INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

THE CONCEPT OF PRODUCT PROPERTIES AND ITS VALUE FOR RESEARCH AND PRACTICE IN DESIGN

Herbert Birkhofer and Martin Wäldele
Technische Universität Darmstadt, Germany

ABSTRACT
Design science has produced a lot of models, definitions, and terms, which may be highly useful for design research as well as design practice. Still this body of knowledge and insights is often neglected and altered concepts are created with a lot of effort and unpleasant consequences. This contribution highlights the product property concept as one important concept for activities related to design. It explains the nature of product properties in detail and addresses their importance for research and practice. The main objective of this paper is to contribute to a consolidation of design research and to counteract the current growth of divergent concepts and terminologies.

Keywords: property, characteristic, value, attribute, technical system, process, product

1 MOTIVATION
If one listens to people from design management, often the "magic triangle" of time, costs, and quality is quoted, which establishes the overall objectives for design work. Whereas "time" addresses a property of the design project, the terms "cost" and "quality" are used by Designers and even design researchers to address properties of the product created in design. Likewise, functionality, behaviour, efficiency, lifetime, or handling and a lot of other properties are called product properties. This is in fact wrong. This misuse or at least incorrect use of terms confuses all the more as the fundamental work of Hubka [1] defines, since about 25 years, quite properly a Theory of Technical Systems and specifies their properties. In addition other authors like Andreasen, Weber, Eder and Hosnedl [2, 3, 4] contributed to Hubkas approach, enlarging and detailing the view on technical systems.
Triggered by different attempts within the context of meetings and conferences organized by the Design Society and based on the scientific work of the Collaborative Center (CRC) 666 at Technische Universität Darmstadt this paper tries to contribute to the consolidation of design research [5] by focusing on a universally valid way for describing products through properties and sort product properties according to their origins. Triggered also by an intensive discussion within the Special Interest Group "Applied Engineering Design Science (AEDS)" on properties, characteristics, values, attributes and related terms [6] this contribution does not struggle with terms only but initially tries to clarify the meaning behind them and to demonstrate it on examples (heat exchanger, cable conduit).
The value of a proper product description through properties enables researchers e.g. to analyse existing technical systems and to create design repositories. Designers may use properties e.g. for structuring existing products and for systematically creating new ones by applying variation techniques. In fact an awareness of properties and their conscious application may be seen as one key element for successful design [7]. Looking at numerous case studies [8] it's evident that the conscious use of properties also boosts creativity and may lead to substantial innovations.

2 GENERAL REMARKS TO DESCRIBE PRODUCTS

2.1 Description of concrete, tangible products
According to Hubka & Eder [9] Technical Systems are understood here as an entirety of (product representing) objects and processes and the relations between them. The focus of this contribution is dedicated exclusively to describe concrete, tangible products. (For the description of intangible products like services see e.g. [10, 11]). A powerful process model [12] may be used for this, but its detailed presentation would enlarge this paper inadmissibly.

In this paper properties are analyzed and categorized for highlighting their role for design science and design methodology and to deepen the understanding of the synthesis character of design. This contribution is based on product and process models used at Technische Universität Darmstadt, which have been proven to work well in design research as well as in design application.

2.2. The formalism of a description

Describing a product through properties is always done in the same way. The length of a heat exchanger may be 2.45 meters; this statement links the value "2.45 meters" to the attribute "length". Attribute and a related value form what we call a property [13] and it is related in our case to the object heat exchanger. This concept of description is truly generic, even if we're often sloppy and deviate from this strict formulation in our daily work. If we say: "The heat exchanger is grey" exactly we mean: "The colour (attribute) of the heat exchanger (object) is grey (value).
Products differ if at least one property differs which means that either a new property can be seen (a heat exchanger without cooling ribs) or another value for the same attribute creates a new product (a heat exchanger with the length of 1.6 meter). Comparing and forecasting properties is the basis for the powerful theory of similarities and also enables systematic variation of product properties.

3. INDEPENDENT AND DEPENDENT PRODUCT PROPERTIES

This chapter explains the different types of properties, separated in independent and dependent properties in order to describe products.

3.1 Independent properties

Looking at a product like a heat exchanger represented in a 3D CAD-drawing one can recognize a lot of properties. Some of them are highlighted in figure 1.

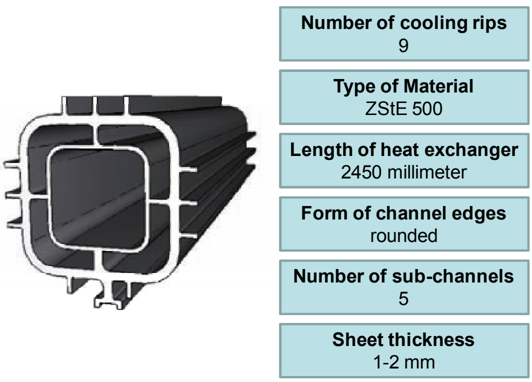

Figure 1. Example "heat exchanger" – independent properties

All these properties are geometrical or material properties. Geometrical properties can be macro-geometrical ones like form, number, arrangement and size of specific elements like profiles or profile-features. Even micro-geometrical product elements like surfaces, surface roughness or grains of metal may be described in such a way. A designer working in 3D-CAD can't give any input but only geometrical one and he can assign certain materials to its model in a part list. The material itself is specified by certain material properties, e.g. the sheet metal ZStE 500 has a certain density or elastic limit. These properties, which are directly fixed by the designer working on a product-model e.g. 3D-CAD, we call independent properties. They are constituents of a specific product and distinguish different ones.

3.2 Dependent properties

When establishing independent properties during the design process e.g. on the 3D-CAD model, we indirectly design a lot of dependent properties. Dependent means that these properties depend on the determination of independent properties. Figure 2 shows a set of relevant dependent properties of a heat exchanger, which a designer has to meet in order to fulfil certain required properties.

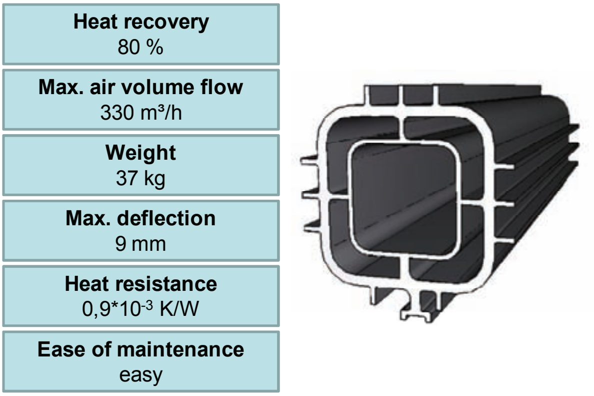

Figure 2. Example "heat exchanger" – dependent properties

To minimize the deflection of a heat exchanger attached to a workshop roof e.g. the designer has to design a "stiff" geometry, providing more support fixings at the roof or choose a "stiff" material.

3.3 The link between dependent and independent properties

The example in chapter 3.2 shows that independent and dependent properties are linked (generally speaking) by knowledge [14]. This knowledge is often stored in scientific literature (e.g. guidelines, textbooks) and it's "transmission" to students is a main task for lecturers. Technical knowledge is based mostly on models (e.g. fatigue models, beam bending models or fluid dynamic models) and is captured e.g. in texts, formulas, graphs and tables.
The physical model of heat resistance e.g. links the heat resistance of the profile to the geometry, as well as to the material properties of the heat exchanger itself. This specific knowledge enables a decision on which independent properties to concentrate on in order to create the required dependent properties. To represent the relation between independent and dependent properties a network structure called property-network (fig. 3) is introduced [15].

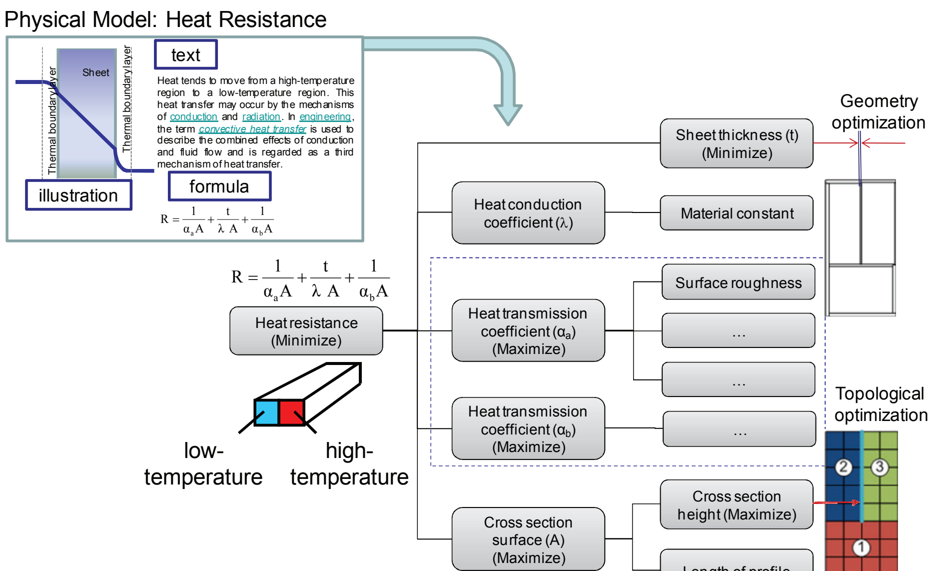

Figure 3. Property network with relation between the dependent property "heat resistance" and related independent properties

Dependent properties have always to be traced back to independent properties. A designer must know which “setscrews”, and therefore independent properties, he needs to adjust in order to achieve his desired dependent ones [15]. If there is no relation known, designers are forced to assume and to guess. It’s therefore a challenging task to think about non-technical (dependent) properties like styling properties where meagre formal relations between independent and dependent properties are fixed. Which geometrical and material properties reflect a well styled product? Probably mental models [16] linking independent and dependent properties are used by designers to create a good styling of a product. Maybe this causes the variety of product styles and the artistic nature of styling.
The CRC 666 addresses these questions and attempts to explain product related knowledge by independent and dependent properties and the relation between them based on models. In general the awareness of this property-concept is of fundamental importance for the design process and defines the real nature of design work.

4 PROPERTIES OF PRODUCT MODELS

The previous chapter highlighted properties regarding geometric product representation within a 3D-CAD model. Beyond geometric models, a number of other product related models are known in design methodology and used. A common approach in systematic design is the approach of the product model pyramid [2, 7, 17], which distinguishes between the four models “Function”, “Effect”, “Working Principle” and “Component”.

4.1 Independent properties of product models

Elements and structure of each partial product-model can be described completely and clearly by their independent properties [18]. The type of a model-element may be described by properties like type, number, form or size of its (sub-)elements (figure 4).

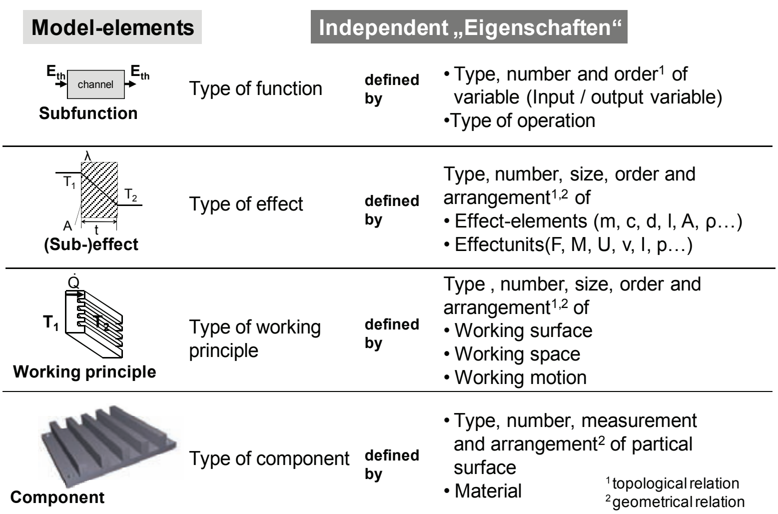

Figure 4. The independent element-properties of product models

The type of a model-structure may be described by properties concerning the type and number of model-elements and logical, topological or geometric relations between the elements (figure 5). Obviously the number of independent properties of each model is quite limited. In fact the number of model-variants is almost infinite due to the huge amount of values for each of its properties as well as due to the unlimited number of combinations of elements.

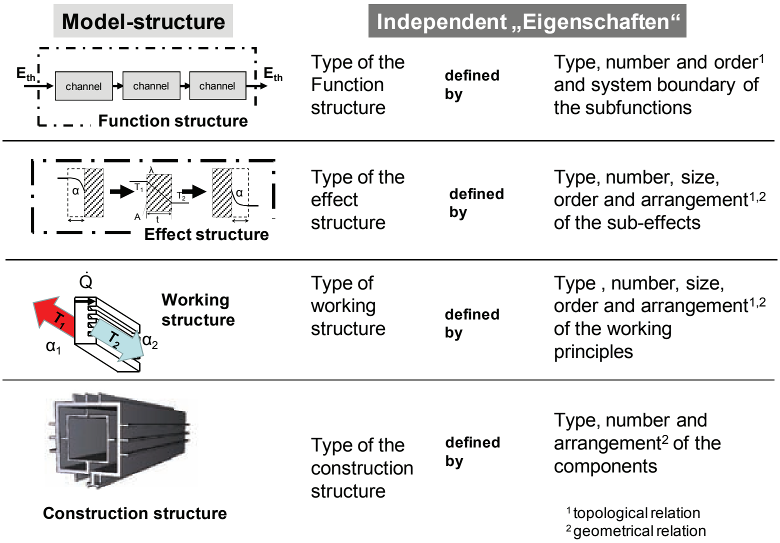

Figure 5. The independent structure-properties of product models

4.2 Dependent properties of product models

The type and size of a heat exchanger has to be tailored to suit a process depending on the type of fluid, its phase, temperature, density, viscosity, pressure, and various other thermodynamic properties. These types of properties depend (not only, but also) on the function, the effects, the working principle and the parts/components the designer has directly fixed. It's the same with numerous other properties like weight, inertia, strength, stresses, heat resistance, corrosion resistance or glance. The entirety of these properties resulting from the initially fixed properties and other influences we call dependent properties. They may be assigned to elements (figure 6) as well as the structure of each model (figure 7).

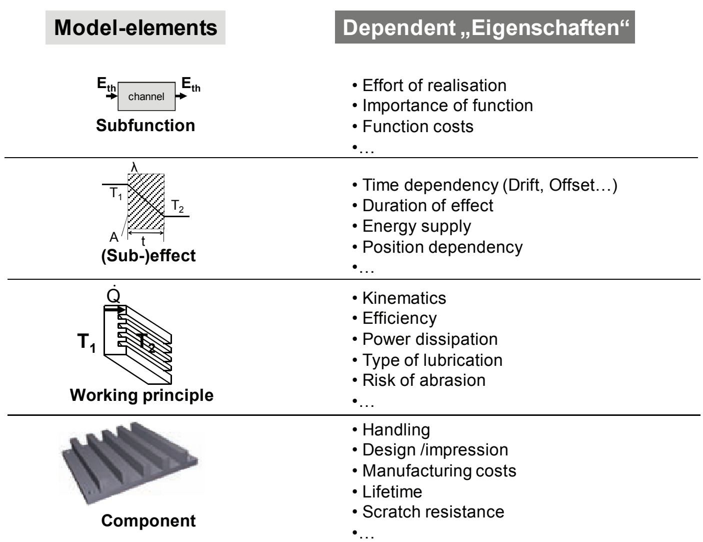

Figure 6. Some dependent properties of elements of product models

Dependent properties are also related to models, but not in such exclusivity as the independent ones. For the heat exchanger e.g. the bending resistance may be of interest in the working principle model as well as in the geometrical model. Of course each product model aims towards a specific area of independent properties (which means each model serves for a specific purpose), but these areas are overlapping, which may cause a lot of trouble in design approaches following a strictly stepwise procedure (waterfall-procedure). By the way, the model-specific assignment of properties is the reason, why the property "function" e.g. cannot be assigned either to an independent or dependent property. Function is an independent property within the functional model, but a dependent property e.g. within the model of working principles.

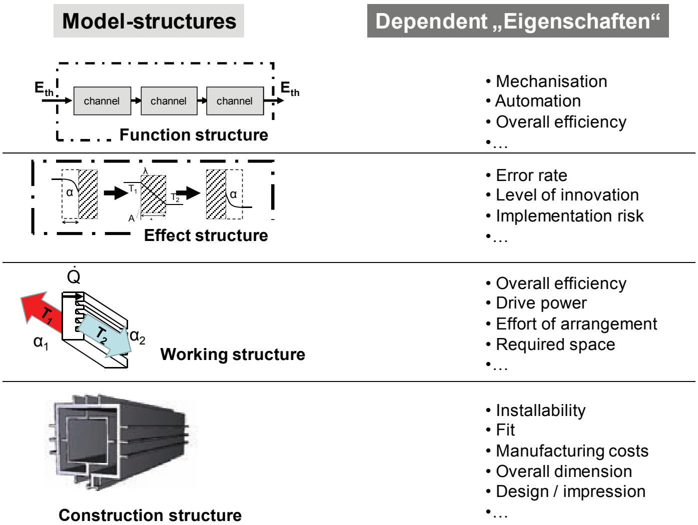

Figure 7. Some dependent properties of the structure of product models

5 PROCESS INFLUENCES ON DEPENDENT PROPERTIES

If we put a load on the heat exchanger like its deadweight or an external weight of assembled tubes we can see or measure its deflection. It is obvious, that this deflection of the heat exchanger is not only caused by geometrical and material properties, but is also determined by external loads and the location of supports. The same goes for the heat flow between the channels. The heat recovery is not only dependent on the geometrical and material properties but also on the temperatures of the fluids, their flow velocity and environmental factors like atmospheric pressure or humidity. Any object gets functionality and creates benefit only if it is integrated in a process. A heat exchanger deposited in space near the Andromeda nebula has no functionality at all and is absolutely useless. But if we connect it in a factory in Japan to an exhaust air outlet and a fresh air inlet and open the valves, then in this process it serves a purpose and has a value for the user.

To get onto the trail of such object and process influenced dependent properties is more complicated than to detail the independent properties of an object. Well settled models like the Life-Cycle-Model [19] and the Process-Model [12] have to be used to get a holistic overview of the role of products within processes as well as a direct access to the related properties.

5.1 Dependent properties of a product in the operator role (use phase)

The role of a product as an operator, which serves a special purpose in the use phase is the standard role, every designer has in mind first when he is designing. A heat exchanger should exchange heat between liquids or gas, should guide these fluids without any leakage, should support his own weight, etc. Dependent properties in such an "active" product role may be detected by applying the process model with the product (or its components) as an operator. Figure 8 demonstrates the process of heat transfer and influencing factors and influences working in the process within a heat exchanger. Influences may also be described by properties, a remarkable amount of which are dependent ones.

These are usually, but in fact erroneously, called product properties (figure 8).There are well established proposals to structure dependent properties further on e.g. in mechanical, thermo dynamical, fluid dynamical or electrical (product) properties. Nevertheless most of these properties are not pure product properties, but are influenced and sometimes dominated by the specific process in which they are used.

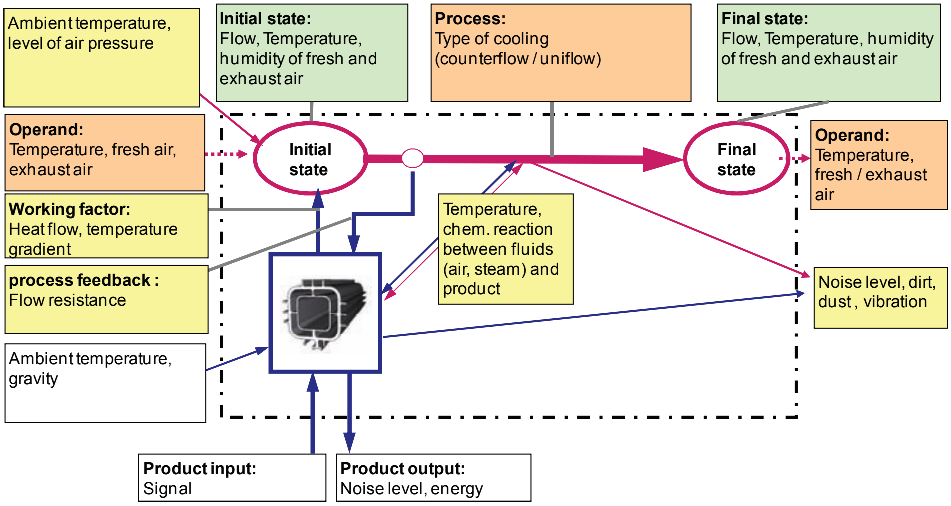

Figure 8: Process model of a heat exchanging process with influences (only examples)

5.2 Dependent properties of a product in the operand role (all non-use phases)

Within a lot of processes a product doesn't only play an active role (which is its purpose), but a passive role too. The passive role means, that the product, its components or parts will be transformed by the process. Figure 9 shows a process of the life-phase "production". The operand in this case is the sheet metal being "transformed" into a profile structure. The operator is the continuous production line with e.g. linear flow splitting stands which consists of components like the splitting roll, the support roll, and so on, and is controlled by parameters like the incremental splitting depth and the position of the splitting and supporting rolls. The linear flow splitting machine represents the operator (or product) in the process model which affects the process using the working factor "roll force" [20].

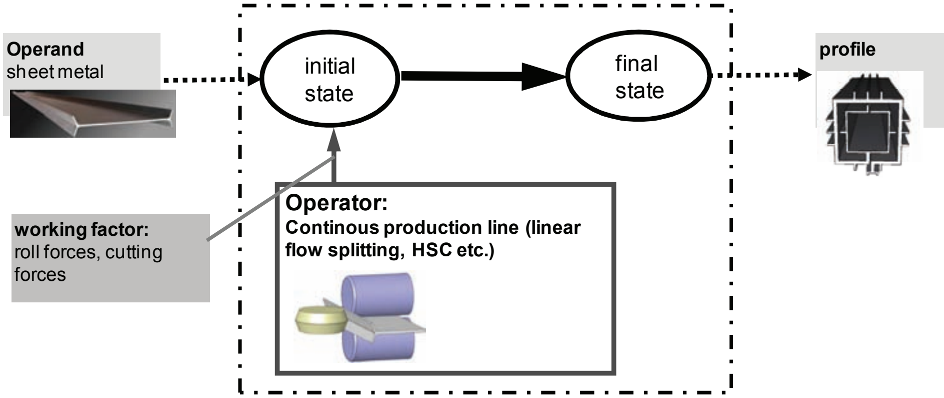

Figure 9. Product as operand being transformed by manufacturing processes

Also, in the use phase the product may not only be an active operator but also a passive operand and we know the often intensive interaction between products and processes through internal influences like wear or friction and external influences like corrosion or temperature of the environment. This emphasises the process related nature of most so-called product properties.

6 SOME CONSIDERATIONS ON PROPERTY RELATED IMPLICATIONS

6.1 The fairytale of product properties

The previous chapters demonstrated that the majority of dependent properties are caused by (independent) properties of the product *and* influences of the actual process. The fact that apparently everybody ignores the junction term “and” by calling them product properties is all the more remarkable.

It’s obvious that manufacturing costs of a shaft e.g. result from the semi finished part going into the production process and from the costs for manufacturing caused by turning and grinding machines, tools and the energy needed. That’s the reason, why nobody may specify the manufacturing costs only on the basis of a precisely defined part. Nevertheless we are accustomed to “glue” the “manufacturing costs” onto the shaft like a paper-based label.

It’s the same with the running costs of a car. We all know that running costs are dependent heavily on the price of crude oil, the relation between offer and demand of gasoline and the current situation on the world trade market, all influences far away from independent properties of a specific car.

The same goes for the quality of a laptop computer. It needs a well defined test program for measuring the dependent properties and defining the quality. Different tests cause different laptop qualities and therefore test magazines and internet chats are full of quite contradictory praises and complaints of the qualities of a specific computer.

On the whole, nobody can imagine how many misunderstanding, faults and deficits in design related methodology have been caused by the simplification of reducing product and process related properties to solely product related ones.

6.2 The need for holistic methods and tools

Coming back to 3D-CAD it is a truly powerful tool, but in its core it represents geometry. A first step to enlarge the field of application of 3D-CAD and to also represent product behaviour was done when animation techniques were integrated enabling the demonstration of kinematics and to analyse collision between parts. Progress in CAx-techniques is dedicated to continuously enlarging the “behavioural part”, which means its dependent properties, of the original geometrical model to FEM (fig. 10), Digital Mock Up – models, Virtual Reality and even Augmented Reality [21].

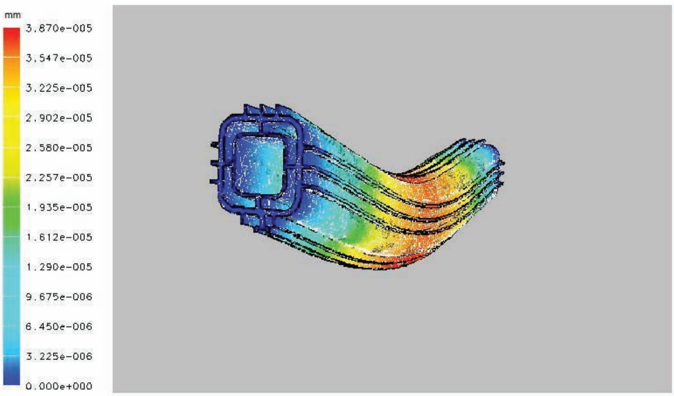

Figure 10. Deflection simulated by FEM of 3D-CAD

For vision let’s think about a tool, which enables designers to model a product and put it immediately into a use process with loads, temperatures and vibrations to recognise its behaviour (without all these nasty, time-consuming transformations we need today).

6.3 The vision of a design-appropriate knowledge representation and presentation

If we limit just for a short moment the work of designers only to 3D-CAD modelling of geometry and assigning material to parts in a part list, then design as a whole may be seen as the appropriate fixing of independent properties in that way, that all generated dependent properties fulfil the requirements and limitations of a given design task best. This idea is the key for understanding the very nature of design and the challenges and difficulties related to design work. Design complexity increases if one takes not only geometric and material modelling into account but the whole variety of product and process related models.

Considering the incredible amount of knowledge in regard to the relations between independent and dependent properties, in regard to the lack of concrete and detailed knowledge in many disciplines and the huge amount of contradictions within this body of knowledge, it's a near-miracle that designers succeed in so many cases.

The property driven approach may be seen as the key for restructuring design product and process related knowledge [22]. It may be unrealistic to demand a representation of design related knowledge, working out the models behind the representation, describing their independent and dependent properties, and building up a data base for design. But it is quite realistic to point out, how many mistakes are made and how much effort is wasted in the present and probably will be wasted in future representing and presenting knowledge in a non-design appropriate manner. If the content isn't understood well and the structure isn't carried out carefully, knowledge databases can inevitably be of only limited value for design.

6.4 The enhancement of algorithm based design

In general, product design can be seen as the selection and optimisation of design parameters to fulfil defined requirements [23, 15]. This underlines the chance of algorithmization of design, which was a distinct objective of the CRC 666. Based on the innovative production technology of Linear Flow Splitting of sheet metal [24] a variety of products like a cable conduit was designed almost purely algorithm-based. Whereas simulation tools need a draft as an input and designers use such tools to optimize part, components or products, the algorithm based approach creates topology and geometry by itself from the beginning. Starting with verbally represented requirements, the corresponding dependent properties were coupled with independent properties (material and geometrical properties). Regarding the low bending of a beam structure, the interrelation of requirements and design-parameters can be linked by physical effects and be expressed in terms of equations (see figure 11).

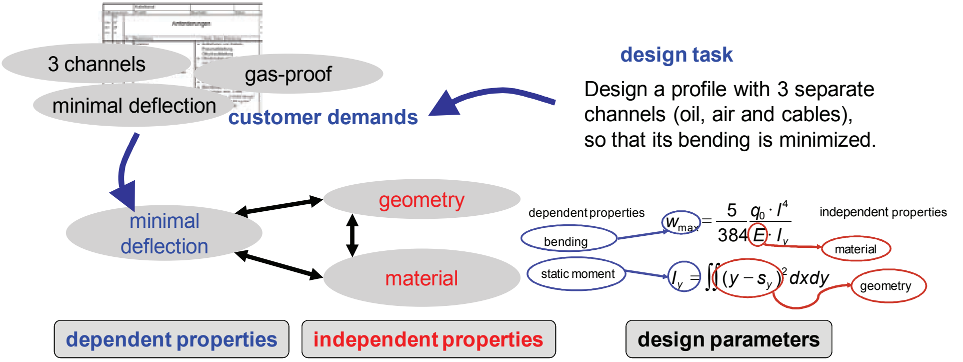

Figure 11. Transforming a verbal design task into an equation as a formal description

In stage one, a coarse mixed-integer programming (MIP) model was solved with linearized functional relations to find the overall topology of the product. Constraints include feasible and exclude non-feasible solutions in the entire solution area whereas objectives and wishes allow ranking the remaining solutions in regard to their performance.

A rectangular pixel-matrix representing the cross-section of the cable conduit is used as a grid-discretisation. Pixels can either represent material (steel) or areas without material (cable, pneumatic, exhaust areas, environment). Using Mixed Integer Problem Optimization algorithms like pre-processing, primal-heuristics, dual algorithms, or branch-and-cut algorithms, one can now generate all pixel arrangements which fulfil the constraints (see figure 12).

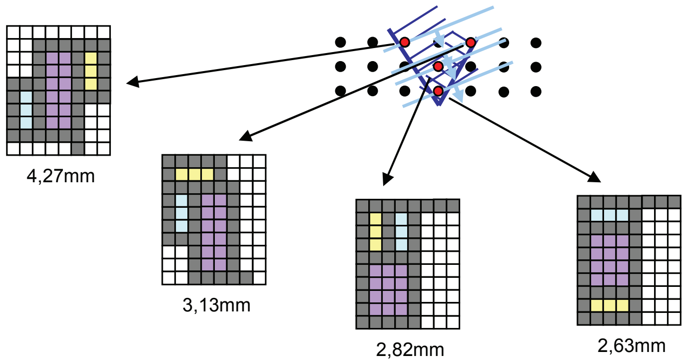

Figure 12. Generating feasible optimal topologies (grey pixels indicate material)

After obtaining the optimized product topology, a detailed non-linear continuous shape optimization model is formulated and solved to obtain a detailed product geometry (see figure 13).

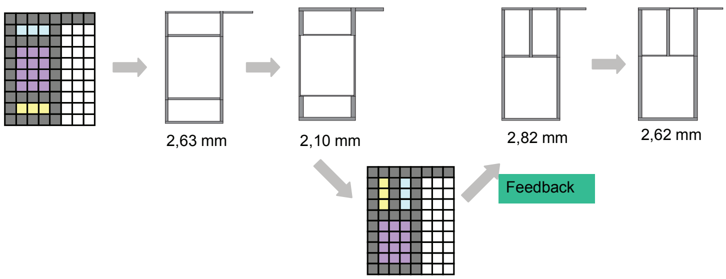

Figure 13. Generating feasible geometries

Even with a minimum of bending deflection (2.10 mm), this profile cannot be manufactured by the linear flow splitting technology due to an "unproducible" thickness distribution of different walls, which makes it necessary to jump back to a slightly worse profile.
Because there are normally a huge amount of ways to design cross-sections, an algorithm-based approach creating so-called "spanning tree" graph must decide where to cut and where to connect sheet metal (see figure 14).

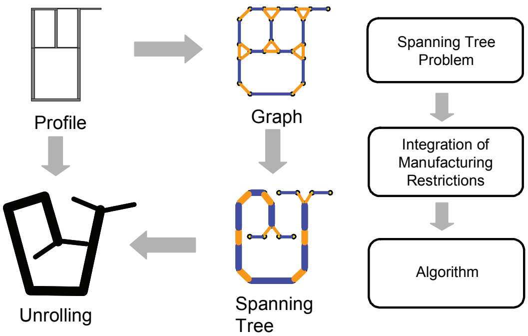

Figure 14. Modelling the cross-section as a spanning tree-graph

Having created the solution so far, there are of course some problems to be solved in generating a 3D-CAD model of the final product. However, it can be said without any exaggeration that the design process has now overcome the most critical challenges and has come "into its own element" (see figure 15).

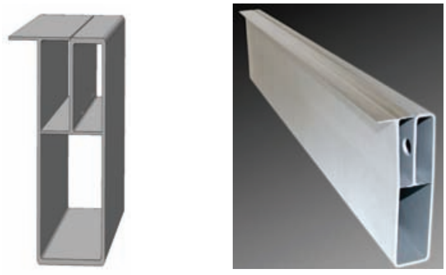

Figure 15. The 3D-CAD model of the cable conduit (left) and the final product (right)

Further optimisation can now be carried out by applying commonly known simulation software like FEM software.

7 CONCLUSION

The approach of properties is of fundamental importance for design science, design research and design application. Apart from the heat exchanger and cable conduit example, the concept of dependent and independent properties has to be seen as a basis for improving the power of design tools, for structuring design knowledge in a design-appropriate manner and for carrying out an algorithm-based design. The property approach may be seen as one element of a highly formalized "Design Language" based on clear terms, definitions and models of a consolidated design science.

ACKNOWLEDGEMENT

Thanks to the German Research Association (DFG) for funding this work (Research Grant SFB 666 / CRC 666).

REFERENCES

[1] Hubka, V., "Theorie technischer Systeme", Springer Berlin Germany, 1983.
[2] Andreasen, M. M., Hein, L., "Integrated Product Development", Springer Berlin Germany, 1987.
[3] Weber, C., "CPM/PDD – An Extended Theoretical Approach to Modelling Products and Product Development Processes", In: Proceedings of the 2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Product and Processes, Fraunhofer-IRB-Verlag, Stuttgart Germany, 2005.
[4] Eder, W. E., Hosnedl, S., "Design engineering – A manual for enhanced creativity", CRC Press Boca Raton USA, 2008.
[5] Birkhofer, H., Weber, C., " The Consolidation of Engineering Design Science", Rohatynski, Ryszard (ed.): EDIProD Poland, 2006.
[6] Birkhofer, H., Waeldele, M.; "Properties and characteristics and attributes and… - an approach on structuring the description of technical systems", Proceedings of the Applied Engineering Design Science workshop, AEDS 2008, Pilsen, Czech, 2008
[7] Lindemann, U., "Methodische Entwicklung technischer Produkte", Springer, Berlin Germany 2006
[8] Birkhofer, H., "There Is Nothing As Practical As A Good Theory – An Attempt To Deal With The Gap Between Design Research And Design Practice", Marjanovic, D.; Birkhofer H.; Andreasen M. (eds.): Proceedings of the International Design Conference DESIGN Croatia, 2004.
[9] Hubka, V., Eder, E., "Design Science", Springer Berlin Germany, 1996.
[10] Ramaswamy, R., "Design and Management of Service Processes – Keeping Customers for Life", Addison-Wesley, Reading, 1996
[11] Bullinger, H-J., Scheer, A-W. (Hrsg.), „Service Engineering – Entwicklung und Gestaltung innovativer Dienstleistungen", Springer, Berlin, Heidelberg, 2006
[12] Heidemann, B., "Trennende Verknüpfung- Ein Prozessmodell als Quelle für Produktideen", VDI-Verlag Düsseldorf Germany, 2001.
[13] Birkhofer, H., "Analyse und Synthese der Funktionen technischer Produkte", VDI Verlag Düsseldorf Germany, 1980.
[14] Wäldele, M., Hirsch, N., Birkhofer, H., "Providing Properties for the Optimization of Branched Sheet Metal Products", Proceeding of the International Conference on Engineering Design 2007,

ICED’07 Paris, France, 2007.
[15] Wäldele, M., Vucic, D., Birkhofer, H., “A new manufacturing process as the seed for an algorithm-based product design in the early phases”, NordDesign2006, Reykjavik Iceland, 2006.
[16] Lindemann, U., “Human Behaviour in Design”, Springer, Berlin Germany, 2003.
[17] Ehrlenspiel, K., “Integrierte Produktentwicklung“, Hanser München Germany, 2007.
[18] Sauer T., “Ein Konzept zur Nutzung von Lösungsobjekten für Produktentwicklung in Lern und Anwendungssystemen“, VDI-Verlag Düsseldorf Germany, 2005.
[19] Abele, E., Anderl, R., Birkhofer, H., “Environmentally-Friendly Product Development”, Springer-Verlag London UK, 2005.
[20] Hirsch, N., Günther, U., Birkhofer, H., “Transforming of Technological Findings for a better Development of branched Sheet Metal Products”, Proceeding of the International Conference on Engineering Design 2007, ICED’07 Paris, France, 2007.
[21] Krause, F-L., Franke, H-J., Gausemeier, J., „Innovationspotenziale in der Produktentwicklung“, Carl Hanser Verlag, München Wien, 2007
[22] Grech, A. K., Borg, J. C., “Towards knowledge intensive design support for the micro surgical domain”, Proceedings of the International Design Conference DESIGN Croatia, 2008
[23] Ulbrich, S., Ulbrich,M., Vincente, M. L.,”A Globally Convergent Primal-Dual Interior Point Filter Method for Nonconvex Nonlinear Programming”, Mathematical Programming100, pp. 379–410, 2004.
[24] Groche, P., Vucic, D, “Multi-chambered profiles made from high-strength sheets”, Production Engineering, Annals of the WGP, Vol. XIII/1, Hannover Germany, 2006.

Contact: Herbert Birkhofer
Technische Universität Darmstadt
Product Development and Machine Elements
Magdalenenstrasse 4
64289 Darmstadt
Germany
Phone +49 6151 16 2155
Fax: +49 6151 163355
Email: birkhofer@pmd.tu-darmstadt.de
URL: www.pmd.tu-darmstadt.de

Herbert Birkhofer is head of the institute “Product Development and Machine Elements” at Technische Universtität Darmstadt. He was founding president of the international society "The Design Society". His main research fields are product development and design methodology, knowledge management in design, empirical design research and development of environmentally sound products.

Martin Wäldele is research associate at the institute “Product Development and Machine Elements” at Technische Universität Darmstadt. He is a researcher of the CRC 666 “Integral sheet metal design with higher order bifurcations” and works on the subproject A1 “Transformation of customer requirements into product properties”.