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DESIGN SCIENCES – AN OVERVIEW

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Abstract: *Sciences have a role in society. Among the hierarchy of sciences, a science about designs and designing should exist, with sub-divisions for various more specialized disciplines. At a more detailed level, an Engineering Design Science is outlined and placed in context.*

Keywords: Science, Design Science, Engineering Design Science

1. Introduction

Human languages are ambiguous, meanings of many common words tend to change over time. Nevertheless, it is important to explore a broader context of our interests in research and application, and a consistent set of word definitions is useful towards that end. Design sciences, our subject of choice, occupy a level in a hierarchical and interconnected arrangement of information.

2. Basis of Terminology

2.1 System

A *system* is a finite set of *elements* collected to form a whole under certain well-defined rules, whereby recognizable *relationships* exist among the elements, and to the system's environment. Both the terms 'element' and 'system' are *relative*. An element can also be regarded as a system, and a system can be regarded as an element within a larger system, i.e. systems are hierarchical, at different levels of complexity. Systems are characterized (and classified) by their purpose; their properties; their behavior and assigned tasks; their structure; their environment; their input/output/throughput/process; their evaluation (e.g. for the purpose of decision-making); their state, condition, and change in time; suitable models (e.g. hierarchical, network or flow-chart, functional, appearance, iconic).
Information ranges from informal hearsay to fact, and from raw sound-bites of information to systems of coherent theory and thought – *knowledge*. Knowledge is derived from information (including data and experience, not necessarily articulated) [Eder 2004] by processes of abstracting, generalizing, classifying, codifying, etc. This knowledge (a system of selected information elements and their relationships about a delimited subject) can be held in tangible records, e.g. in library books and other publications, private files, etc. Information and knowledge can be learned and internalized by a human, i.e. integrated into a mental structure that is unique to that person (but that has many features in common with other persons) – *knowing*.

2.2 Science

Science (from Latin 'scientia' – having knowledge) has the task to produce and verify knowledge, independent of its potential use, to isolate and study (reproducible) phenomena, abstract and codify from available and observed information. Normally, the main aim of *science* is to study what exists, and to try to explain it in a generally agreed way. Scientists claim to proceed from observation to formulate these explanations. They must therefore try to isolate the phenomenon to be studied, to make the task of observation simpler, and to avoid effects that arise from 'outside' influences. The information obtained from observations is abstracted and generalized.

In strict *deductive* logic, inferring from the particular to the general is forbidden [Eekels 2000]. Yet the development of science depends on it, and also in daily life, in management and in engineering design, we regularly meet *induction*, without which life would hardly be possible. According to Koen [2003], this implies that all science should be regarded and used as heuristic. Science and daily life also depend on *abduction* and *reduction*, taking away parts to simplify a situation so that it may be better understood, and *innoduction*, concluding from one or a few observations to a presumed rule. All of these require intuitive steps in order to proceed. Intuition should not be excluded from rationality, but should be considered as an indispensable ingredient of it. This understanding should then be synthesized into a more *holistic* view.

It is necessary to study the individual elements of a system, and their relationships within and across the boundary of the system. Whilst this may sound *reductionist*, it is only with this information that the full implications of whole system can be discovered, and a good understanding of the system as a *holistic* entity can be achieved. Neither a reductionistic nor a holistic view alone are sufficient. Equally, both synthesis and application of information must be accompanied by analysis.

Each *science* is a system of ordered, organized, systematized, categorized, codified, and recorded knowledge about a bounded region, a delimited set of subjects, that includes theories and hypotheses about the region and its behaviors. This knowledge is preferably published (and peer-reviewed). Practical application is not a prior condition.

The natural and sociological sciences developed mainly on the basis of observing, recognizing (perceiving) and understanding phenomena from nature, societies, and humans with their artificial systems – many of which have preceded the early development of the relevant science. Only after the knowledge was tested, systematized, generalized into laws and theories, and verified by numerous extending experiments and by practical applications, did these sciences start to become effective instruments of human society and, as a secondary effect, a source of knowledge for a higher level of abstraction.

NOTE: Nagel [1961, p.8] writes: 'No one seriously disputes that many of the existing special sciences have grown out of the practical concerns of daily living: geometry out of problems of measuring and surveying fields, mechanics out of problems raised by architectural and military arts *(interjection: note the use of the word 'arts' as activities of human beings that result in artifacts)*, biology out of problems of human health and animal husbandry, chemistry out of problems raised by the metallurgical and dyeing industries, economics out of problems of household and political management, and so on. To be sure there, have been other stimuli to the development of sciences than those provided by problems of the practical arts. Nevertheless, these latter have had, and still continue to have, important roles in the history of scientific inquiry. In any case, commentators on the nature of science who have been impressed by the historical continuity of common-sense convictions and scientific conclusions have sometimes proposed to differentiate between them by the formula that the sciences are simply 'organized' or 'classified' common sense.' Yet scientific knowledge is not the only sort of knowledge.

In most cases, scientists make *conjectures* about possible explanations, based on hunch, insight and feel. They then experiment to try to verify those conjectures, and refine them into *hypotheses*. Further refinement and reformulation based on further observations lead to an agreement on the explanation, an 'accepted truth', which is as complete and coherent as possible – a *theory*.

NOTE: 'Science is supposed to advance by erecting hypotheses and testing them by seeking to falsify them. But it does not. Just as the genetic determinists of the 1920s looked always for confirmation of their ideas and never for falsification, so the environmental determinists of the 1960s looked always for supporting evidence and averted their eyes from contrary evidence, when they should have been actively seeking it. Paradoxically, this is a corner of science where the 'expert' has been more wrong than the layman' [Ridley 2000, p. 79-80]. 'The fuel on which science runs is ignorance. Science is like a hungry furnace that must be fed logs from the forest of ignorance that surrounds us. In the process, the clearing we call knowledge expands, but the more it expands, the longer its perimeter and the more ignorance comes into view.' and 'A true scientist is bored by knowledge, it is the assault on ignorance that motivates him – the mysteries that previous discoveries have revealed. The forest is more interesting than the clearing.' [Ridley 2000, p. 271-272].

Each region of science deals with only a small range of phenomena – and over time the range of each science tends to narrow as further specialized sciences arise. Many of these regions of science are regarded as 'pure', with little regard for any possible application in real life. Other regions are deliberately adapted to applications – e.g. the engineering sciences.

Science, and scientific information, are often regarded as 'value free'. This is not necessarily so, the values of the researchers (and their funding agencies and employers) are to some extent reflected in the resulting information.

2.3 Other Regions of Activity

Art intends to produce items that appeal to the senses, usually in a favorable, pleasurable and/or beneficial way. Art, the results of artistry, is closely related to craft, the result from craftsmanship. The emphasis is less on utility, and more on esthetic and sensual appeal.

It is now acknowledged that there are distinct differences in scope and approach between sciences and engineering, and that art also plays a role in engineering [Eder 1995].

In contrast to both art and science, engineering intends to create what does not yet exist, in a form that is most likely to work for the benefit of (a section of) humanity. Engineering, and especially designing, thus needs awareness of the whole range of existing knowledge and its complex interactions. Engineering designers need to take into account and accommodate all possible influences of scientific, technical, economic, societal, cultural, political and other areas to achieve a successful and optimal designed system. What is beyond the 'clearing' can hardly be used to design technical systems.

Engineering has the task to create functioning devices (*technical systems*) with added value, even when their ways of working are not fully understood, and with complex interaction among phenomena. Engineers use science among a vast array of other information.

Applying science is not (yet) engineering. An important feature of engineering is application of methodical and systematic procedures to accomplish its tasks. Quoting Klaus [1965]: *'Both method and theory emerge from the phenomenon of the subject.'*

A general procedure for engineering (and business) consists of planning (of an enterprise product), (contract), *designing* (of an enterprise product and its usage process), manufacturing planning (designing of manufacturing processes), manufacturing, distributing, using, disposing – Life Cycle Engineering. *Designing*, establishing in principle and in detail, in advance, what needs to be made or implemented to achieve that product, for all its life phases, can be sub-divided into

(a) *industrial design*, establishing the appropriate appearance, ergonomic properties, and economics, with emphasis on customer appeal and satisfaction; and
(b) *design engineering*, establishing the ways in which the product will function, the components of which it will be made, as well as influencing all other properties of the product [Eder 2003].

For design processes that emphasize the *artistic elements*, external appearance, ergonomics, marketing, customer satisfaction and other properties of the artifact to be designed, the task given to or adopted (chosen) by the designers is usually specified in rough terms, with few data, but the design team should agree about their task. The process consists initially of conceptualizing possible future artifacts (including products), especially regarding their appearance. Then, rendering and or physical modeling of the artifact provides a 'final' presentation for approval. The artifact can then be made as a single display item, or as a quantity-produced product. Economic assessments and calculations are common, but technical/scientific analysis is largely absent. Designing is mainly intuitive, with few methods – and these emphasize 'creativity' and artistic judgment, e.g. brainstorming.

Alternatively, design engineering emphasizes the *internal functioning*, workings, functionality and life cycle (design engineering) of a future artifact (i.e. a *technical system*). The processes should anticipate as much as possible the intended (and unintended) usage of the artifact (system) to be designed, its manufacturing processes, impacts on the environment (life-cycle engineering), etc. Designing should proceed by first (usually from a given design brief) developing a comprehensive design specification (list of requirements, contract brief) to obtain a full understanding of the problems, and to obtain concrete criteria by which to choose among possible alternative proposals – *clarifying the problem*. Several abstract structural elements are available to search for candidate solutions and to investigate their behavior – transformation process operations, technologies, functions, organs (abstract function-carriers in principle), hardware (constructional parts), and others – these also represent different levels of abstraction of the technical system (most abstract to most concrete) [Hubka 1996]. The elements from transformation process operations to organs can be used for *conceptualizing*, the hardware components in configuration and parametrization are used for *embodiment* (in sketch layouts and dimensional layouts) and *detailing* (in detail and assembly drawings, parts lists, etc. or their computer-resident equivalent models). Even though all these elements and structures are always present, they need not be used for a particular design engineering problem. The processes can thus range from 'purely' intuitive to very systematic, and can apply several methods (including computer applications) for steps of the design process.

In many design processes, a combination of these two forms of process is needed, either because the appearance and customer attraction is the primary aim, or because the results of design engineering may not be acceptable from the marketing and/or ergonomic viewpoint. Integrated product development [Andreasen 1987, Ehrlenspiel 1995] places emphasis on the artistic forms of designing for an artifact to be quantity-produced, and then, if needed, involves design engineering.

The range of information, knowledge and data needed by engineers to perform their duties is much larger and more interconnected than for almost any other profession. It includes information about technologies that are of little interest to science, and cannot be verified by experiments – heuristics and guidelines, enterprise decisions, standards and codes of practice, laws and regulations, etc. [Constant 1980, Vincenti 1990].

3. Science Hierarchy

Depending on the subject, sciences can be arranged into a hierarchy. The more specific levels of this hierarchy should inherit all the features of the next more general level.

At the most general level (top or base, as the reader desires) should be a Science of Sciences, with a range of properties concerning [Horvath 2004]:

- (a) *ontology*, that branch of meta-physics dealing with the nature of being (existing), the theoretical philosophy of being and knowing, a philosophy of the mind;
- (b) *epistemology*, the theory of the method or grounds of knowledge, the nature of knowledge, its origins, foundations, limits and validity (including epistemic considerations – the degree of acceptance of knowledge);
- (c) *methodology*, the science of method, the body of methods used in a particular branch of activity, relationships among theory, subject and method [Klaus 1965];
- (d) *axiology*, the theory of values, advocating value judgements and embracing ethics and esthetics;
  - (d1) *ethics*, relating to morals, treating of moral questions, moral correctness, honor, and conformance to standards of good behavior
  - (d2) *esthetics*, appealing to the senses (in humans, the senses of sight, touch, smell, hearing, emotions – conscious and sub-conscious perception, cognitive processes; and
- (e) *situatedness* [Clancy 1997, Gerö 2000], the interactions among three 'realities': an external world, an interpreted world (by processes of interrogating, perceiving and interpreting the external world to formulate concepts of existence), and an expected world (by processes of hypothesizing and designing an anticipated external world, formulating goals, and taking action to realize that world based on a theory of the expected outcomes [Klaus 1965]).

Some attempts to formulate such a general science were active in Warsaw, Poland, some decades ago.

NOTE: Gregory [1966] states that the maturity of science about a body of knowledge (e.g. knowledge about designing) 'is characterized by a gradation of behavior which may be expected, and which causes that knowledge to be reckoned as scientific.' Clearly, this relates to the *epistemology* of the knowledge. This behavior and the state of organization of the body of knowledge may range through:

(1) description of phenomena (natural history phase);
(2) categorization in terms of apparently significant concepts;
(3) ordered categorization whose pattern may be deemed a model (the evolutionary taxonomy or periodic table phase);
(4) isolation and test of phenomena, with implied reproducibility by independent observers;
(5) quantification (classical physics phase).

Even the first of these is commonly acknowledged as 'science' when applied to a traditional area of study (e.g. biology). And those areas of knowledge that reach level (5) still need the other levels, especially to relate that area to others. Many areas of science cannot reach the final 'quantification' stage in which mathematical relationships are formulated. Engineering design, the process of designing, is obviously such an area, but this observation must be qualified by the connections to other knowledge. Designing as an area which has been subjected to scientific investigation, codification of knowledge and theorizing can, in parts (especially with respect to its results), not even reach stage (4), because the human element is not strictly reproducible – humans are idiosyncratic, and have their own decision powers. Some of the knowledge we use and interpret for engineering design exists at the highest scientific levels – it may be useful for analysis of proposed solutions, but the choices and values are human.

At the next level we should find sciences of art (in general), of physical phenomena, of mental constructs (e.g. history, sociology, politics, etc.), and of processes. The boundaries between such sciences will be fluid and fuzzy, ill defined, and their maturity will differ. At this level there should be a general Design Science [Horvath 2004]. Note that Design Science(s) are concerned with 'designs' (designed artifacts) and with designing (design processes, the activities and documentation of designing) as their subject, not (or only by connection) with the sciences of phenomena that are used (analytically) in the design process or in the designed products.

Relationships among these sciences exist (e.g. engineering sciences and 'pure' sciences), but the recorded and codified knowledge contained in these sciences is not directly suitable for the purposes of designing, and needs to be re-classified and transformed. Arrangements of information can be as archival collections (libraries) of scientific insights and agreed understandings, or as a useful search medium for design engineering (e.g. design catalogs, decision charts, systemic DfX collections for synthesis especially of TS-properties). The advantages of computer-resident files of information are that searching can be done for either purpose with little re-arrangement [Eder 2004].

Attached to the general Design Science should be a series of more specific Design Sciences such as Industrial Design Science, Science of Integrated Product Development, Architectural Design Science, Artistic Design Science(s), and Engineering Design Science. To the author's knowledge, only Engineering Design Science has received a more rigorous treatment [Hubka 1996].

4. Engineering Design Science

A *system of knowledge* for and about engineering design has been developed since about 1960 [Hubka 1967], by observing, researching and theorizing, and by collating a broad selection of the works of others, based on many years of designing experience of the authors. Up to then, mainly the existing knowledge about objects and their engineering sciences had been codified as islands of object knowledge. Some process knowledge (i.e. human mental processes) has been published as individual methods, but hardly integrated into any scheme. The knowledge about designing was largely anecdotal, with little theory, few relationships and incomplete, even in the specialized branches of designing (and of technical systems – enterprise products).

It is one of the tasks of Engineering Design Science to explore the reasoning patterns, models and methods needed by engineering designers, how to use them and how to safeguard them from going astray. This safeguarding function will be performed by engineering design methodology, and by the specific engineering design methods. Engineering Design Science [Hubka 1996] strictly differentiates between (1) the process *system* and/or object *system* (artifact) that is to be designed, the left hemisphere of figure 1, and (2) the process and activity of *designing*, the right hemisphere. It also intends to provide a mapping of the relevant theories (southern hemisphere) to applicable practice knowledge (northern hemisphere), both existing and newly developed.

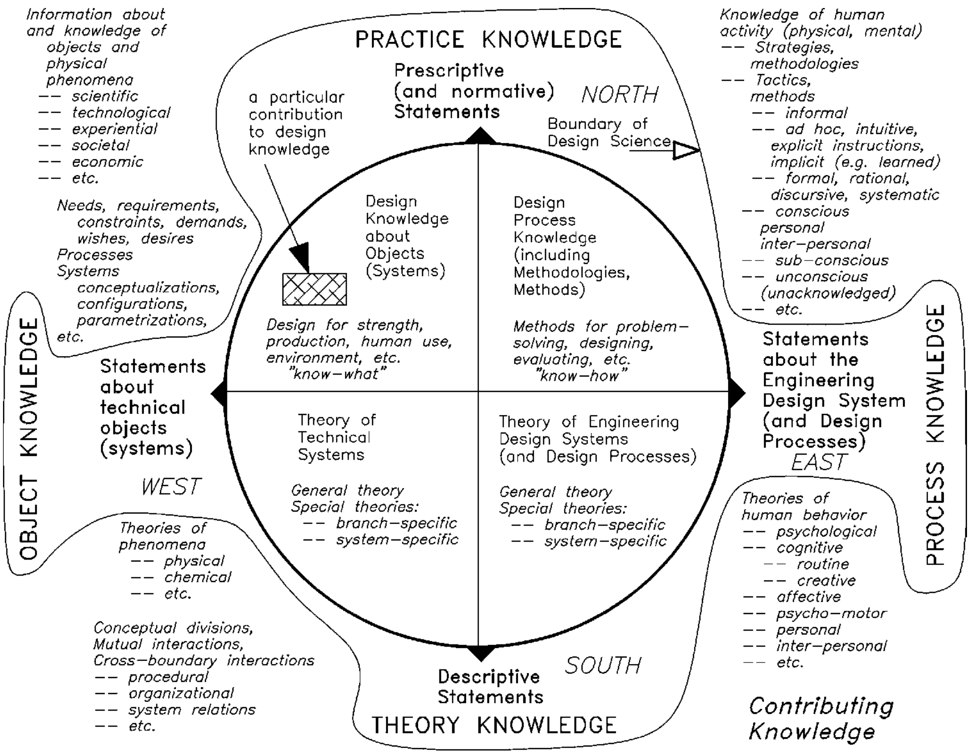

Figure 1. Model (Map) of Design Science

The purpose of Engineering Design Science [Hubka 1996] is to define a comprehensive description and logical framework, a categorized body of knowledge, a science about design engineering from which theory-based methods can be proposed and pragmatically formulated methods improved. This science should obviously cover the existing knowledge about designing (of technical systems and transformation processes) and design processes [Hubka 1996], but should also present generalized knowledge about the technical systems that are designed [Hubka 1996]. It creates a basis for rationalizing the practical work of designing, for educating future engineering designers, and for stimulating further research. A next, more detailed level may be generated as Specialized Engineering Design Sciences, treating a particular 'sort' of technical system (e.g. electrical power transformers, transformer coil winding machinery).

A theory of designing of technical systems, as part of Engineering Design Science, should present:

(a) a conception of the relationships between facts about the processes of designing and about the objects being designed, especially the causal connections, as a structure for Engineering Design Science, see figure 2;

(b) a system of laws or principles to define a generic (generalized and ideal) form or paradigm of action, which should also support intuitive and emotional procedures – including procedural models from which procedural plans and approaches can be developed;

(c) a sphere of speculative thought or doctrine, consisting of certainties and practice;
(d) abstract knowledge of any sort, as contrasted to practice;
(e) relationships among theory, subject and method [Klaus 1965]. This is one of the guiding premisses of Engineering Design Science, but this relationship needs to be further explored.

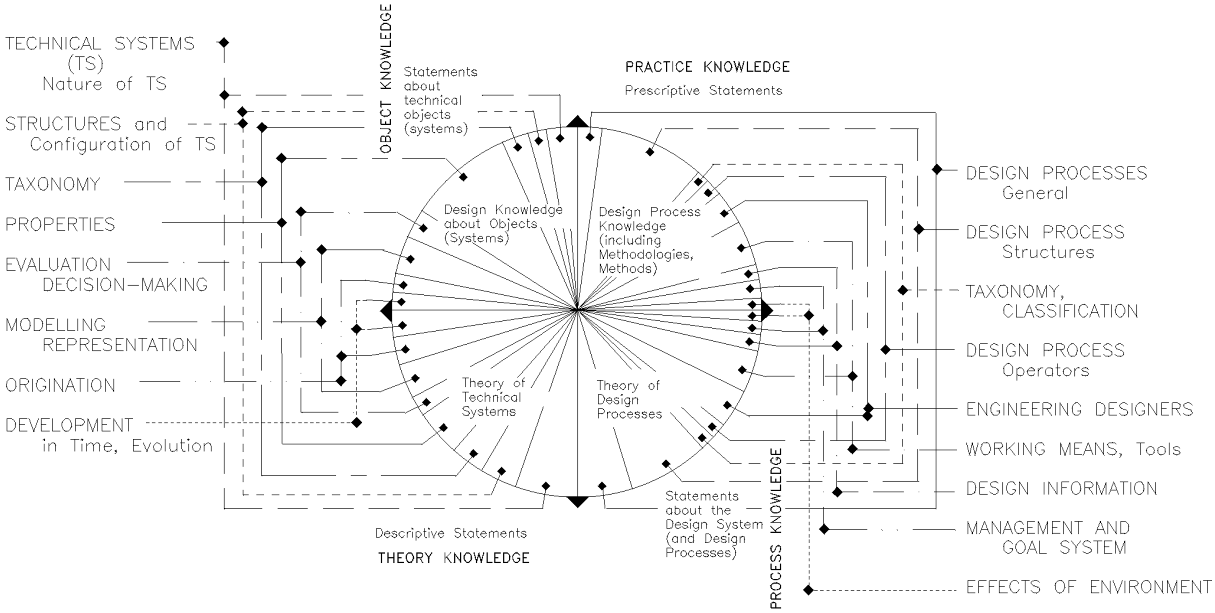

Figure 2. Design Science – Structure and Contents

The theory is augmented and explained by a series of interrelated models, see figure 3, including a transformation system (with its process and operators); life cycle, properties and structures of technical systems that may be used for designing; and a complete procedural model of designing, with a hierarchical scheme of design operations, and guidelines for adapting the theories to practical application.
This system of knowledge, Engineering Design Science, should be of general utility, and is particularly needed if the design problems are situated in the more abstract levels of modeling (the phase of conceptualizing), especially for designing novel systems. A systematic and consistent procedure containing no theoretical discontinuities (jumps or intuitive leaps), such as the one presented in Engineering Design Science, is the best way in which a rational, effective, economic and optimal solution can be found in minimum time, with a reasonably high probability of success.
Intuition has its place among the designers' tools. Yet systematic work wins out unless the problem remains only at the most concrete and routine level – the constructional structure, especially from the dimensional layout onwards into the details. At these concrete levels, the sufficiently trained human mind tends to be quicker if left to itself, using intuitive working modes (i.e. using the learned and internalized object and design process knowledge), without the need to follow a carefully prescribed procedure. But the human mind is unreliable, and therefore a systematic procedure and preferably independent check (design audit, systematic reflection) must be implemented, both on the process of designing and on the results (the designed technical system), best based on Engineering Design Science.
Research is, of course, still needed. Many gaps exist in our knowledge of designs and designing, especially about the psychology of human designers, and acceptance of newer methods. Newer research can thereby act as feedback to verify existing knowledge and to reveal gaps. Researchers therefore need some comprehensive (but not necessarily detailed) knowledge of prior publications, which in turn demands an in-depth study and understanding (by the researchers and their supervisors), not just skimming for convenient catch-phrases.

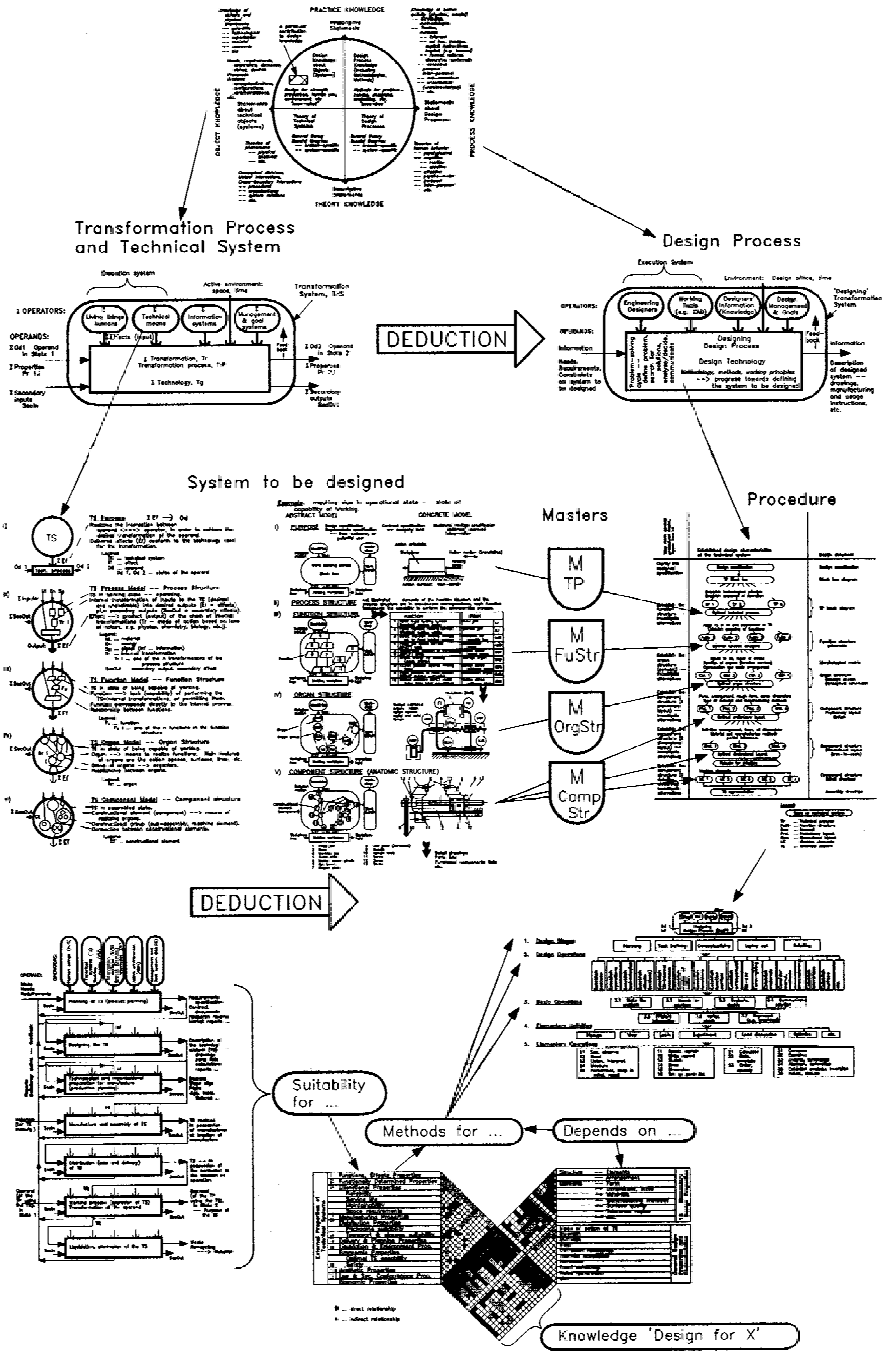

Figure 3. Relationships Among Some Models for Engineering Design Science

References

Andreasen, M.M., & Hein, L. (1987) ***Integrated Product Development****, London: IFS Publ. and Berlin/Heidelberg: Springer-Verlag*
Clancy, W. (1997) ***Situated Cognition****, Cambridge: University Press*
Constant, E.W. (1980) II, ***The Origins of the Turbojet Revolution****, Johns Hopkins Studies in the History of Technology, Baltimore: Johns Hopkins U.P.*
Eder, W.E. (1995) 'Engineering Design – Art, Science and Relationships', Design Studies, Vol. 16, p. 117-127
Eder, W.E. (2003) 'A Typology of Designs and Designing', in ***DS 31 – Proc. ICED 03 Stockholm****, p. 251-252 (Executive Summary), full paper number 1004 on CD-ROM, The Design Society, 2003*
Eder, W.E. and Hosnedl, S. (2004) 'Information – a Taxonomy and Interpretation', in ***Proc. International Design Conference - Design 2004****, Dubrovnik, May 18 - 21, 2004, p. 169-176.*
Eder, W.E., & Gosling, W. (1965) ***Mechanical Systems Design****, Commonwealth and International Library # 308, Pergamon Press, Oxford*
Eekels, J. (2000) 'On the fundamentals of engineering design science: The geography of engineering design science. Part 1', Journal of Engineering Design, Vol. 11, Nr. 4, pp 377–397 (Part 2 is in Vol. 12, Nr. 3, 2001, p. 255–281)
Ehrlenspiel, K. (1995) ***Integrierte Produktentwicklung****, München: Carl Hanser Verlag*
Gerö, J.S. (2004) 'Situated Design Computing: Introduction and Implications', in ***Proc. International Design Conference - Design 2004****, Dubrovnik, May 18 - 21, 2004, p. 27-36, on CD-ROM*
Gregory, S.A. (1966) 'Design Science', in Gregory, S.A. (ed.), ***The Design Method****, London: Butterworths, p.323-330*
Horvath, I. (2004) 'On Methodical Characteristics of Engineering Design Research', in ***Proc. International Design Conference - Design 2004****, Dubrovnik, May 18 - 21, 2004, on CD-ROM.*
Hubka, V. (1967) 'Der grundlegende Algorithmus für die Lösung von Konstruktionsaufgaben' (Fundamental Algorithm for the Solution of Design Problems) in ***XII. Internationales Wissenschaftliches Kolloquium der Technischen Hochschule Ilmenau****,* ***Heft 12*** *Sektion L - Konstruktion, Ilmenau: T.H.I., p. 69-74*
Hubka, V., & Eder, W.E. (1996) ***Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge****, London: Springer-Verlag, http://deed.ryerson.ca/DesignScience/*
Koen, B.V. (2003) ***Discussion of The Method: Conducting the Engineer's Approach to Problem Solving****, New York: Oxford Univ. Press*
Klaus, G. (1965) ***Kybernetik in philosophischer Sicht*** *(Cybernetics in Philosophical View) 4th ed., Berlin: Dietz Verlag*
Nagel, E. (1961) ***The Structure of Science****, London: Routledge, p.8*
Ridley, M. (2000) ***Genome****, New York: Perennial (HarperCollins)*
Vincenti, W.G. (1990) ***What Engineers Know and How They Know It*** *– Analytical Studies from Aeronautical History, Baltimore: Johns Hopkins Univ. Press*

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