FIVE MINUTES FROM THE TASK TO THE OPTIMAL SOLUTION – A CONTRIBUTION TO AN ALGORITHM-BASED CONCEPTUAL DESIGN

H. Birkhofer

Technische Universität Darmstadt, Germany
Chair Product Development and Machine Elements
e-mail: Birkhofer@pmd.tu-darmstadt.de

Keywords: Early phases in design, computerised algorithmisation, product modelling, product topology, internal and external properties

Abstract: *The paper describes an approach to the algorithmization of conceptual design in product development. The conceptual process can be understood as a transformation and enrichment process from customer needs to product properties. The vague and incomplete design task is concretized to the point that the optimal product can be found with mathematical optimization methods and new CAD modelling technologies. Thus computer-aided work is applied on all the processes of the task clarification and conceptual phase. The application is demonstrated at the generation of integral sheet metal profiles, produced with the innovative technology of linear flow splitting, which was the starting point of the newly launched Collaborative Research Center 666 "Integral sheet metal design with higher order bifurcations".*

1. Introduction

Linear flow splitting is a quite new technology enabling the forming of branched sheet metal products in an integral style. To design these products one has to consider the variety of feasible process chains as well as the huge amount of technological and market influences on product geometry and material. This paper focuses on the scientific prerequisites of an algorithm-based approach of the early phases of design, starting with market needs and ending at the optimal product representation. The scientific innovation is the computer-based creation of topology and geometry from formalised verbal requirements without needing at least a rough geometrical concept created by humans [1]. The research, begun in July 2005, was carried out at the Collaborative Research Centre 666 at TU-Darmstadt.

2.1. Sheet metal products

Sheet metal is one of the most commonly used semi-finished products in metalworking. Countless everyday products are made from it. Its main characteristic is the ability to be formed and shaped up to high deformation degrees. But in many cases, additional branches like stringers are required to give sheet metal a sufficient rigidity. Nowadays such branches are welded, bonded or riveted onto the sheet metal. This differential design causes several disadvantages, such as shape distortion, notch effects or worsened heat transfer.

2.2. Linear flow splitting of sheet metal

A newly created massive forming process, called "linear flow splitting" [2], provides the opportunity to form branched profiles out of sheet metal in an integral style. The new roll forming process uses obtuse-angled splitting rolls and supporting rolls to increase the surface of the band edge (see figure 1), which form the work piece in discrete work steps up to a profile with the final geometry. Every additional branch leads to a new geometry and new properties of the produced part.

Due to the progress in linear flow splitting technology, less than 2mm thick sheets can now be branched. This provides excellent perspectives for application in highly loadable lightweight structures used in cars and airplanes. Combined with welding and cutting processes, profiles with variant channels in different geometries and arrangements can be produced easily for application, e. g. in chemical or power plants.

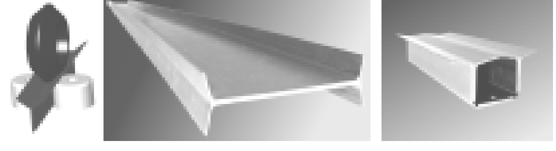

Figure 1. *Process principle and produced profiles*

2.3. A true algorithm-based design process approach

It was seen as a challenge to supplement this new manufacturing technology by an innovative “design technology”.

Analysing current proposals for human-based design, they mostly promote a kind of “egg-timer” shaped process, where variants are generated at different levels and then selected (see figure 2 left-hand side). This procedure has been presented in literature since the evolution of systematic design and is adapted to the problem-solving processes of human beings. Human cognition is able to deal with uncertainty, but it is quite limited in dealing with high complexity and big numbers. Enlarging the solution space and reducing it in the next step and repeating this several times (from the task definition to the final drawings) is promoted as a guiding strategy for human beings to solve complex problems.

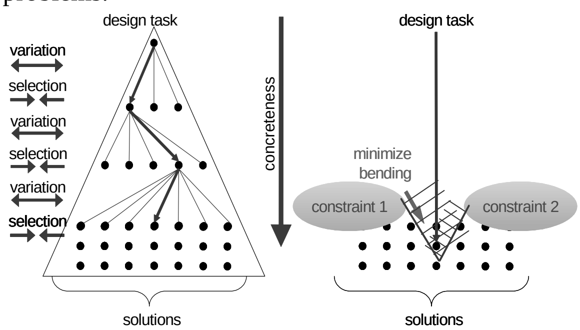

Figure 2. *Human and algorithm-based design approach for the early phases of design*

Compared to the well-known design process models for the early phases presented, for example, in [3], the “design process” of the cable conduit differs quite a lot (see Figure 2 right-hand side). An algorithm-based approach [4] should be set up in a different way, due to the fact that the capabilities and faculties of computers differ enormously from those of humans. It cannot at all be expected that the human oriented design process is the appropriate or even the only design procedure model that is also suitable for computers. Figure 2 (right-hand side) demonstrates the “design procedure” of the algorithm-based approach, which elaborates the customer- and market requirements in such way that a mathematical optimisation process can follow, which directly satisfies the optimal solution. This “directly-working” process is based on a stepwise transformation of a verbal, incomplete and vague product representation in formal product representations, which are able to be processed by algorithm-based computer application into a 3D-product representation.

3. The cable conduit case study

3.1. The task

As a case study, a cable conduit of sheet metal with specific properties should be designed. All requirements are given verbally (see table 1); no graphical representations such as sketches or drawings are added.

Table 1. *Requirements for a specific cable conduit*

Number of channels	3 (self-contained)
Channel 1 for cables	cross-section 100mm^2
Channel 2 for pneumatic	cross-section 30mm^2, minimised circumference
Channel 3 for exhaust air	cross-section 30mm^2, minimised circumference
Size of cable conduit	maximum height 90mm
	maximum breadth 80mm
	length 2500mm
Sheet metal size	maximum breadth 170mm
	thickness 3mm
Sheet metal material	steel ZStE500
Production technology	linear flow splitting
Deflection of cable conduit	Minimised

3.2. The algorithm-based transformation of a verbal task into a graphical product model

Solving this task means transforming a verbal product representation into a graphical one, which comprises all product properties needed for manufacturing. Therefore, design may be regarded as a step-by-step synthesis from vague customer wishes and requirements to the final shape and material of a technical product.

3.2.1. The transformation of verbal representations

Regarding the transformation process, the most important aspect was the fact that products can be completely defined by so-called “internal-properties”, which correspond to a huge set of “external-properties” [5]. The requirements-list describes the properties or feasible areas of properties the customer is looking for (e. g. “low bending”). These external-properties cannot be established in a direct way by the engineer. The engineer has to choose and specify parameters which are related to the external-properties, but can be established in a direct way (e. g. material and geometry) [6]. Regarding the stiffness of the cable conduit, it is defined by the bending w and the momentum Iy as external-properties. These external-properties are coupled with internal-properties (material and geometrical properties) using the equations illustrated in figure 3.

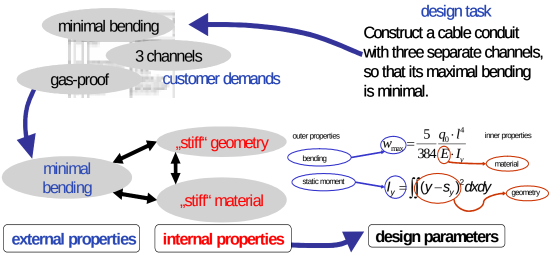

Figure 3. *Transforming a verbal design task into an equation as a formal description*

For the cable conduit example, this transformation was initially done by hand, using logical reasoning and knowledge about models of mechanics. In general, product design can be seen as the selection and optimisation of design parameters to fulfil defined external-properties [7, 8].

3.2.2. With algorithms from formal representations to product topology

Regarding the low bending of a beam structure, the interrelation of requirements and design-parameters can be modelled by physical effects and be expressed in terms of equations (see figure 3). In stage one, a coarse mixed-integer programming (MIP) model was solved with linearised functional relations to find the overall topology of the product. Once again, a well-defined methodical basis proves as a major advantage for the computerization of such a design sub-process:

- Constraints include feasible and exclude non-feasible solutions in the entire solution area.
- Objectives and wishes allow one to rank 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. These pixel arrangements were evaluated and ranked in regard to objectives and wishes (see figure 4).

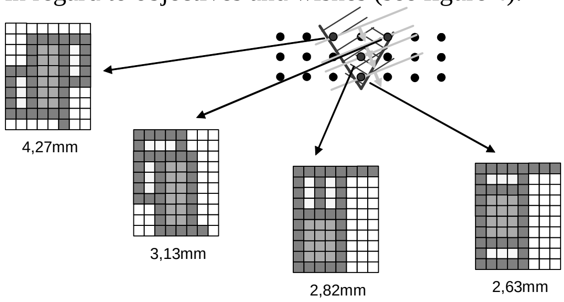

Figure 4. *Generating feasible optimal topologies and evaluating them*

It is easy to see that the optimised topology includes all requirements and corresponds well to the rules of beam bending. Having the material as far from the bending axis as possible results in low beam deflection. Human-centred conceptual thinking is overcome with this decisive step from a verbal to a topological product representation.

3.2.3. With algorithms from product topology to product geometry

After obtaining the optimized product topology, a detailed non-linear continuous shape optimization model is formulated and solved by non-linear optimization methods to obtain a detailed product geometry (see figure 5).

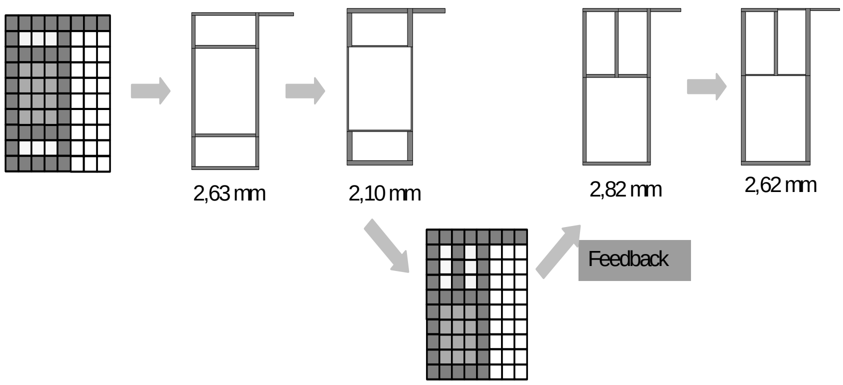

Figure 5. *Generating feasible geometries*

It is shown that continuous shape optimization on its own does not necessarily create the optimal product in terms of manufacturing. Anticipating the model of a spanning tree used to create a producible cross section, a step backward has to be made, as the optimized geometry does not fulfil decisive manufacturing constraints. Even with a minimum bending deflection (2.10mm), this profile cannot be manufactured by the linear flow splitting of sheet metal due to an “unproducible” thickness distribution.

3.2.4. With algorithms from functionally optimised to producible product geometry

Given a profile with functionally optimised product geometry, it must still be determined how it can be manufactured using a linear flow splitting process. Every branch in the profile can be obtained by either splitting up the piece of sheet metal or by connecting two branches together.

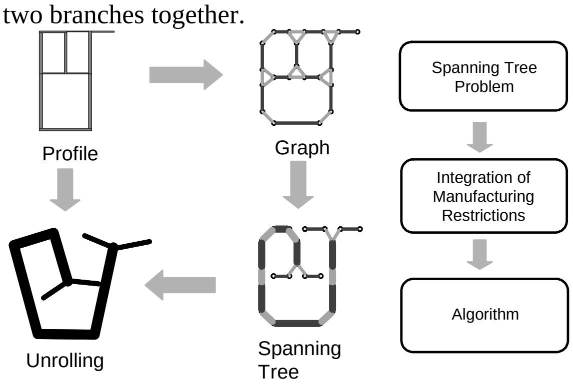

Figure 6. *Modelling the cross-section as a spanning tree-graph*

Because there are normally many ways to design one cross-section, an algorithm-based approach must decide where to cut and where to connect. To this purpose, a specific graph was introduced representing the edges and nodes of a profile (see figure 6).

Erasing links within every node systematically, the algorithm gradually computes these spanning trees and creates the optimal unrolling with regard to the constraints of linear flow splitting processes. Once again, it has to be mentioned here that all distinctive algorithms are used simultaneously to create an optimal solution in terms of functionality and producibility and to avoid dead ends in the design process. This may be seen as a fundamental strategy similar to human problem-solving in design with its creative linking of different elements and aspects within the entire world of product and process models.

3.2.5. With algorithms from producible geometry to a 3D-CAD model

Having created the solution so far, there are of course some problems to solve in generating a 3D-CAD model of the final product. For the application on the design of sheet metal profile structures specific features and functions can be implemented in a CAD workbench. Those features and functions, like a cut-out at the edges or reinforcing rip structures, have to be made available to the designer (figure 7).

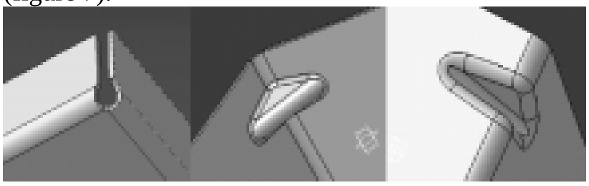

Figure 7: *Specification of 3D-CAD systems for profile structures*

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 8).

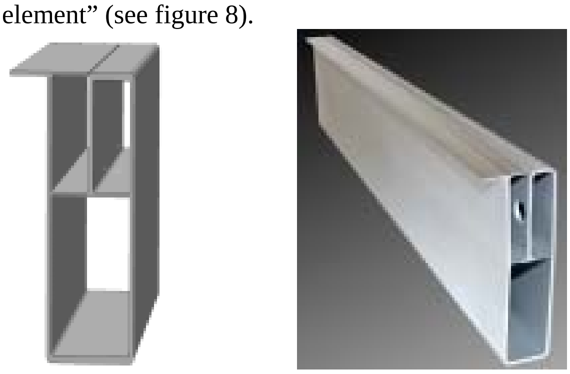

Figure 8. *The 3D-CAD model of the cable conduit (left) and the final product (right)*

4. Lessons learned – some findings in regard to a computerised algorithmisation of the early phases of design

The starting point was the new manufacturing technology of linear flow splitting, which triggered hope for creating a similar innovation in “design technologies” [9]. The case study was carried out to obtain insights into the feasibility of a computer-based algorithmisation of the early phases of design, which is usually described as the most appropriate domain of human problem-solving.

4.1. The performance of an algorithm-based design

Without any doubt, the cable-conduit case study demonstrated the chance to generate a “product” out of a formalised description of properties on principle. For the cable conduit example one need about half an hour computing time to get the solution mentioned in figure 8. Using a more powerful computer instead of a conventional desktop pc (2,6 GHz Pentium IV), the promise of the headline “…in five minutes” seems to be quite realistic.

4.2. Prerequisites for an algorithm-based transformation of tasks into a product model

In the "cable conduit" case study, several prerequisites for an algorithm-based design became obvious.

4.2.1. Development of a well defined terminology

Usually, a design process starts with market and customer needs that are often vaguely, incompletely and inconsistently articulated. But an algorithm-based approach requires precisely defined parameters and relationships. A first requirement for a successful algorithmisation therefore should be to develop a well-defined vocabulary and terminology for "breaking down" the cloudy wishes of customers to precisely defined attributes and requirements.
This can be done by

- analysing expressions and descriptions in related brochures and documents to get a set of terms that people use verbalise their wishes and needs,
- developing a thesaurus linking these terms and tracing vague verbal annotations to predefined requirements by estimating similarities and relationships between different terms.

Especially the second approach will have a major influence on the acceptance from the customer and marketing sides. Even though a computerised design in the early phases needs a well-defined and highly formalised design language, any attempt to force customers to use it will surely end in failure. A major challenge, therefore, is the successful realisation of such a powerful thesaurus. In all honesty, one has to admit that such a thesaurus could hardly be developed for universal applications. It seems more realistic to expect a domain- branch- or even product-specific thesaurus, e.g. a thesaurus for designing linear flow spitted profiles.

4.2.2. Grasping the models used in engineering design

Hubka [5] was one of the first design scientists to emphasize the role of internal and external properties of products as crucial for the understanding of the real nature of design. The case study "cable conduit" uses this perception for settling equations, which relates deflection to the length and cross-section of the conduit profile.

First attempts in analysing technical knowledge warrant the assumption that a reasonable amount of knowledge, transferred in education, training or experience in real design work is knowledge, which can be seen as a kind of formalised exchange between internal and external properties.
If a designer asks

- What shall I add or change in my sketch, drawing, or product model to meet requirements?
- Which consequences for the production, use or recycling result from my design fixation?

Then these questions may be reformulated in a more formalized style:

- Which internal properties like geometry or material shall I choose or change in respect to the given requirements representing customer and market needs?
- How can I predict product properties for manufacturers, customers and recyclers regarding the internal properties (geometry and material) established in my sketches or drawings?

The link between internal and external properties is often given by models like the beam deflection model. It links the deflection of a beam to the load as well as to the geometrical and material properties of the beam itself. This specific design knowledge enables one to decide what to do in order to meet the requirements.

Apart from the linear flow splitting-example, the concept of internal and external properties may prove as a basis for structuring design knowledge in general. However, it remains a great challenge to grasp those relationships, which are not yet fixed or known, e. g. internal properties that represent good styling.

4.2.3. Recording the entirety of design knowledge

Designers obviously tend to internalise design knowledge acquired during design as experience. This tacit knowledge may be highly sophisticated as well as apparently trivial knowledge.

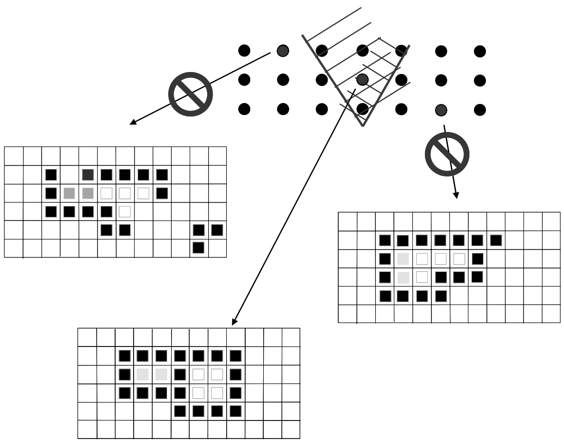

Figure 9. *Internal and external properties as a basic concept of knowledge capture*

For experienced designers, it is quite trivial that two channels - one for exhaust and one for pneumatic - have to have hermetically closed shapes that do not meet at their edges. An algorithm "doesn't know" these fundamental rules and as a result creates quite funny cross-sections, such as those shown in figure 9. When trying to transfer design competence to algorithms and software, we have to accept that we have to start with quite fundamental models and relationships based, for example, on common sense. The use of algorithms and software with their inherent rationalism and transparency forces the recording of all knowledge needed for a successful design.

5. Conclusions

The cable conduit case study may be regarded as a simple one, but it is no trivial one as anyone can see by solving the task "conventionally". Especially the exponentially increasing number of variants in terms of cross-sections and unrollings for more complex profiles with a higher number of edges and nodes demonstrates the limitations of design outcomes based on human thinking. To handle thousands or even billions of variants and at the same have an overview of the inter-linked network of requirements and product properties, and finally to meet the optimal solution in the entire solution space seems to be an exaggerated expectation of human design.

Future work on an algorithm-based design approach for the early phases of design will consist, on the one hand, of detecting the influence of technological findings from downstream production line and integrating them into the design knowledge base. At time the algorithm-based approach is only used to create cross-sections of linear and homogenous profiles. No flange-mountings, no connecting devices, no cut-outs are regarded. And it is an open question, if all these devices, which separate a profile as a semi-finished part from a marketable product, may be treated only by an algorithm-based approach.

On the other hand, it seems to be promising, that these technological findings may be used to develop a methodology in order to systematically derive technology-pushed innovations. Turning round the algorithm-based transformation of customer wishes into product properties may be a key to derive innovative products systematically. If this will lead to a kind of computerised creativity is uncertain, but not impossible.

Besides the actual work on design research in the field of algorithmisation of profile designs produced by linear flow splitting technology, one may expect a reasonable insight into the mechanisms of how design works. This kind of research may also be regarded as a specific kind of empirical design research. But rather than observe human designers in companies, it observes a computer in the progress of doing real design.

Acknowledgement

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

References

[1] Birkhofer, H. "Computer aided early phases in design – from market needs to the optimal product representation" Proceedings of the INTERNATIONAL DESIGN CONFERENCE - DESIGN 2006, Dubrovnik - Croatia, 2006.

[2] Groche, P., v. Breitenbach, G., Jöckel, M., Zettler, A., "New tooling concepts for the future roll forming applications" ICIT Conference, Bled, Yugoslavia, 2003.

[3] VDI 2221. „Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte". Düsseldorf: Beuth-Verlag, 1993

[4] Suh, N. P., "Axiomatic Design - Advances and Applications", Oxford University Press, New York, 2001.

[5] Hubka, V., Eder, E. W., „Design ScienceTheorie technischer Systeme – Grundlagen einer wissenschaftlichen Konstruktionslehre", Springer-Verlag, Hamburg, 1984.

[6] Birkhofer, H. „Analyse und Synthese der Funktionen technischer Produkte", Düsseldorf: VDI-Verlag, 1980

[7] Sauer, T., Wäldele, M., Birkhofer, H., "Providing Examples for Students and Designers", Proceedings of the NordDesign 2004 Conference, Tampere, Finnland, pp. 340-349.

[8] 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.

[9] Birkhofer,H., A. Martin, S. Ulbrich, M. Wäldele, A. Fügenschuh, U. Günther, D. Junglas, T. Sauer, S. Walter. „Topology- and shape-optimization of branched sheet metal products". In print in: H. Kopfer (Ed.), Operations Research Proceedings 2005, Springer Verlag, Berlin