Theory of Technical Systems – Relationships to Engineering Sciences

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Abstract

Products (process or tangible systems) are defined with reference to standard ISO9000:2005. Designing products with a substantial engineering content, technical systems (TS), means to fully describe them ready for manufacture – in detail and assembly drawings, parts lists, adjustment instructions, customer instructions, etc. Designing must take into account all recognized requirements, especially implied and stated requirements for the designing-manufacturing-distributing organization, the intended transformation process (TrfP), and all other phases of the TS-life cycle, including societal norms, economic considerations, etc. The theory of technical systems (TTS) and its associated engineering design science (EDS) provides a framework for design considerations about engineering products, including the technology, TS-life cycle, properties, and other aspects of artificial transformations and their operators. The triad 'theory - subject - method' suggests that a systematic engineering design method can be derived from TTS and EDS, to augment the usual intuitive design procedure, especially where the design problem is not routine. Engineering sciences are essential in this design process, (a) for analysis of existing systems and/or proposals for synthesis of designed systems, and (b) to assist as heuristics during design synthesis. Design synthesis is the more difficult operation, it requires iterative working. Several case examples have been published to demonstrate the application of the recommended systematic design method. Some of the relationships between engineering sciences and systematic design processes are explored to show their interdependence, and the need to provide a wider context in this area.

1 Introduction

A 'product' is defined by ISO 9000:2005 [1,2] as a 'result of any process', classified as:

- a) *hardware*: tangible, material objects, with countable quantity;

- b) *software*: information, and intangible objects – insurance policies, laws, computer programs, etc., usually on hardware carriers;
- c) *service*: intangible results of an activity (a process) performed at the interface between supplier and customer – providing electricity, water, fuel, transportation, garbage removal, policing, wholesale and retail, advertising, ambience, etc.; and
- d) *processed material*: solid, liquid or gaseous (bulk) material that can be measured in units of volume, mass, energy, etc. – plastic pellets, fuel, grease, coolant liquid.

Energy is not uniquely classified by ISO (fuel appears in two sections). Electrical energy can be measured – implies 'processed material'. Some changes in hardware, software and/or processed material may be included in '(c) service', e.g. garbage removal treats garbage as hardware and processed material.

A classification better coordinated with the mathematical expressions of theories in the engineering sciences, and used in this paper is:

- (A) living material – L – can only appear as operand being transformed,
- (B) inanimate material – M,
- (C) energy – E, and
- (D) information – I, including signals, commands, data, etc.

Where the products are manufactured or processed, both the product, its operational (usage) process (if applicable), and its manufacturing process needs to be established in advance of its existence – a process usually called 'designing'. If the designed product has a substantial engineering content, the product is either a transformation system, TrfS, or only a technical system, TS, and needs design engineering to satisfy the requirements. A classification of many sorts of products has been published [3 (Ch. 1.7), 4 (Ch. 3)].

2 Theory Of Technical Systems (TTS)

A generalized theory to (non-mathematically) describe any artificial transformation and its causes (operators) and conditions has been under development since the

1960's [3-12], and has been expanded to an engineering design science (EDS) [3,4,11,12] – a scientific explanation of the general phenomenon of design engineering (as a process) and its expected outcome, a full and implementable description of a proposed transformation system.

The concept of the system of Engineering Design Science (EDS) [3,4,11,12] is based on the triad ‘theory – subject – method’ [13]: ‘both theory and method emerge from the phenomenon of the subject’. A close relationship should exist between a *subject* (its nature as a concept or product), a basic *theory* (formal or informal, recorded or in a human mind), and a recommended *method* for voluntary application. A *theory* about a subject allows a *method* to be defined and heuristically applied, for using or for designing the *subject*.

A further consideration is that knowledge and information about design engineering can be ‘mapped’ onto two orthogonal axes, see figure 1 [3,4,11,12]. The north-south axis ranges from ‘practice information’ to ‘theory knowledge’. The west-east axis ranges from ‘information about existing transformation systems’ to ‘information about designing and design processes’. This points to the importance of (a) information about technical and other objects, existing and to be designed, and (b) information about design processes, including the mental activities and the methods that may be useful for designing.

Figure 1. Map of Engineering Design Science [3,4,11,12]

The basis of the theory of technical systems, TTS [3,4,8,10], the south-west quadrant of figure 2, is an axiomatically complete abstract model applicable for all (artificial, man-made) transformation systems, see figure 2.

Figure 2. General Model of a Transformation System [3,4]

The model of the *transformation system* in figure 2 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 HuS, technical systems TS, active and reactive environment AEnv, information systems IS, and management systems MgtS, as output effects from their internal and cross-boundary processes, acting separately and/or jointly), 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.

The operators can be active or reactive in their interaction with each other and in their technology-interaction with the operand. For example, a bridge is almost purely reactive, a hand power tool is reactive to its human operator, but active towards the operand, an automotive automatic transmission is mainly active.

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

The general environment (regional, national and global) covers physical, chemical, societal, economic, cultural, political, ideological, geographic and all other influences indirectly acting on or reacting to the transformation system.

A generalized life cycle of technical systems, TS(s), is axiomatically complete, and consists of typically seven (classes of) transformation systems: LC1 - product planning, LC2 - designing the product, LC3 - technological and organizational preparation for subsequent life-cycle phases, especially manufacture and a supply chain, LC4 - manufacture and assembly,

LC5 - distribution, LC6 - operation of the product, including tool changing, maintenance, repair, upgrading, LC7 - liquidation and disposal.

Classes of properties of existing transformation processes and technical systems are separated into *observable* (previously ‘external’), *mediating* (previously ‘internal’), and *elemental design properties*. TS-observable are the properties that anyone can see, assess and/or measure for the chosen boundaries of the TS. TS-mediating are the properties that are not observable, they are hidden by the chosen boundaries of the TS, and those related to the engineering experiential information (*intrinsic* properties, including mode of action) and engineering sciences (*general design* properties). TS-elemental design properties are those that are under the direct control of engineering designers during the design process, and include the TS-structures (function, organ and constructional, see figure 3), their elements and relationships, and for the elements the classes of arrangement, form, size, materials, anticipated manufacturing methods, deviations, surface quality, etc. Any one property can appear in one or more classes, and the classification can change according to the situation, e.g. a change of the assumed TS-boundary and ‘window’ of attention [14].

Figure 3. Model of a Technical System – Structures [3,4]

Conceptually, ‘TS-internal’ refers to the volume (or equivalent) occupied by TS itself. Properties include its crystal structure, depending on temperature changes, embrittlement, piezo-electric effects, state of

static and dynamic stress, etc. A ‘TS-enclosed space’, not occupied by TS itself, is an ‘interior’ (usable) space, e.g. in a car for the operator and passengers, in a refrigerator for food and other items to be cooled, in a gas turbine for thermodynamic and gas-dynamic processes. These represent the transformation processes, TrfP, that must be considered ‘TS-external’ for the TS-boundary chosen at that time.

3 Systematic Design Process

The theory outlined in section 2 is the basis for the recommended systematic engineering design method, to be applied when needed.

Once the logic of the transformation system (TrfS), figure 2, and of the structures of TS, figure 3, is understood, it is easily possible to derive a systematic approach to design engineering of *transformation* systems as products – usage processes, LC6, and technical systems, TS(s). Initially, a design specification (list of requirements) should be generated, including requirements for life cycle phases LC1 - LC3 (organizational requirements), for the transformation process (TrfP) and the technical system, TS(s) to be designed – recommendations for this have been published [4]. Attempting to satisfy such a list of requirements, a designer (or team) can establish (in approximately that order) a TrfP(s), the needed technologies, a suitable TS-internal and cross-boundary function structure, a suitable TS-organ structure, and a suitable TS-constructional structure in preliminary layout, definitive/dimensional layout, and detail (first described in [5]). At each stage it is possible (advisable) to search for candidate alternative solutions, and to select the most promising for further processing, whilst keeping full records of the (temporarily) rejected solution proposals.

Any recommended systematic and methodical approach to design engineering must adapted (usually by the individual designer) to the personal style and experience, and parts or the whole used as needed for novel and re-design. Most published methods derived from other theories, from pragmatic practice, or intuitive approaches can be combined into this formal systematic method [3,4].

Redesign is then easily accomplished by analyzing an existing TS-constructional structure (e.g. assembly drawing) to derive a TS-organ structure and a TS-function structure, then altering the function structure to suit the new design specification, and proceeding with the systematic method towards a revised TS-constructional structure.

Normally, innovations are limited to a relatively small section of the engineering product, partly to

limit the risks involved, partly to bring a ‘new’ product to market as quickly as possible. Sample case studies showing the application of this systematic approach, using models from the theory of technical systems [3,4,8], are available [3,4,9,15,16,17,18,19].

The apparent linearity of this procedure is only a broad approximation [20], parts of the TrfP(s) and/or TS(s) will inevitably be at different stages of concretization, and will force iterative and recursive working [21] – repeating a part of the design process with enhanced information to improve the solution proposals, and breaking the larger problem into smaller ones to solve and re-combine. In the process, the perceived or assumed TS-boundary is frequently redefined to restrict and focus the designer’s ‘window’ of observation [14].

Superimposed on the systematic approach to design engineering is a frequently applied sub-process of problem solving (first defined in [6]). In its latest manifestation, this problem solving process appears as in figure 4. Noteworthy are the three auxiliary processes: Op-H3.5 ‘Prepare information’, Op-H3.6 ‘Verify, check, reflect’, and Op-H3.7 ‘Represent’ – these have not been specifically stated in any other model of problem solving.

Figure 4. Basic Operations – Problem Solving in the Design Process [3,4,22-28]

The main cycle, Op-H3.1—Op-H3.4, first published in [6], has recently been confirmed in cognitive psychology under the designation of ‘creativity’, with phases of ‘analysis’, ‘generation’, ‘evaluation’, and ‘communication/implementation’ – the identity is obvious, with creativity residing mainly in Op-H3.2 and ‘generation’.

4 Engineering Sciences

For design engineering, a knowledge of the individual relevant engineering sciences is absolutely necessary, but not sufficient. Designing also needs information that is not capable of description in scientific terms, stemming from technological experience (e.g. of manufacturing), human, societal, economic, and many other aspects. Much of this information is not available in mathematical form, but verbal, numerical

and/or graphical representation is often available for interpretation. All the requirements given by a customer (or his/her representative) and demanded by the supplier and general society should be satisfied by the resulting products.

The engineering sciences formulate (usually mathematical) theories of behaviour of aspects of existing processes, TrfP, and tangible systems, TS, based on simplifying assumptions about the situation, usually looking at a single form of physical phenomenon in isolation. They are therefore essential (a) for analysis of existing systems, and of proposed solutions to design problems to determine its properties, and (b) for heuristic ‘what-if’ explorations and simulations – part of design synthesis [29,30]. Design synthesis is the more difficult operation, it requires iterative and recursive working.

Quasi-separate subjects covered include thermodynamics, statics and dynamics of mechanical system, strength and properties of materials, fluid statics and dynamics, electro-magnetic phenomena, digital and analog electronics, mathematics, and many others.

The engineering sciences are interdependent, yet any attempt to combine two or more individual engineering sciences would usually fail, the mathematical expressions would be far too complicated. Yet for both analytical and heuristic-synthesizing applications, a conceptual context and connectivity among these sciences must be established, especially in the mind of the user [31]. In addition, their use as heuristic tools towards designing must be developed and practiced.

5 Relationships between TTS and Engineering Sciences

The TrfS (and/or its operator TS) to be designed should (eventually) fulfill its required task, i.e. provide its performance as expected during usage. This means that the transformation process, TrfP, should become operational, the technologies, Tg, should operate as expected, and the operators should behave as expected. Each of these can be analyzed by using the appropriate engineering (or other) sciences after (and/or during) designing, and these sciences can be used heuristically to assist in synthesizing the systems.

For the only operator that is subject to deliberate designing, the TS(s), its internal and cross-boundary constituents and their structures should be established in the design process as outlined in section 3. A TS-function structure (with possible alternatives in arrangement and/or formulation) describes and establishes the required TS-internal and cross-boundary behaviour, some of which can be analyzed

and/or simulated from that function structure – maybe only in verbal and/or graphical terms.

With the help of a morphological matrix, a TS-organ structure (with alternatives) can be established, which provides a possible arrangement of the TS-internal ‘mechanism’ – usually without sizes such as wall thickness and distances between organs. By adding a (3D) overall geometry, a topology, analysis by engineering science techniques such as statics, free-body diagrams, kinematics, etc. becomes available.

Derived from the organ structure, a TS-constructional structure (with alternatives) in the form of a preliminary layout allows first heuristic use of strength of materials, electro-magnetic loading, etc. to establish estimates of required sizes from the appropriate engineering sciences. The TS-constructional structure can then be progressively refined, to a definitive (dimensional, true-to-size) layout, and detail and assembly drawings (or their computer-resident equivalents), with improved estimates of required sizes. CAD application is really only feasible from a dimensional layout into detail, although some CAD application programs can cope with changes in geometric proportions. Designing is complete if the future TS(s) is fully described in manufacturable form.

By (creatively) generating alternatives at every such level of abstraction, a sufficiently wide range of the solution space can be covered. In order to avoid combinatorial complexity, at each level of abstraction a choice should be made to select only the most promising alternative(s) – but this must be made reversible by good record-keeping, in case a selected alternative (at any level) becomes less promising. This procedure results in conceptual, verbal, graphical and/or mathematical optimization – the resulting proposed TS(s) will then likely be optimal, i.e. not a single optimum, it cannot exist to satisfy all potential customers/users, but close enough to satisfy most.

6 Closure

The insights about theory of technical systems, design processes, and engineering sciences presented in this paper give a reasonable argument for revising engineering curricula in all programs. It is necessary to provide a conceptual framework to connect the essential engineering sciences with each other, and with the needs of systematic design engineering. For this purpose, education in systematic and methodical design engineering is essential, and differentiates engineering graduates from science graduates. In this way, competent graduates who can take their place in industry with a minimum of further training can be educated.

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