil pump [36], and a hospital intensive care bed, with support compensation for bed tilting.

These theories and methods have been taught in engineering at the Eidgenössische Technische Hochschule, Zürich (1970 - 2000), at the Royal Military College of Canada (1981 - 2006), and at the University of West Bohemia, Pilsen, Czech Republic (1989 - present). The advantage for students seems to have been in learning a consistent design methodology, and in added general understanding of the context of engineering in society. In Pilsen, post-graduate degrees have been achieved, and courses and consultations have been held for industry, where the methods have been found useful for innovative work.

6 Closure

Engineering Design Science [1,2,3,4] has been under development since the mid-1960's. The theory and its design methodology have now reached sufficient maturity to be useful for teaching and practice.

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