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SPECIALIZED DESIGN SCIENCES – QUESTIONS FOR THE FUTURE

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1. Introduction

In engineering practice, the designers always have the task of designing a concrete object. In most cases they have a relatively clear impression (a mental picture) about the result – they must design a milling machine, a bicycle, or a dish-washer – but sometimes no such picture is available. We pose the question about what knowledge (external and internalized/tacit) and insights are needed by designers to successfully complete their task, i.e. to achieve the quality of a product that is acceptable on the market, and to make the design process short and effective – right first time.

At the moment of 'solving' a task, the internalized knowledge of a designer is known to consist of (a) the systematically acquired knowledge from schooling, literature, formal discussions, etc. – collectively the 'theoretical branch knowledge' – and (b) the informally acquired 'experience (branch) knowledge'. Both are progressively incorporated into the designer' idiosyncratic tacit knowledge system. They are a primary requisite for the designer's creativity [Eder 1994]. The proportions of these types of knowledge and their quality are different for various designers and for differing tasks. In general, the theoretical branch knowledge tends to be of higher quality, because it is more objective, homogeneous, categorized, cross-related and confirmed (tested). The transfer distance is also important – if the knowledge is found in a region that is distant from the task and experience (in direction of relationship of branch areas, level of abstraction, etc.) the transfer may be difficult and subject to errors. Transfer ability should thus be an educational goal [Pahl 1995].

It is therefore one of the tasks, starting from the theoretical basis contained in Design Science [Hubka & Eder 1996] and its constituents [Hubka & Eder 1988, Hubka 1976, Hubka & Eder 1992, Hubka & Andreasen], to prepare more specialized knowledge systems for designers that are as 'close' as possible or feasible to their tasks, such that their work leads more reliably to an optimal technical system, in effective work and within a short time.

In order to explain the formation of a specialized design science for an example, machine tools, we must first define a terminology and describe the structure of the general Design Science [Hubka & Eder 1996]. The reader can then transfer the knowledge of his/her own area into this structure.

2. General Design Science

Every artificial process, and every artificial material object must be thought out in advance of any realization or implementation, i.e. they must be designed. Designed objects that have a substantial engineering content are called 'technical systems' (TS), and are the subjects of 'engineering design'.

In Design Science [Hubka & Eder 1996], the scientific investigation of engineering design, we have chosen to systematize the knowledge about designing using a morphology (a systematic study of form) as follows:

Characteristics of Statements of Design Science, and States of Embodiment

Methodological Category of Statement

a) Primarily descriptive (d-statement), i.e. theorizing, not merely a narrative ;
b) Primarily (voluntary) prescriptive (p-statement), and (compulsory) normative (n-statement).

Empirical Support for Statement

a) Pre-scientific (practice – experiences);
b) Scientific: singular ‘understanding;’
c) Scientific: inductive – statistical.

Recipient of Statement (typically)

a) Novice, student;
b) Teacher, researcher;
c) Practitioner, engineering designer.

Aspects of Designing

a) The technical system, i.e. the engineering product to be designed;
b) The process of designing.

Range of Objects as Subject of Statement

a) Universal: all artificial real and process systems;
b) Technical real systems = TS;
c) Branch-specific reference objects of engineering: machine, etc., constructional elements

Experience and Status of Author of Statement

a) Branch or discipline of the authors;
b) Position in organization;
c) Primary activity: practice, research, education.

Declared Aims of Researcher

a) ‘Automation’ of (all or part of) a process of designing;
b) Better empirical foundation for a methodology or method;
c) Others.

Other Classes

Two viewpoints in this morphology seem to be the most important:

1) the subject under discussion: the TS, and the design process; and
2) the methodological categorization: descriptive/theory, and prescriptive/advice and/or normative/compulsion – the last two are usually combined.

This leads to four sectors in a ‘map’ of Design Science:

- theory of technical systems [Hubka & Eder 1988], a general theory, and many specialized theories, differentiated according to the complexity of TS, degree of abstraction, and other aspects
- practice knowledge about technical systems
- theory of design processes [Hubka 1976], a general theory, and many specialized theories
- practice knowledge about design processes

Within each sector, a sub-structure can be identified. The parts for technical systems include (see section 3 of this paper):

- nature of transformation processes and their operators, including technical systems
- structures and configuration, including elements, relationships, and modes of action
- taxonomy, systematics, ways of classifying technical systems
- properties of technical systems, their classes
- evaluation and decision-making for technical systems
- modelling and representation of technical systems
- origination and usage, life cycles of technical systems
- development in time of technical systems, evolution

The sub-structure for design processes includes (see section 4 of this paper):

- design processes and their operators, basic knowledge of designing
- design process structure, activities

- taxonomy, systematics, ways of classifying design processes
- operators of design processes:
  - engineering designers – human systems (HuS)
  - working means, tools, means for representing TS, including computers – technical systems (TS)
  - design information, branch design process knowledge, methods – information systems(IS)
  - parameters and systems to perform design work – management and goals systems (M&GS)
  - working conditions for engineering designers – active environment (AEnv)

3. Insights from Design Science about Technical Systems

The general model of a transformation system (figure 7–2 in [Hubka & Eder 1996], figures 3.1 and 3.2 in [Hubka & Eder 1988], and figure 2–1 in [Hubka & Eder 1992]) is used as the starting point for deriving many process models, including the design process. These process models can be concretized for particular design situations, and indicate appropriate methods, procedures and approaches that can be used during designing.

The general transformation shows an operand being transformed in a transformation process, from state 1 to state 2, subjected to secondary inputs and delivering also secondary outputs. The process is driven by the effects delivered by the five classes of operators: human systems, technical systems, information systems, management and goals systems, and the active environment. The assisting inputs of energy, material and information (including signals and commands) affect both the operand in its transformation, and the operators.

Every technical system allows several different kinds of structures to be formulated (figure 7–3 in [Hubka & Eder 1996], figure 5.4 in [Hubka & Eder 1988], and figure 4–9 in [Hubka & Eder 1992]). The most obvious is the constructional structure, consisting of constructional elements (‘hardware’, machine elements, etc.) and their relationships (arrangement in space, configuration, parameters). More abstract is the organ structure, consisting of the active connections between constructional elements (and their relationships) which establish the mode of action and behaviours of the technical system. Still more abstract is the function structure, which describes (mainly in words – a verb phrase plus a noun phrase) the internal capabilities of the technical system that allow it to deliver the needed effects.

Every technical system carries appropriate properties, whether they have been consciously designed, or appear as incidental (accidental) from designing. These properties can be gathered into typically 11 classes of external properties and a class of internal properties (see figure 7–5 in [Hubka & Eder 1996], figures 7.1 and 7.5 in [Hubka & Eder 1988], and figures 4–5, 4–5 and 4–6 in [Hubka & Eder 1992]). In general, the external properties cannot be designed directly, they are generated by designing the internal properties (class 12) consisting of:

- the design characteristics, containing the principles of operation and construction applicable for a family of technical systems (e.g. power transformers, cranes, machine tools, etc.), including any heuristic advice and values;
- the general design properties, mainly analyzable with the help of the engineering sciences; and
- the elementary design properties that consist of the precise manufacturing definitions, geometries, dimensions, tolerances, surface conditions, (etc.) of all constructional elements and their interconnections.

Each technical system experiences a life cycle (of transformation processes, most of which contain several other more detailed processes, see figure 7–8 in [Hubka & Eder 1996], figure 10.1 in [Hubka & Eder 1988], and figure 4–10 in [Hubka & Eder 1992]), starting typically with product planning, leading through designing, production planning, manufacturing, distributing, using (the intended working process of the TS), and disposing (recycling and/or scrapping).

Technical systems are ‘evolved’ over time, each new redesign introduces changes that reflect the latest state of the art in that branch of engineering. The tendencies include:

- improvements in all (or selected) properties of the TS:

  - instrumentalization, mechanization, automation, computerization;
  - introduction of new technologies, especially those derived from scientific research;
  - application of ergonomics and relief from damage to the natural environment;
  - making recycling and disposal of the spent TS easier;
  - improving efficiency and effectiveness;
- acceleration of growth laws (e.g. learning curves);
- changes in the constructional structures, especially in new modes of construction, new materials and manufacturing technologies, new arrangements of modularization and 'construction kit' applications, new ways of lightweight construction or low-cost construction, etc.

4. Insights about Design Processes

A general model of the design system (with its process) can be directly derived from the general transformation system. Within this model, the design process can be structured according to various criteria. A first structuring can occur according to a hierarchy of complexity of the design operations, from the conventional 'clarify, conceptualize, embody/layout, elaborate/detail' at the highest level, to operations like 'sketching, discussing, calculating' (see figure 7–12 in [Hubka & Eder 1996], and figure 5–4 in [Hubka & Eder 1992]). At the second level of this hierarchy, the most important structuring is shown as a full procedural model of designing as outlined below (see figure 7–13 in [Hubka & Eder 1996], and figures 6–1 and 6–2 in [Hubka & Eder 1992]), as a block diagram which can be iteratively (with feedback) traversed for a novel design process. A third level of the hierarchy contains the operations of problem solving: 'stating and clarifying the immediate problem, searching for solutions, evaluating and deciding, communicating', supported by operations of 'preparing and presenting information, verifying and checking, and representing'. In each of these design operations (level two and three), various thinking and acting modes can be used [Eder 2000]: iterative, recursive, interactive, searching and selecting, abstracting, sequential, simultaneous, discursive, intuitive.

The general procedural model (level two) presents the engineering designers with many tasks: they should establish an appropriate action principle, technology, mode of construction, criteria, etc.; calculate, represent, evaluate, optimize; act as team members, consult and obtain consultations; etc.

Every task demands a certain way of proceeding ('how'), and knowledge ('what'). Several disciplines and published methods can be applied to assist within the process of designing, e.g. brainstorming, finite elements, Taguchi methods, QFD, etc. Support for designers is also provided by various technical means ('with what'), including computers. It is one of the tasks of Design Science, both at the abstract/theoretical level, and especially at the specific/concrete levels, to point out to engineering designers what knowledge, methods and techniques (including means) are available for specific tasks within designing, and to recognize procedural gaps and develop appropriate methods.

The quality of designing is decisive for the quality of the designed technical system, but also influences the efficiency and effectiveness of all subsequent life-cycle processes, the time needed for designing, reduction of risks from and for the designed TS, design costs and committed costs for the future realized TS, teamwork, etc. This quality is influenced in varying degrees by several factors, i.e. by the operators of design processes (see figure 7–18 in [Hubka & Eder 1996], and figure 5–8 in [Hubka & Eder 1992]).

4.1 Designing

Designing can use the structures and other insights of the Theory of Technical Systems [Hubka & Eder 1988], with the procedures derived from the Theory of Design Processes [Hubka 1976]. This is a prescription, and like all other prescriptions it is a choice of the engineering designers whether they use it or not. We claim that a more effective and efficient design process, with a more optimal TS as designed object, is more likely to result from using these theories and the appropriate methods.

For a novel design problem, the initial requirements can be developed with the help of the properties of technical systems, and the life cycle and its operators. If a transformation process can be recognized or established (designed), the requirements for effects from the operators can be derived. In particular, the requirements for effects from the technical systems need to be established. From these, the (TS-internal and cross-boundary) functions can be established. These lead to establishing the needed

organs. The organs need to be concretized, 'fleshed out', embodied into material, leading to layouts, assemblies and details of the constructional structure. That this process must be iterative, always recognizing further needed process operations, functions, organs and/or constructional elements to (eventually) completely fulfill the requirements, should be obvious.
Where a technical system already exists, and should be redesigned (by far the most common kind of engineering design problem), the existing function structure and organ structure may be recognized and analyzed. These may need revisions for the new design specification. Then the 'novel' procedure can be followed to concretize into a revised TS.

5. Specialized Design Sciences

In contrast to the general Design Science [Hubka & Eder 1996], a specialized design science should provide appropriate information for a particular concrete branch area of engineering. Providing that a general formation of information exists about the specific branch, the general Design Science can be concretized into specialized models, documents, proforma, etc., and others can be generated appropriately. The following examples should outline how the abstract models can be concretized for a specific branch of engineering.
It is not possible in the space of this paper to present a complete Specialized Design Science. The examples are taken from two complexity levels of technical systems, level I for connections – sliding bearings, and level III for machine tools (see figure 6.2 in [Hubka & Eder 1988], and figure 4–14 in [Hubka & Eder 1992]).

5.1 Sliding Bearings

For product families especially in the range of machine elements (constructional elements), specialized procedural models can be derived from the general procedural model (see figure 7–13 in [Hubka & Eder 1996], and figures 6–1 and 6–2 in [Hubka & Eder 1992]). For movable connection elements, especially bearings, this derivation leads to the procedure shown in figure 8–8 in [Hubka & Eder 1996]. This procedural model assumes that several alternatives can be found, and this is demonstrated in figure 8–11 in [Hubka & Eder 1996]. Decisions at the various juncture points in this hierarchical scheme are based on the known criteria for bearing selection, i.e. the demanded degrees of freedom, rotational speed, load-carrying ability, number of bearing locations, etc. The selection of (for instance) a cylindrical or a two-arc sliding bearing can be further detailed in a procedure (including parameter calculations) illustrated in figure 8–9 of [Hubka & Eder 1996]. The various resulting structures, including a master list of requirements (design specification) are shown in figure 8–10 of [Hubka & Eder 1996]. This demonstrates another important aspect of systematic working procedures, the duty to work out an 'enterprise-internal list of requirements' for specific recurring and novel design tasks.

5.2 Machine Tools

The basic design process follows closely from the procedural model (see figure 7–13 in [Hubka & Eder 1996], and figures 6–1 and 6–2 in [Hubka & Eder 1992]). As first step, the design task should be clarified and a list of requirements (design specification, classified according to the properties of technical systems) should be generated. It is usually sensible to formulate a master list of requirements for the individual sorts of machine tools (engine lathes, universal milling machines, etc.). For a concrete machine tool design task, a proforma can then be filled out and completed, but the whole problem must be understood by the engineering designers.
Conceptualizing is relatively simple in the range of machine tools. The transformation process is already known for each of the sorts of machine tool (see figure 8–4 in [Hubka & Eder 1996], figure 6.8 in [Hubka & Eder 1988], and figure 4–13 in [Hubka & Eder 1992]), but a difficulty may arise for combinations of machine tools such as a machining flow-line for a mass-produced complex component, e.g. a cylinder block. All machine tools have a common transformation process (details and operations of the process are somewhat different), namely changing the form of a constructional element from a scantling to a (semi) finished part. The different sorts of machine tools specify in more detail the operands, the operations and their technologies. Therefore the function structures for individual classes and families of machine tools are established, as illustrated in the example of engine

lathes (see figure 8–4 in [Hubka & Eder 1996], figure 6.8 in [Hubka & Eder 1988], and figure 4–13 in [Hubka & Eder 1992]). If the task as given is more specific, even the organ structure, the mode of construction, and in part the constructional structure is predetermined, e.g. for variant design – changing the machining capacity and power levels form one lathe size to another.

From the point of view of design methodology, after the design specification has been worked out, a leap can occur that largely by-passes the conceptualizing steps, and continues work in the layout and detailing phases. It is clear that in such cases (the majority of engineering design cases in industry) a set of similar 'design situations' arises, for which methods and documents (masters) can be generated.

A different situation can arise at the lower levels of complexity. If for some of the functions or organs the conventional means are not re-used, i.e. if an innovation is demanded, the design process for that recursively selected section of the overall problem may need to follow the complete method of the general procedural model, e.g. as shown above for the connection – bearing.

A further important concretization of knowledge can be transacted in the area of the theory of properties (figure 7–5 in [Hubka & Eder 1996], figures 7.1 and 7.5 in [Hubka & Eder 1988], and figures 4–5, 4–5 and 4–6 in [Hubka & Eder 1992]). Concrete methods and data to achieve specific properties such as stiffness, precision, wear resistance, etc. should be generated as accurately and completely as possible for each known design situation – this has been done in the region of civil engineering construction by laws and codes of practice. But also newer and hitherto insufficiently realized properties must be respected, such as efficiency, suitability for recycling, environmental impact and costs. In these regions, new insights are continually being formulated, e.g. for life-cycle engineering – form-giving and arrangement (configuration) for least environmental impact.

Further sections of the Specialized Design Sciences can include insights about origination (see figure 7–8 in [Hubka & Eder 1996], figure 10.1 in [Hubka & Eder 1988], and figure 4–10 in [Hubka & Eder 1992]), and development (evolution) in time of TS families.

Following the guidelines of these theoretical models, a unified and complete information system with an adequate structure can be built up. This allows a good overview of the branch area, transfer of insights and experiences from older designer to the enterprise, establishing gaps in the available knowledge, etc.

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