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WHAT IS "COMPLEXITY"?

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1 Introduction

The main challenge for all companies developing and producing technical products or systems today is a strong – and still increasing – competition in a world-wide ("globalised") scale. For companies in highly industrialised (hence "expensive") countries, there are two possible basic strategies to cope with this challenge:

1. Economic strategy: Decrease cost by shifting production (as well as, subsequently and increasingly, engineering) to low-cost sites.
2. Technical strategy: Maintain high prices necessary to cover high production (and engineering) cost by offering better products and systems.

Both strategies bear risks, so quite often a combination of the two is implemented.

This contribution concentrates on the technical strategy. This can be broken down to the following main components:

- Increase product/system complexity
- Increase number of product/system variants ("mass customisation")
- Increase speed of product/system innovation (which is much the same as decreasing development time or "time to market")
- Implement new forms of work distribution and organisation (e.g. supplier-integration, co-operative work, etc.)

Interestingly, all these components of the technical strategy have to do with "increased complexity" of the products/systems involved and/or of the processes to develop these.

The term "complexity" or "complexity management" is often used in current discussions (in engineering and other disciplines), but different approaches to and aspects of "complexity" are often mixed up.

This contribution discusses the aspects of "complexity" relevant for product development and engineering design, asks for methods to cope with them, and considers existing as well as new tools that support the management of complexity in this context.

2 “Complexity” as Discussed in Other Fields

Despite the fact that “complexity” is a mayor issue of discussion in engineering, and particularly in product development and engineering design, neither in theory nor in practice of the field there seems to be a sharp concept of the term. Therefore, a look into other fields and their concepts of “complexity” is presented as a starting point.

The traditional, in fact rather intuitive approach to the term “complexity”, which still has a mayor influence on our concepts in engineering, is verbalised in [1]:

- “Let us go back to the original Latin word *complexus*, which signifies ‘entwined’, ‘twisted together’. This may be interpreted in the following way: in order to have a complex you need two or more components, which are joined in such a way that it is difficult to separate them. Similarly, the Oxford Dictionary defines something as ‘complex’ if it is ‘made of (usually several) closely connected parts’. Here we find the basic duality between parts which are at the same time distinct and connected.

  We may conclude that complexity increases when the variety (distinction), and dependency (connection) of parts or aspects increase, and this in several dimensions. ... In order to show that complexity has increased overall, it suffices to show, that – all other things being equal – variety and/or connection have increased in at least one dimension.”

In the last couple of decades, the “complexity issue” has been taken up by several disciplines, and a vast number of concepts, publications, magazines and conferences in different fields of science evolved. The state of the art is nicely summarised in [2]:

- “The more general name for the field is complexity theory ... It is concerned with the behaviour over time of certain kinds of complex systems. Over the last 30 years and more, aspects of this behaviour became the focus of attention in a number of scientific disciplines. These range as widely as astronomy, chemistry, evolutionary biology, geology and meteorology. Indeed there is no unified field of complexity theory, but rather a number of different fields with intriguing points of resemblance, overlap or complementarity. While some authors refer to the field as ‘the science of complexity’, others more modestly and appropriately use the phrase in the plural.”

Any discussion about “complexity” leads to the question, whether and how the complexity of something can be measured. One of the earliest and still best known concepts of “complexity”, which originates from information theory and computer science, basically defines the term by defining a measure:

- Complexity is “the intrinsic minimum amount of resources, for instance, memory, time, messages, etc., needed to solve a problem or execute an algorithm” [3].

This concept evolved from contributions of A.N. Kolmogorov in the 1960s [4], which themselves were based on Shannons’s and Weaver’s mathematical theory of communication [5]. It was, therefore, called the “Kolmogorov complexity” and still is extensively referred to in computer science.

Here, in principle, “complexity” is linked to “information content”, and at the same time introduced as a measure of “randomness” (or “uncertainty”): The more “random” the behaviour of a system the more (maybe an infinite amount of) information is required to describe it.

This fits well to intuitive conceptions of "complexity" and subsequently sparked off more formalised approaches, e.g. linking "complexity" to "entropy" [6].

The definition of "complexity" in computer science can, retrospectively, be seen as an (early) example of (today) various discipline-specific concepts of different types of complexit*ies*.

Another discipline, where "complexity" is discussed very intensively in the last couple of years, is biology [7, 8]. The main topic discussed here are the mechanisms that, in the course of evolution, lead from nucleic acid sequences to ever more complex biological systems and a vast number of varieties of life.

Interestingly, in biology there is an ongoing debate, whether it is in fact true that complexity increases over time or not: "... concrete observations in diverse domains seem to confirm in ever more detail the intuitive notion of increasing complexity. ... Once we enter the biological realm, things become more ambiguous, and examples can be found to illustrate both increase and decrease of complexity" [1].

It may be added that some of the considerations, especially from biology, stress that there might be no "complexity" as such, but that "to a certain extent, complexity is in the eye of the beholder: what is complex for one observer, may be simple for another one" [1].

In the last two decades "complexity" is also intensively discussed in social sciences, which seems to have broadened up the perspective considerably. Many contributions in this field refer to the philosopher N. Luhmann (e.g. [9]), who is seen as the founder of a very stringent (and considered very difficult) system-theoretical approach in social sciences. Some elements of his work could also be of interest for our considerations on "complexity" in product development and engineering design:

- Luhmann links "complexity" (of social systems) to (a stream of) decisions, the degree of complexity (of a social system) at a particular point of time being determined by the totality of all possible decisions that could have been taken in the past.
- Luhmann also dedicates substantial consideration to the "reduction of complexity", which he sees as one of the basic requirements to make (social) systems function.
- One of the most important means to reduce complexity is to take decisions (and stick to them).
- The previous three points in combination cause a paradoxon, which was shown by Luhmann: Every decision taken in order to reduce complexity increases complexity.
- Another interesting idea in Luhmann's work on "complexity" is that decision making is not possible without "trust", because only trust allows us to make a decision without the possession of complete knowledge [10].

In engineering in general and in product development and design in particular there are very few considerations on the topic of complexity, one notable exception being documented in [11]. This is quite remarkable, because handling or managing complexity has always been a mayor issue in the field and is increasingly so (see section 1).

An interesting concept of "complexity", which the author came across, comes from the psychologist M. Csikszentmihalyi [12] (himself a multi-coloured personality spanning several scientific disciplines). As phrased in [13]: Csikszentmihalyi "provides a definition of complexity based on the degree to which something is simultaneously differentiated and integrated. ... While high levels of differentiation without integration promote the complicated, that which is highly integrated, without differentiation, produces mundane. And, it should be rather obvious from personal experience that we tend to avoid the complicated and are uninterested in the mundane. The complexity that exists between these two alternatives is the path we generally find most attractive."

A comprehensive overview on the state of complexity research across several disciplines and on attempts to find a general concept of "complexity" is given by the philosopher C. Emmeche in [14]. He clearly points out that, "from a scientific point of view, doubts can be raised about the use of any *general* (author's italics) notion of complexity". He sees, however, "the search for common structures across individual theories and local fields of knowledge (as a) truly legitimate aim of science" and proposes "complexity studies ... as a cross-disciplinary field of research and meeting place for dialogue between specialised groups of people".

3 "Complexity" in Product Development and Engineering Design

A very comprehensive introduction into "complexity" in product development and engineering design from the specific perspective of managing increasing numbers of product/system variants is presented in [15] (figure 1). This concept corresponds to the traditional view, as described at the beginning of section 2 (first dot).

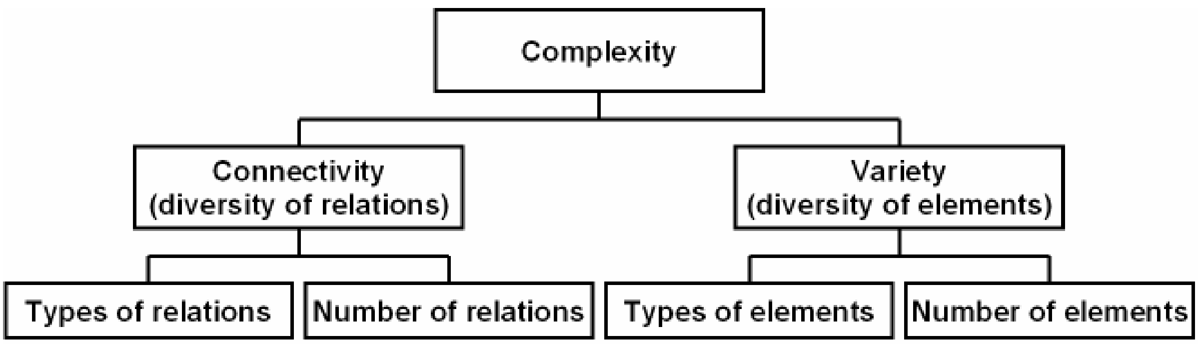

Figure 1. Complexity according to [15] with reference to [16]

For product development and engineering design, the author proposes an extended concept of "complexity", which has five main dimensions:

- "Numerical complexity": number of components in a product or system
- "Relational/structural complexity": number of relations and inter-dependencies between the components
- "Variational complexity": number of variants of a product/system
- "Disciplinary complexity": number of disciplines involved in creating the product/system
- "Organisational complexity": distribution of work, "global co-operation", "top-down" instead of "bottom-up" development/design procedures, etc.

The first three dimensions of complexity in engineering (numerical, relational, variational) refer to the product/system to be developed/designed, the last two (disciplinary, organisational) primarily have to do with the development/design process and people involved in it.

The first two dimensions of complexity (numerical, relational) correspond to the traditional, intuitive view on complexity (see first dot in section 2), the third (variational complexity) could have close links to concepts of complexity in (evolutionary) biology. The last two dimensions (disciplinary, organisational) point to more recent concepts in social sciences (see end of section 2).

If mirrored against the components of the technical strategy of companies developing and producing technical products or systems (see section 1) one can see that all five dimensions of complexity have to be increased at the same time (figure 2).

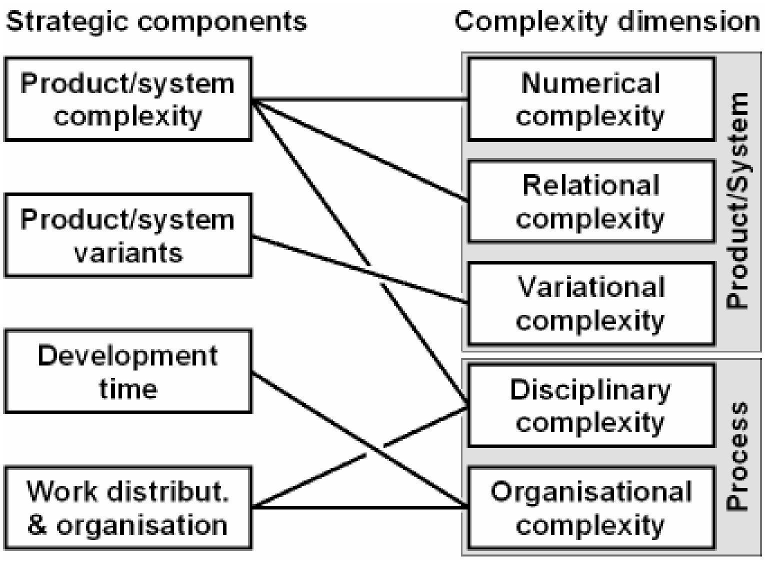

Figure 2.
Components of technical strategy mirrored against dimensions of complexity in product development and engineering design

It could be argued whether "variational complexity" is an own category or not, as it obviously carries aspects both of numerical and relational complexity (see also figure 1). The reason it is introduced independently here lies in the peculiar antagonistic influences of numerical and relational complexity on variational complexity:

- A required number of product variants could in one extreme be realised individually and independently, i.e. causing numerical complexity, but minimal relational complexity (mainly hierarchical relations of the "consists-of" type, no cross-relations between the variants).
- In the other extreme, product variants could be realised by combining a minimal set of pre-defined modules, i.e. generating minimal numerical complexity at the cost of increased relational complexity (e.g. multiple component hierarchies, functional and life-cycle structures, as well as many relations of the "A-requires-B" or "C-excludes-D" types).

4 Existing Approaches to Cope with Complexity in Product Development and Engineering Design

If we accept the strategies to meet the challenges of an ever more competitive market situation (see section 1), then in engineering there seems to be no way to escape (increasing) complexity as such. We can, however, look for approaches, methods and tools to cope with it.

4.1 Product Structuring and Modularisation

A very prominent approach to cope with the complexity of products is “product structuring”, “modular engineering”, etc., with closely related terms like “product family design”, “product platform” concepts, etc. An overview over the terminology is given in [17]; extensive discussions have been taking place in the up to now 7 workshops on product structuring organised under the umbrella of WDK (Workshop-Design-Konstruktion) and the Design Society as its successor.

Looked upon form the complexity point of view as introduced above, “product structuring” and “modularisation” primarily aim at reducing variational complexity, which is a most important concern of many “high-tech” companies. “Product structuring” and “modularisation” decrease variational complexity by decreasing numerical complexity – but at the cost of higher relational complexity, as was already described at the end of section 3.

Disciplinary complexity could hypothetically be reduced by modularisation, if the module structure was defined along disciplinary borders (opposed, e.g., to functional borders). Without being able to present a more detailed analysis, the author thinks that this option would, in fact, be counter-productive, because in mechatronics already now we can observe big problems with interfacing of “disciplinary modules” – again a question of increased, not sufficiently solved relational complexity.

Organisational complexity seems to be not inherently influenced by modularisation; depending on a more or less “clever choice” of a module structure it could go up or down.

In [15] the “product structuring” and “modularisation” as an approach to reduce variational complexity is deeply studied (with applications primarily in the field of low-volume manufacturers). Most interesting is the fact that this publication also considers the inter-dependencies between variational and organisational complexity, thus reasoning from product-related to process-related complexity issues.

4.2 Computer Support

Many current CAx-systems claim that they can support the handling of complexity in product development and engineering design, especially CAD-, PDM/PLM-, and ERP-systems[1].

There is no doubt that software tools can well cope with numerical complexity (i.e. dealing with [numerous] products or systems having many components), especially if they are based on large data-base management technology. The current paradigm of data-base systems in

[1] CAD – Computer Aided Design. PDM/PLM – Product Data Management, Product Life-Cycle Management. ERP – Enterprise Resource Planning.

practice is “relational DB-systems”, the term “relational”, however, having another meaning in this context (relations between entities being represented by tables).

When scrutinised more closely, it has to be stated that most PDM/PLM- as well as ERP-systems are limited to hierarchical relations in order to decompose a product or system along the traditional parts tree or bill of materials (“consists-of”-relations). To cope with the evolution of solutions during the process, often “successor-of”-relations are adopted as an overlay.

Most of the PDM/PLM- and ERP-systems provide, however, just *one* hierarchical view on products or systems; engineers very often wish for several or multiple views [18], depending on the task performed (e.g. functional as well as embodiment as well as manufacturing decomposition, etc.).

Until today, it has to be regarded as an exception if PDM/PLM-systems can capture and manage anything else than hierarchical relations. Already today, this causes some difficulty if they are combined with parametric CAD-systems (see below).

PDM/PLM- and ERP-systems also still have big problems in representing additional relations like “A-requires-B” or “C-excludes-D” types, which are most important, for instance, for products with many complex structured/modularised variants. It is common practice to capture and manage these types of relations by additional software tools outside PDM/PLM or ERP, respectively (variant tables, “buildability” analysis tools). These tools are sometimes also based on relational data-base systems, in other cases they are rule-based.

Mechanical CAD-systems are regarded as the backbone of product development and engineering design processes, “digital master” concepts being broadly implemented especially in “high-tech” companies. They have turned or at least are in the process of becoming 3D, “parametric” and “feature-based” in most industries. Their main focus is, however, still on geometric modelling. Besides this, current CAD-systems can also well capture parts tree or bill of materials information, i.e. hierarchical relations. They even extend this concept “downwards” by arranging the geometrical modelling steps inside the individual parts in so-called history trees.

Additionally, parametric CAD can capture and manage an extended range of relations between elements, namely geometric and mathematical relations, sometimes even more (e.g. conditional relations). In principle, it does not matter, whether these relations are defined between geometric elements which form the part, or between several parts that form a larger assembly or the product.

At present, this is not always appreciated, because a competing situation with PDM/ PLM and ERP occurs (with better relation-modelling capabilities often on the CAD side).

Feature technology is, in principle, a means to support the handling and management of relational complexity, as it aims to link different aspects (e.g. functional, manufacturing, assembly aspects) with geometry [19, 20, 21]. While the geometry side of features is well covered in current feature-based CAD-systems, there is no common mechanism, however, to maintain and use the – until now only implicit – links from there to the different application aspects (the different “semantics”) of features. This is a very big obstacle for taking practical advantage out of feature technology as it was conceived in research many years ago.

Besides PDM/PLM, ERP, and CAD an increasing number of software tools is available to support different aspects of product development and engineering design, e.g. FEM-systems to analyse the mechanical, electrical or thermal behaviour of products, DMU-tools to study packaging, assembly or service issues, MBS-systems to simulate the dynamics of products/ systems consisting of many individual masses, springs, dampers, CFD-programmes to simulate fluid dynamics, various (and increasingly comprehensive) software tools to simulate manufacturing and assembly, etc.[2]

All these tools serve the purpose of analysing particular aspects of product/system behaviour (particular product/system properties) as early as possible in the product development and engineering design process in order to decrease development time (see section 1). They may be "complicated" to make, understand or use, but they offer no support to deal with product- and process-related "complexity" as introduced in section 3.

Quite the opposite opinion could be held: At present, the existence of ever more (and more "complicated") tools and their results add to relational, disciplinary and organisational complexity, mainly because the tools and results are weakly or not at all inter-related, stem from and cover different disciplinary aspects and are difficult to integrate in (distributed) processes.

None of the CAx tools known to the author provides support in dealing with disciplinary complexity.

In the area of supporting organisational complexity, two quite separate streams of discussion have to be considered:

- One comes from the field of computer science and is mainly technology-centred (hardware and software for CSCW[3]). This issue shall not be discussed any further in this paper.
- The second one is dealing with the structure and control of development and design processes ("workflow management"), part of it being led in engineering disciplines, another part in business administration.

Workflow management of development and design processes is today an additional functionality of PDM/PLM- and/or ERP-systems. The basic concept is: At first a sort of "reference process" has to be defined (i.e. a structure of activities with milestones or "gates", partners/departments/people carrying these activities out, information flows between activities and people involved); then this scheme is implemented in PDM/PLM or ERP, its execution triggered by pre-defined events or deadlines.

The resulting organisational schemes and procedures may make sense from the enterprise-wide business process level, but they usually do not support the product development and engineering design process itself. (In many cases developers/designers even complain that their work becomes more complex than without workflow management tools.)

In the author's view the reason is that the development/design process with its many iteration loops and its "situatedness" [22] can not be properly represented by more or less rigid schemes.

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[2] FEM – Finite Element Method. DMU – Digital Mock-up. MBS – Multi-Body Simulation. CFD – Computational Fluid Dynamics.
[3] CSCW – Computer-Supported Co-operative Work.

5 Research Needs

If the concept of complexity in product development and engineering design presented here (section 3) is compared with existing approaches to cope with complexity issues in the field (section 4), the least concern is with approaches, methods and tools to deal with numerical complexity. There are some deficits, however, in dealing with relational and variational complexity. In the field of coping with disciplinary and organisational complexity very little or no concepts exist.

Handling relational complexity seems to be the key issue with regard to the product-related complexity dimensions (see figure 2): If that is solved, also variational complexity can successfully be tackled.

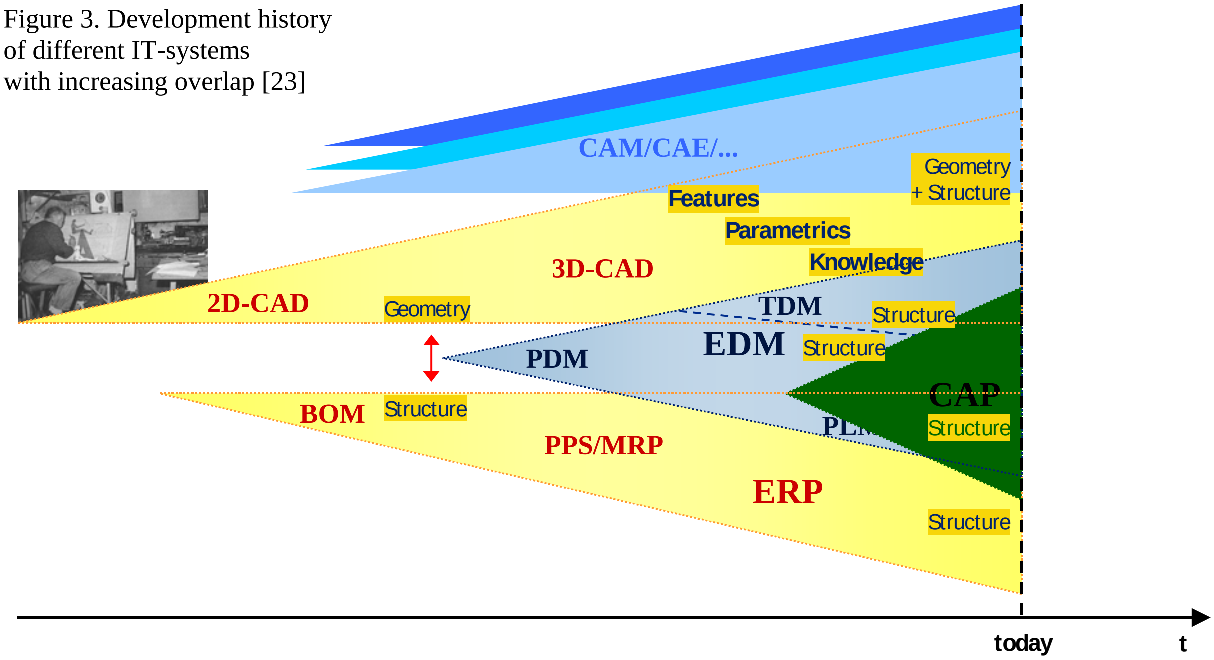
The author sees three open research questions connected with relational complexity in product development and engineering design:

- We do not have a concise answer to the question, which types of relations are relevant in our field. As was shown in the argumentation in section 4, we are quite familiar with and have good software support of hierarchical “consists-of”-relations, because they are the base of parts trees or bills of materials. There is also good command and (by parametric CAD-systems) increasing support of geometric and mathematical relations. We know of a lot more relation types that are relevant in some stages or aspects of product development and engineering design (e.g. conditional “if-then-else”-relations, “successor-of”-relations, “A-requires-B”, “C-excludes-D”, etc.), but we do not have the complete overview; additionally (probably: because of not having an overview), there is weak or no proper software support to capture and handle these types of relations.
- What are the IT-concepts to deal with the different types of relations relevant in product development and engineering design (e.g. relational data-base systems, rule-processing, semantic nets, neural nets, ...)?
- Finally, what types of relations should be captured and processed by which software component? As was discussed in section 4, already now we have problems in separating tasks between CAD- and PDM/PLM-components [23]; the situation might get worse, if further development of existing or new software components is left to chance (figure 3). This question is not only of scientific interest, is also has immediate practical implications: The difficulties in interfacing an increasing number of software components, which practitioners often complain about, is not a problem in its own right, but an effect of inappropriate or ill defined task distributions between the software components involved.

Disciplinary and organisational complexity as the two process-related complexity dimensions require different, more fundamental approaches:

- All process theories and models for product development and engineering design are based on certain product model concepts (term “product model” used in a general, not an IT-sense here), even if they are implicit sometimes. Existing product models are still heavily biased towards individual disciplines (e.g. mechanical engineering in [24, 25]); therefore extended model platforms for interdisciplinary products/systems have to be developed:
  - An immediate need already exists in the area of adequate product model concepts for mechatronic systems/products as combinations of mechanical, hydraulic, electrical/ electronic, and software components.

Figure 3. Development history of different IT-systems with increasing overlap [23]



  - The next step will probably be the integrated modelling of products consisting of material plus immaterial components ("Product-Service Systems", one proposition in [26]).

- Revised process models for product development and engineering design have to be considered. They should meet the following requirements:
  - based on extended product models of interdisciplinary products/systems, as mentioned above;
  - must consider new forms of work distribution and organisation (e.g. supplier-integration, globalised co-operative work, etc.);
  - must be seen and positioned as part of more general business process (re-) engineering approaches.

  Some activities in the field of mechatronic systems/products have already been taken up (e.g. [27]), but they do not yet meet all of the requirements presented here.

- In the last step, conclusions for revised or new methods and tools must be drawn. Ideally, the architecture of software supporting product development and engineering design have to follow the revised process fundamentals (one proposition for revised PDM/PLM-concepts shown in [28, 29]), not vice-versa.

6 Conclusion

At present, there is a broad discussion on "complexity" in various fields of science. No general concept is visible, it might even not be possible (or sensible) to develop one. In a way "complexity is too complex for conceptual representation" [9].

Instead, various disciplines offer their individual views on "complexity". Very few contributions, however, deal with the topic in product development and engineering design – despite the fact that handling or managing complexity has always been important in this field.

The author thinks that engineering could gain a lot of benefit from starting a discussion and elaborating an “own” perspective on complexity in its field – not only scientific, but also quite practical benefit (e.g. addressing strategies, methods, and tools to cope with complexity).

This paper is tries to spark off such a discussion by providing an overview over concepts of “complexity” in other fields, proposing a taxonomy for product development and engineering design, and discussing existing approaches as well as research needs to cope with “complexity” in engineering.

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