AEDS 2006 WORKSHOP
27 – 28 October 2006, Pilsen – Czech Republic

ENGINEERING DESIGN SCIENCE – WHAT ARE THE REQUIREMENTS TODAY?

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Keywords: Engineering Design Science

1. Introduction

Engineering Design Science has evolved over the last 40-50 years. The first mention of the term (in German: ***Konstruktionswissenschaft***) goes back to Hansen [Hansen 1974], but it is today mainly connected to the names of Hubka and Eder [Hubka & Eder 1992, Hubka & Eder 1996] whose concepts are based on much earlier studies on the theory of artefacts [Hubka 1973, Hubka 1984] as well as the theory of creating them [Hubka 1976].
Besides the term "Engineering Design Science", the term "Design Theory and Methodology" has been used – with the relation between the two often being not very clear. With first dedicated activities during the late 1950s and the 1960s mainly in Europe (Czechia, Germany, Great Britain, Russia, Scandinavia, Switzerland), Design Theory and Methodology became an important and interesting research and teaching issue also in Australia, Canada, Japan, and the United States of America.
A comparative view on different approaches to Design Science, or Design Theory and Methodology respectively, is presented in another contribution to the AEDS workshop 2006 [Eder & Weber 2006].
Today, the question of how to consolidate the knowledge in this area is imminent – the merit of bringing up this question to a great extend going to the AEDS series of workshops in Pilsen. A complementing contribution to this year's AEDS workshop 2006 by one of the authors shows more details and proposals in this respect [Birkhofer 2006].
Thus, Design Science, or Design Theory and Methodology respectively, after evolving through experiental, intellectual and empirical phases, could finally reach a theory-based phase [Wallace & Blessing 1999].
In this contribution another question is to be discussed: What is required of a comprehensive Design Science from today's perspective?
The background of raising this question is threefold:

1. At last year's AEDS workshop in Pilsen/Czech Republic intensive discussions about the achievements and consolidation of Engineering Design Science took place. These were continued during the so-called science day of the joint meeting of the Design Society's Board of Management and Advisory Board in Heraklion/Crete, March 2006.
2. The authors of this paper, who had the pleasure of attending both aforementioned meetings, then organised a workshop "Engineering Design Science – Consolidation and Perspectives" at this year's DESIGN 2006 conference in Dubrovnik/Croatia (as a joint venture of the two relevant Special Interest Groups of the Design Society: Applied Engineering Design Science, chaired by S. Hosnedl, and Design Theory and Research Methodology, chaired by L.T.M. Blessing). For a pre-conference day and another workshop running in parallel, an astounding 39 participants turned up, intensive-

ly discussing the state and perspectives of Engineering Design Science and in the process also raising the topic of who are the "stakeholders", their views and needs.

3. When the authors of this paper summarised the outcome of the workshop held at DESIGN 2006 for a presentation at the final plenary session, the question came up: In practically all approaches to Design Science, or Design Theory and Methodology respectively, the first step of the synthesis process is a thorough clarification of the requirements, because its results will not only support the process but also enable proper evaluation and selection of solutions. So, why did we never do it when synthesising a comprehensive science of designs and designing?

In its core section (4), this paper tries to provide some (initial) reasoning about the question raised above.

Because our focus is basically the 21st century, at first some considerations about changes in engineering design practice during the last 10 to 20 years are made (section 2).

In order to discuss the question raised, several "stakeholders" of Engineering Design Science are introduced and their views and requirements are discussed (just like in product design where several "stakeholders" – e.g. manufacturing and assembly engineers, sales people, customers, users, maintenance experts, etc. – would pose their views and requirements on the product to be designed).

This approach might seem critical at first glance: Shouldn't "science" be value-free, something "pure" and "absolute", beyond criteria of usefulness? Is it permissible to have expectations, even requirements of a science? Therefore, in another section (3) prior to the core of this paper some considerations about the term "science" in general and about "Engineering Design Science" in particular are presented.

2. Changes in Engineering Design Practice

Engineering design is primarily seen as one phase in the product life-cycle which, due to being in a very early position and being responsible for the determination of the internal and external properties of the forthcoming product, has a dominating influence on all subsequent phases of the product life-cycle, such as manufacturing, assembly, sales, use, maintenance, replacement, etc. Besides this rather technically oriented view, engineering design is part of the business (-creating) process in a company which imposes various constraints in terms of human and technical resources, time and money. Finally, engineering design is a highly creative activity which is increasingly performed in teams – thus having many socio-cultural implications. A nice breakdown of all these views into manifold dimensions of "design is …" is given by [Hubka & Eder 1996] and will not be repeated here.

With respect to practically all of the aforementioned views on engineering design quite radical changes have taken place in the last two decades (and are still ongoing):

– Mainly because of price and, subsequently, cost pressure, but also due to new requirements (e.g. environmental awareness and legislation) the consideration of all phases of the product life-cycle has become a much more tough and diverse matter, at the same time being brought up to the front of the process as much as possible ("front-loading"): Today DfM, DfA, DfE, DfC[1] etc. are both early and integrated activities in engineering design.
– More innovation is required (at least in "high-tech" countries) which means that market-lives of products and, subsequently, development time ("time to market") are decreasing. At the same time, risks (technical and economical) are increasing.
– Product complexity increases: Products become increasingly a multi-discipline/multi-domain affair (e.g. "mechatronic" products, i.e. intelligent combinations of mechanical, hydraulic/pneumatic, electric/electronic and embedded information processing), having more (and more intensively interlinked) components than in the past. At the same time, the number of product variants is exploding („mass customisation").

[1] DfM – Design for Manufacturing. DfA – Design for Assembly. DfE – Design for Environment. DfC – Design for Cost. These and other considerations (Design for Ergonomics, for Recycling, ...) are often summarised by the term "DfX " (Design for X).

– Information technology plays an increasing role in today's engineering design and all subsequent phases of product creation (in some industries even beyond): A multitude of CAX-tools[2] is available to support various activities; among them the concept of the so-called Digital Master (i.e. the one and only valid reference of the product at all times being a comprehensive digital model, usually based on a 3D representation) and an appropriate (digital) management of the vast data connected to it (via PDM/PLM and/ or ERP) are the most influential. Interfacing of and interaction between CAX-tools is still sub-optimal, however, thus also hindering the flow of activities along the design and overall product creation process.
– Business-creation increasingly involves service components besides the material product itself ("Product-Service Systems"), the development of the two sides being also intensively interlinked.
– All phases of the product life-cycle are today performed on a global scale, with partly dramatic changes in organisation and work distribution, both institutional (between different sites, between different companies) and regional (between different countries, continents, cultures). This also has a severe influence on the use of information and communication technologies in engineering design and in all subsequent phases of the product life-cycle.
– Somewhat opposed to some of the issues mentioned before (e.g. shorter market-lives of products), engineering design has to increase efforts in the field of sustainable development. This question is more a socio-political, even ethical issue than a purely technical one, it is also not (yet?) addressed full-heartedly by industry. But who else apart from Engineering Design Science should try to think some years, maybe decades ahead and develop appropriate concepts?

Many existing approaches to Design Science, or Design Theory and Methodology respectively, do not give answers to the questions and problems listed above. This is, of course, not their deficiency, as they were usually formulated years or even decades before the mentioned influences became relevant.

Seen from today's perspective, however, a comprehensive and up-to-date Design Science will ***also*** be judged by the criterion whether it can provide answers to current questions and problems. This is the reason why this short summary was given before collecting requirements of a Design Science in the next section.

3. Why "Science"? May We Have Requirements of a Science?

The definition of what is a "science" (and, consequently, what is not) has been discussed roughly for 3,000 years and is still not finally answered. [Lenk 1998] shows that the issue was taken up again during the last 4 or 5 decades (by the way: mainly, but not entirely because of human-made artefacts and technology and related disciplines of science had to be accommodated).

A good, if quite conventional round-up of the definition of the term "science" is given by Webster's Revised Unabridged Dictionary which today can be consulted via internet [www. hyperdictionary.com/dictionary/]:

1. Knowledge; knowledge of principles and causes; ascertained truth of facts. …
2. Accumulated and established knowledge, which has been systematized and formulated with reference to the discovery of general truths or the operation of general laws; knowledge classified and made available in work, life, or the search for truth; comprehensive, profound, or philosophical knowledge. …
3. Especially, such knowledge when it relates to the physical world and its phenomena, the nature, constitution, and forces of matter, the qualities and functions of living tissues, etc. ...

[2] CAD – Computer-Aided Design. CAE – Computer-Aided Engineering, usually used in the sense of calculation/simulation. CAPP – Computer-Aided Process Planning. CAM – Computer-Aided Manufacturing. PDM/PLM – Product Data/Life-Cycle Management. ERP – Enterprise Resource Management. These and other tools are often summarised by the term "CAX " (Computer-Aided X).

4. Any branch or department of systematized knowledge considered as a distinct field of investigation or object of study; as, the science of astronomy, of chemistry, or of mind. ...
5. Art, skill, or expertness, regarded as the result of knowledge of laws and principles. …

In this definition the term “science” refers back to the term “knowledge”, with additional attributes such as “accumulated”, “established”, “systematised” and “formulated”. It is also explicit that “science” may well have both sides: collecting and systematising knowledge about “what is” (descriptive approach) as well as collecting and systematising knowledge about actions and skills that eventually interfere with the present “what is” state (prescriptive approach).

The concept of “science” as outlined above does give no indication whatsoever that there is anything wrong with striving for an Engineering Design Science[3]. Engineering Design Science has, in fact, always contained both aspects at the same time – the descriptive as well as the prescriptive side (see e.g. [Hubka & Eder 1992, Hubka & Eder 1996]).

In the – often concurrently used – notion “Design Theory and Methodology”[4], these two aspects are split up: If seen as a unit and assuming close relations between the two parts, then “Design Theory and Methodology” is synonymous to “Design Science”; if seen separately and/or with the two parts having weak or missing links, then “Design Theory and Methodology” is quite different from “Design Science”.

The definition of “science” quoted above requires that, in order to form a science, knowledge has to be “accumulated”, “established”, “systematised” and “formulated”. It is, at the same time, quite open to different “branches”, “departments”, “distinct fields of investigation”, etc. where this might take place. Therefore, the authors think that nothing contradicts having “stakeholders” pose requirements of a science – mainly in the sense that the borders of a particular “distinct field of investigation” are defined and that criteria for “accumulation”, “establishing” and “systematisation” of knowledge are formulated.

A more radical approach to the term “science” was formulated by the philosopher T.S. Kuhn [Kuhn 1962, Kuhn 1970]. His concepts are quoted quite frequently in the context of Engineering Design Science, therefore should be mentioned here.

In Kuhn’s argumentation, the term “science” refers back to the term “paradigm”, where a paradigm is “... a constellation of concepts, values, perceptions and practices shared by a community which forms a particular vision of reality that is the basis of the way a community organises itself”.

To put it frankly: According to Kuhn, science is not really rational and objective. Instead, it is based on a consensus between people (the members of the “school of scientists” adhering to that particular paradigm). And consensus is a ***social*** as well as ***time-dependent*** activity, not a “scientific” one in the traditional sense. Furthermore, paradigms (and with them sciences, theories, etc.) definitely have life-cycles, which are limited in time (main topic of [Kuhn 1962, Kuhn 1970]).

In Kuhn’s concepts, there is not even a clear distinction between descriptive and prescriptive aspects of a science or a paradigm, respectively (it’s any form of a “constellation of concepts, values, ***perceptions*** and ***practices***”). His notion of a science/paradigm being “a particular vision of reality ... shared by a community” as well its time-dependency practically provokes that the members of this community in a given time project their expectations and requirements on the science/paradigm they are prepared share.

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[3] Despite of this, some participants of the workshop “Engineering Design Science – Consolidation and Perspectives” at this year’s DESIGN 2006 conference proposed to drop the term “science” in engineering design altogether because they regarded it as imposing too many limitations.

[4] For reasons of space the detailed argumentation – based on definitions of the terms “theory” and “methodology” – is not presented here. Interested readers may again look up [www.hyperdictionary.com/dictionary/].

4. "Stakeholders", their Views and Requirements

In this core section of the contribution several "stakeholders" of Engineering Design Science are introduced and their views and requirements are discussed. Where appropriate, remarks on the present state of Engineering Design Science are added in order to show achievements and deficits, thus maybe giving hints for further work.
The groups of "stakeholders" considered are scientists, designers in practice, students (including PhD students), and tool/software developers.

4.1 Scientists:

The main interest of any type of "scientific community" is in collecting, systematising, structuring/formalising, but also discussing, verifying/falsifying knowledge in the respective field of investigation. This can be translated to the following requirements of Engineering Design Science:

- Knowledge about the field (in our case engineering design) has to be "established" and "systematised". This requirement mainly addresses the "establishing" and "systematising" of a common terminology.
- Furthermore, Engineering Design Science has to formulate its hypotheses, conclusions, recommendations, etc. in such a way that by using scientific methods verification – or, as Popper put it [Popper 1935] and as is recognised particularly in the so-called exact sciences[5]: falsification – is possible.
- Connected to the last point: What are scientific methods and procedures that could verify/ falsify elements of Engineering Design Science? How can we measure "truth" (or the opposite) especially with regard to its prescriptive elements?
- Engineering Design Science has to ***describe*** the objects in the field. In this particular case there are two different "objects" to be considered, the design***s*** (as artefacts) and the design***ing*** (as a rationally captured process to create artefacts):
    - o What are the basic properties of (existing) technical products? What are basic relations between them? What is common to all types of products, what is specific for particular types? How to formalise and express ("model") all this?
    - o How are design processes (i.e. the "set-up" of properties and their relations) actually performed? Can we find common procedures ("processes") and elements? Where do we find specific procedures and elements (and: specific to what – types of products, situations, people, companies, cultures, …)? How to formalise and express ("model") our findings?

As was discussed in section 3, "science" in general, besides describing "what is", may well have a prescriptive dimension. In Engineering Design Science in particular, this component is regarded indispensable. Therefore:

- Engineering Design Science should ***prescribe*** how to deal with objects not yet existing. Again, both types of "objects" have to be considered:
    - o How to systematically predict and optimise properties of technical products/systems, especially when the products do not yet physically exist? How to relate product properties to business goals (e.g. time to market, image, risk, profits, …)?
    - o How to perform and optimise engineering design processes – in new as well as in well known fields? How to assign methods and tools? How to optimise work distribution?

Seen from today's perspective, the authors think that some elements of the requirements listed above should be re-visited in order to improve, but also modernise present approaches to Engineering Design Science. The following (certainly not complete) list of remarks may serve as a more detailed version of some of the requirements stated above:

- – Until today, terms in Engineering Design Science are not coherent, there still is a confusing variety of individual "schools" of Design Science, or Design Theory and Methodology respectively. Therefore, the "establishing" and "systematising" of a common

[5] The authors imply here that engineering is part of "exact sciences". It has to be admitted, however, that this is ***not*** entirely clear.

terminology has to be regarded as a requirement of utmost importance. See more details and proposals in a complementing contribution to this year's AEDS workshop 2006 [Birkhofer 2006].

– We still do not have clear concepts about the criteria we might use to check statements from Engineering Design Science (is it "truth", "quality", "completeness", "level of detail" or rather "generality" as the opposite, "timeliness", …?). Clearly empirical studies of the design process have enhanced Design Science a lot during the last 10 to 15 years (see [Lindemann & Birkhofer 1998]) – so much so that we are inclined to ask why they were not done much earlier. And clearly, this type of descriptive studies (first in "laboratory", now progressing to "practice" environments) will be of additional importance as an instrument to verify – or falsify – design methods, tools, and methodologies [Blessing & Chakrabarti 2006]. But is it the only instrument? And: How do we check product-related statements?
– Interestingly, not all approaches to Design Science, or Design Theory and Methodology respectively, do in fact clearly distinguish between the two "objects" that Engineering Design Science deals with – the products/systems on one hand and the processes on the other – and between the two dimensions – the descriptive and the prescriptive one. The notable exception can be found in [Hubka & Eder 1992, 1996] where a "map" of Design Sciences, having four quadrants is introduced (figure 1).

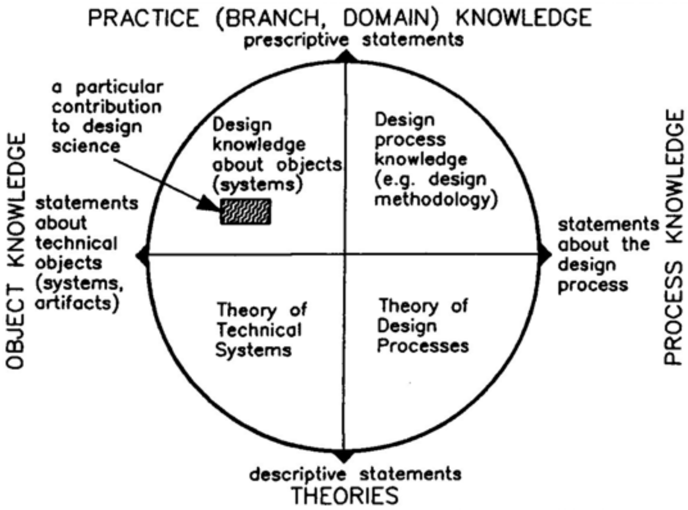

Figure 1.
The four categories of Engineering Design Science according to [Hubka & Eder 1992, 1996]

– Today, a lot more product properties than in the past have to be considered, and as early in the process as possible (see section 2). On the other hand, we have a lot more methods and tools (in particular: CAX tools). All this is not fully reflected in the present approaches to Engineering Design Science.
– Products become increasingly a multi-discipline/multi-domain affair (e.g. "mechatronics", "Product-Service Systems", see section 2). In existing approaches of Engineering Design Science we still have answers primarily related to purely mechanical products, but besides this we find approaches in other disciplines that are rather pragmatic, concentrate on methods (sometimes methodological fashions) and usually do not claim to be "scientific" [Weber 2004]. These aspects have to be integrated into Engineering Design Science – into the product/system- as well as the process-related part of it.
– What is "general" and what is "specific" knowledge in engineering design and how to come from one to the other is not very thoroughly discussed, despite the fact that the gap between design science and design practice (see [Birkhofer 1991, Franke 1999, Birkhofer 2005]) could be closed if we manage to find good concepts in this respect. It should also be mentioned that this question was the initial impact to found the AEDS (Applied Engineering Design Sciences) series of workshops in Pilsen and, more recently, the Special Interest Group of the Design Society sharing the same name.
– As a consequence, the existing knowledge about specific products (e.g. even machine elements, despite some attempts dating back to WDK – Workshop-Design-Kon-

struktion, [Hubka & Rovida 1987]) and specific design processes, methods and tools (e.g. DfX methods, practically all quality engineering methods which have great importance in industrial practice, most CAX-tools) is still only weakly integrated into Engineering Design Science.

- In this context, considerations about specific design situations have been introduced into Design Science by Gero [Gero 1998, Gero & Kannengießer 2003].
- Formalisations of product and process descriptions become more important because of an increasing amount of computer-support. One contribution which tries to integrate several existing approaches is offered by [Weber 2005].
- The relation between product properties and their establishing via an engineering design process on one hand and reaching business goals on the other hand has not been considered very deeply. The best we have in this respect is the concept of so-called Integrated Product Development ([Andreasen & Hein 1987], further developed in [Schäppi et al 2005]) plus some more recent propositions to expand the focus of engineering to the product planning phase [Gausemeier et al 2001]. These activities run rather peripheral to Design Science, we have to ask whether we want them outside or inside our focus.
- Cultural influences on engineering design are a quite recent focus of research at several places (see e.g. [Felgen et al 2004]), will probably become of increased importance along with increasingly cross-cultural engineering processes in practice.

4.2 Designers (and design managers) in practice:

Designers in practice will be mainly interested in updating and optimising their methods, tools and procedures. In most cases they will already have an overview about basic design methodologies – maybe not so much scientific and broad-scale, but influenced by their practical experience in a particular field of products, in a particular branch of industry, maybe even in a particular company.

Therefore, the requirements which are top-of-the-list for scientists will be of lesser importance to them. They will, however, be strongly interested in product- as well as process-related ***new*** knowledge:

- With regard to describing objects – i.e. products as well as processes – designers in practice would probably require information about what is new in the field:
  - What are new properties of technical products/systems that have to be considered? When do they have to be considered? How do they relate to known ones? How to formalise and express (“model”) these, how to integrate additional model elements into existing product models?
  - What are new procedures (“processes”) and their elements in engineering design? Which ones to apply where?
- Requirements of the prescriptive part of Engineering Design Science from the perspective of designers in practice would be:
  - Which new methods and tools are relevant to systematically predict and optimise properties of technical products/systems (for “old” properties as well as newly introduced ones). How to integrate them into an existing landscape of procedures, people, methods, tools, etc.? How to relate product properties to business goals (e.g. time to market, image, risk, profits, …)? Are there examples from areas similar to the own field?
  - How to perform and optimise engineering design processes – in new as well as in well known fields? What is an “optimal” design process? How to assign methods and tools? How to optimise work distribution? Are there examples from areas similar to the own situation?
- For all aforementioned issues: What does a change of existing practice cost in terms of time and money? How to quantify benefits? Means and effort necessary to further qualify people in the company? How to enhance acceptance of changes in the own company?

- Finally, designers in practice are dearly looking for answers on how to deal with the huge amount of existing and still increasing knowledge. Beyond approaches for accumulation and systematisation of knowledge, this requirement also addresses the education and life-long training of designers with regard to better conceptualisation as well as the need for research (and science) to create generalised solutions instead of solution islands.

In summary, the requirements of designers in practice will be more biased towards ***modular-isation*** of knowledge gained in Engineering Design Science (see also [Birkhofer et al 2001]). Therefore:

- Engineering Design Science should present its findings in an appropriately modularised way and
- Engineering Design Science should also make greater effort in collecting, systematising, structuring/formalising knowledge about individual methods and tools,
- should even not refrain from statements about their usability and quality.

Again, some remarks to the list of requirements posed from the perspective of designers in practice in order to stress the issues that should be re-visited from today's perspective (some of which were already mentioned in section 4.1, will be therefore be only covered again very briefly):

  – As already stated, a lot more product properties than in the past have to be considered, but we also have a lot more (even still increasing number of) methods and tools offered "on the market".
  – Products as well as processes to design them become increasingly a multi-discipline/ multi-domain affair.
  – Designers in practice will in most cases tend to look for "specific" rather than for "general" knowledge on products and processes. Therefore, in order to increase benefits and acceptance of Engineering Design Science, it has to invest work in into application- as well as situation-specific "bundles" of methods and tools.
  – Formalisations of product and process descriptions become more important, not least because of an increasing amount of computer-support.
  – The perspective of designers in practice drawn up here is very closely related to what in Engineering Design Science in the 1990ies became known as building and using "designer's workbenches" or "designer's toolkits" (comprehensive overviews are given in [Jensen 1999, Vroom et al 2002]). These approaches so far have been very experimental, sometimes entirely theoretical, and were not really accepted in engineering practice. As the commercially available CAX-technology has changed a lot in the last decade (e.g. parametric 3D-CAD as base, market concentration, decreasing problems with interfaces, first steps into "knowledge-based engineering") the topic could and should be taken up again and realised in close relation to commercial tools, if not in cooperation with commercial vendors.
  – Only in the last couple of years studies investigating the acceptance of methods and tools in engineering practice have been conducted [Birkhofer et al 2005, Jänsch & Birkhofer 2006]. Engineering Design Science has to watch and integrate these findings when defining, systematising and commenting upon methods and tools.

4.3 Students:

The term "students" covers a wide range of "stakeholders", from undergraduate, to graduate, finally PhD students who will have slightly different requirements of Engineering Design Science:

- Particularly in undergraduate courses, Engineering Design Science, besides providing knowledge about the nature of products and about design processes, methods and tools, has an important role as a framework to fit in practically all other engineering disciplines students are confronted with (as was already described in [Albers & Birkhofer 1997]):
  - o Systematisation aspects are particularly important (e.g. distinguishing between products/systems and processes on one hand and between descriptive and prescriptive dimensions on the other hand)

  - Besides this, building up knowledge about (internal and external) product properties and their determination via methods and tools is necessary (see remarks to sect. 4.1).
- The view of graduate students will probably be more similar to the view of designers in practice (see section 4.2), i.e. they will require:
  - Focus on modularisation of the (product- as well as process-related) knowledge.
  - Help in the selection and proper use of methods and tools.
  - In some cases additionally: Guidelines for the development and test of new methods and tools.
- Finally, for PhD-students the view of scientists (see section 4.1) will become more and more important as they work on their projects. From experiences with the yearly Summer School on Engineering Design Research (SSEDR) the authors know (see also [Andreasen 2002, Flanagan & Jänsch 2004, Blessing & Andreasen 2005)]:
  - PhD students mainly criticise the lack of coherence in Engineering Design Science in general and in the terminology in particular.[6]
  - Additionally, the question of a proper research methodology implying scientific rigour as well as "craftsmanship" (e.g.: How to verify/falsify results?) is to be discussed.

Comments upon these requirements would be very similar to what was already stated in sections 4.1 and 4.2, respectively, and shall not be repeated here.

4.4 Tool/software developers and users:

The promotion of Engineering Design Science, or Design Theory and Methodology respectively, took place in roughly the same period of time as the evolution of computer models and tools supporting product development (CAX-tools). The results of the latter activities, however, have always been more readily accepted in engineering practice (some cynics say: because in industry it's much easier to buy a tool than to change the thinking). Today, we almost have an abundance of CAX-tools, some of them being introduced into companies in a rather haphazard way in terms of methods and methodology, requiring an adaptation of procedures instead of supporting existing and proven methods/methodologies.
One reason for this situation is that the development of CAX-tools and decisions on their application follows business rather than technical considerations. While this is outside scientists' influence, the second reason could well be tackled: Engineering Design Science should involve itself more deeply into the definition and development of (CAX-) tools. Therefore:

- Engineering Design Science should provide a sound formalisation base for the development and application of computer methods and tools. This requirement has, again, two sides – supporting the design***s*** and the design***ing***:
  - Which tool to use in order to model particular properties of products and their relations with computers? Which kind of tool to use in which situation (e.g. early/late phases)? Where are "white spots" on the map of CAX-tools (properties that can not yet be modelled properly)? How to systematise, store and provide product-related information and knowledge?
  - How to link CAX-tools and the information they process along with the progress of engineering design? What can be automated, what requires user interaction and human decisions? How to build customised chains (or networks?) of CAX-tools out of a toolbox? How to systematise, store and provide process-related information and knowledge?

Again, some remarks to these requirements posed from the perspective of tool/software developers and users designers, most of which were already mentioned in the previous sections and will be therefore be only covered very briefly:

  – As stated before, the computer support of engineering design processes is the main driver to formalise product and process descriptions much more rigorously than in the past.

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[6] To avoid misunderstanding: Of course, a PhD-student should be and is able to cope with that (as we all have done …). But better coherence and an established terminology would save a lot of time in the project.

– A lot more product properties have to be considered. For some, there is no computer-supported modelling strategy yet. On the other hand, some quite remarkable new tools have been proposed by researchers (e.g. [Dankwort & Podehl 2000]). This area should be investigated more sincerely, guided by findings of Engineering Design Science about product properties.
– Products as well as the processes to design them become increasingly a multi-discipline/multi-domain affair.
– As was already stated in the context of practitioners' requirements (see section 4.2), and even more strongly so, tool/software developers have to think in terms of modularisation, building (digital) "designer's workbenches" or "designer's toolkits" to support product as well as process models.
– Finally, issues of acceptance of tools in engineering practice are not at all addressed appropriately yet.

Table 1: Requirements of Engineering Design Science confronted with "stakeholders"

Requirement	Scientists	Practitioners	Students			Tool-/SW-developers
			Undergrad.	Grad.	PhD	
Establishing and systematising terminology	●		○	○	●	○
Scientific reasoning:						
– Formulation of hypoth., findings conclus.	●				●	
– Research methodology	●				●	
– Verification/falsification methods & tools	●	○			○	**?**
Coherent description and prescription of products:						
– Properties and their relations	●	●	●	●	●	●
– Multitude of properties and relations	●	●	○	○	○	●
– Multi-discipline/-domain approach	●	●	○	○	○	●
– Formalisation	●	○	○	○	●	●
– Modularisation		●	○	○	○	●
– Devel./applic. of tools for product modelling	○	●		○	○	●
– Acceptance of methods and tools	●	●			●	●
– Relation to business goals		●			○	●
– Integration into existing environments		●			○	●
Coherent description and prescription of design processes:						
– General framework	●	○	●	●	●	●
– Specific/"situated" processes	●	●	○	○	●	●
– Assigning methods and tools to processes	●	●		○	●	●
– Assessing methods and tools	○	●		●	●	**?**
– Formalisation	●	○	○	○	●	●
– Modularisation, designer's workbench		●		○	●	●
– Devel./applic. of tools for process support	○	●		○	○	●
– Acceptance of methods and tools	●	●			●	●
– Work distribution	○	●		○	○	●
– Integration into existing environments		●			○	●
"Map" of product- and process-related as well as descriptive/prescriptive knowledge	●	○	○	○	●	○

● Core issue ○ Depending on particular project

5. Conclusions

This contribution discusses what different "stakeholders" (scientists, designers in practice, students, tool/software developers) require of a comprehensive Design Science from today's perspective. **Table 1** summarises the results by confronting requirements (in a compressed from) with "stakeholders". The individual lines of the table show which issue is important for whom and, in aggregation, which issue is of bigger or lesser importance. The columns of the table give a profile of requirements according to the respective "stakeholder". Finally, the table presents a sort of classification "map" to find potential addressees of particular contributions to Engineering Design Science.

In summary, this paper proposes a new systematic framework of activities within Engineering Design Science which is at the same time in accordance with Engineering Design Science's own claims (i.e. "clarify requirements first").

However, the authors do not claim to present final solutions, but rather first ideas to spark off discussions amongst experts which might, eventually, lead to an agreed and joint approach to consolidate and further develop of Engineering Design Science.

References

[Albers & Birkhofer 1997] Albers, A.; Birkhofer, H. (eds.): Heiligenberger Manifest, Vorträge, Workshop-Ergebnisse. Workshop „Die Zukunft der Maschinenelemente-Lehre", April 23-24, 1997. Universität Karlsruhe/TH Darmstadt 1997

[Andreasen & Hein 1987] Andreasen, M.M.; Hein, L.: Integrated Product Development. Springer, London, 1987

[Andreasen 2002] Andreasen, M.M.: Experiences from a PhD-Course on Engineering Design Research. In: Proceedings of the Research Seminar on Operations Management and Innovation, CIP, Aalborg, 2002, p. 1-10

[Birkhofer 1991] Birkhofer, H.: Methodik in der Konstruktionspraxis – Erfolge, Grenzen und Perspektiven. In: Proceedings of ICED 91 (Int. Conf. on Engineering Design), Zürich, 1991, p. 224-233

[Birkhofer 2005] Birkhofer, H.: Some Comments on the Use of Systematic Design Methods in Industry. In: Clarkson, J.; Huhtala, M. (eds.): Engineering Design – Theory and Practice: A symposium in honour of Ken Wallace, University of Cambridge, 2005, p. 22-31

[Birkhofer 2006] Birkhofer, H.: The Consolidation of Design Science – A Critical Review of the Status and some Proposals to Improve it. In: Proceedings of Workshop AEDS 2006 (Applied Engineering Design Science), Pilsen/Czech Republic 27.-28.10.2006

[Birkhofer et al 2001] Birkhofer, H.; Lindemann, U.; Albers, A.; Meier, M.: Product Development as a Structured and Interactive Network of Knowledge – A Revolutionary Approach. In: Proceedings of ICED 01 (International Conference on Engineering Design), Glagow, 2001, p. 457-464

[Birkhofer et al 2005] Birkhofer, H.; Jänsch, J.; Kloberdanz, H.: An extensive and detailed view of the application of design methods and methodology in industry. In: Proceedings of ICED 05 (International Conference on Engineering Design), Melbourne, 2005

[Blessing & Andreasen 2005] Blessing, L.T.M.; Andreasen, M.M.: Teaching Engineering Design Research. In: Clarkson, J.; Huhtala, M. (eds.): Engineering Design – Theory and Practice: A symposium in honour of Ken Wallace. University of Cambridge, 2005, p. 32-41

[Blessing & Chakrabarti 2006] Blessing, L.T.M.; Chakrabarti, A.: How to Do Design Research – a Design Research Methodology. Springer, London, 2006 (in preparation)

[Dankwort & Podehl 2000] Dankwort, C.W., Podehl, G., A New Aesthetic Design Workflow – Results from the European Project FIORES. In: Brunet, P.; Hoffmann, C.M.; Roller, D. (eds.): CAD Tools and Algorithms for Product Design. Springer, Berlin, 2000, p. 16-30

[Eder & Weber 2006] Eder, W.E.; Weber, C.: Comparisons of Design Theories. Proceedings of Workshop AEDS 2006 (Applied Engineering Design Science), Pilsen/Czech Republic 27.-28.10.2006

[Felgen et al 2004] Felgen, L.; Grieb, J.; Lindemann, U.; Pulm, U.; Chakrabarti, A.; Vijaykumar, G.: The Impact of Cultural Aspects on the Design Process. In: Proceedings of DESIGN 2004, Dubrovnik, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 2004

[Flanagan & Jänsch 2004] Flanagan, T.; Jänsch, J.: Models, Methodology and Finding Focus – Dealing with the Challenges of PhD-Research. In: Proceedings of DESIGN 2004, Dubrovnik, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 2004

[Franke 1999] Franke, H.-J.: Ungelöste Probleme der Konstruktionsmethodik. In: Franke, H.-J.; Krusche, T.; Mette, M. (eds.): Konstruktionsmethodik – Quo vadis? Proceedings of a Symposium on

the occasion of the 80th birthday of Prof. Dr.-Ing. Karlheinz Roth. TU Braunschweig, Institut für Konstruktionslehre, Report No. 56, 1999, p. 13-30

[Gausemeier et al 2001] Gausemeier, J.; Ebbesmeyer, P.; Kallmeyer, F.: Produktinnovation – strategische Planung und Entwicklung der Produkte von morgen. Hanser, München, 2001

[Gero & Kannengießer 2003] Gero, J.S.; Kannengiesser, U.: The Situated Function-Behaviour-Structure Framework. Design Studies 25 (2003) 4, p. 373-391

[Gero 1998] Gero, J.S.: Towards a Model of Designing which Includes its Situatedness. In: Grabowski, H.; Rude, S.; Grein, G. (eds.): Universal Design Theory. Aachen, Shaker, 1998, p. 47-55

[Hansen 1974] Hansen, F.: Konstruktionswissenschaft – Grundlagen und Methoden. Hanser, München-Wien, 1974

[Hubka & Eder 1992] Hubka, V.; Eder, W.E.: Einführung in die Konstruktionswissenschaft. Springer, Berlin-Heidelberg, 1992

[Hubka & Eder 1996] Hubka, V.; Eder, W.E.: Design Science. Springer, London, 1996

[Hubka & Rovida 1987] Hubka, V.; Rovida, E. (eds.): WDK 14 – Methodical Design of Machine Elements (Readings), Heurista, Zürich, 1987

[Hubka 1973] Hubka, V.: Theorie der Maschinensysteme. Springer, Berlin-Heidelberg, 1973 (1st ed.)

[Hubka 1976] Hubka, V.: Theorie der Konstruktionsprozesse. Springer, Berlin - Heidelberg, 1976

[Hubka 1984] Hubka, V.: Theorie technischer Systeme. Springer, Berlin - Heidelberg, 1984 (2nd ed. of [Hubka 1973])

[Jänsch & Birkhofer 2006] Jänsch, J.; Birkhofer, H.: Providing Motivation to Use Design Methods and Systematic Design. In: Proceedings of the 5th International Conference on Advanced Engineering Design (AED), Prague, 2006

[Jensen 1999] Jensen, T.A.: Functional Modelling in a Design Support System – Contributions to a Designer´s Workbench. PhD thesis Danish Technical University, Institute of Engineering Design and Control Engineering (IKS), Lyngby, 1999

[Kuhn 1962] Kuhn, T.S.: The Structure of Scientific Revolutions, University of Chicago Press, Chicago, 1962

[Kuhn 1970] Kuhn, T.S.: The Structure of Scientific Revolutions (2nd ed., enlarged). University of Chicago Press, Chicago, 1970.

[Lenk 1998] Lenk, H.: Epistemological Remarks Concerning the Concepts “Theory” and “Theoretical Concepts”. In: Grabowski, H.; Rude, S.; Grein, G. (eds.): Universal Design Theory. Shaker, Aachen, 1998, p. 341-353

[Lindemann & Birkhofer 1998] Lindemann, U., Birkhofer, H.: Empirical Design Research – Its Contribution to a Universal Design Theory. In: Grabowski, H.; Rude, S.; Grein, G. (eds.): Universal Design Theory. Aachen, Shaker, 1998, p. 291-304

[Popper 1935] Popper, K.: Logik der Forschung. Springer, Wien, 1935

[Schäppi et al 2005] Schäppi, B.; Andreasen, M.M.; Kirchgeorg, M: Handbuch Produktentwicklung. Hanser-München, 2005

[Vroom et al 2002] Vroom, R.W.; van Haarlem, L.F., Ootes, F.P.A.: Overview of the Initiatives on the Development of Designer’s Toolkits. In: Proceedings of DESIGN 2002, Dubrovnik, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 2002, p. 443-448

[Wallace & Blessing 1999] Wallace, K.M.; Blessing, L.T.M.: Visions for Design Research. In: Mortensen, N.H.; Sigurjónsson, J.B. (eds.): Critical Enthusiasm – A Contribution to the Development of Design Science. Festschrift for Mogens Andreasen. Tapir, Trondheim, 1999, p. 193-199

[Weber 2004] Weber, C.: Modern Products – New Requirements on Engineering Design Elements, Development Processes, Supporting Tools and Designers. In: Dankwort, W. (ed.): Holistic Product Development, 5th Int. Workshop on Current CAx Problems, Shaker, Aachen, 2005, p. 165-178

[Weber 2005] Weber, C.: CPM/PDD – An Extended Theoretical Approach to Modelling Products and Product Development Processes. In: Bley, H.; Jansen, H.; Krause, F.-L.; Shpitalni, M. (eds.): Proceedings of the 2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Products and Processes, Fraunhofer-IRB, Stuttgart, 2005, p. 159-179

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