DESIGN PROCESS AUTOMATION – A STRUCTURED PRODUCT DESCRIPTION BY PROPERTIES AND DEVELOPMENT OF OPTIMIZATION ALGORITHMS

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ABSTRACT
Automation of the product development process or of sub-processes is one possibility to support designers by their daily work. A concept for a formalized and structured description of profile-structures (assemblies of bifurcated sheet metal profiles) by properties is needed as basis for designing and optimizing them automatically. The high object complexity requires dividing profile-structures into defined design elements. The inputs of an algorithmbased design process are on the one hand the target properties and the relations between the properties. Furthermore rules, principles and guidelines of embodiment design as well as restrictions of manufacturing have to be transformed and included in an automated design process. The algorithms are the key elements of the chosen approach. A developed algorithm to design welded connections between linear flow split profiles proves that the independent properties of this design element can be determined automatically and the design can be optimized.

Keywords: design process automation, product and process properties

1. INTRODUCTION
The intention of design research is to develop methods and tools that support designers to develop better (respectively optimum) products in less time. Automation of the product development process or of sub-processes is one possibility to support designers by their daily work. In this contribution an algorithmbased approach to automate the design process is chosen. The task is transformed in constraints and objectives. A formalized and structured description of the products by properties is needed to design and optimize the products automatically by using mathematical procedures. This contribution analyzes on the one hand the requirements regarding to a formalized and structured description and on the other hand how properties have to be classified in this context (chapter 2 and 3). Partially, describing profile-structures is very complex. So, solutions have to be developed to reduce this complexity in the design process (chapter 4).
To automate the design process it is necessary to know the inputs. They should be identified on the basis of an analysis of the product creation process. In the next step it has to be clarified how the inputs can be utilized for an algorithmbased optimization (chapter 5).
The algorithms are the key elements of the chosen approach. Therefore new algorithms to design and optimize profile-structures have to be developed. To exemplify how an algorithm can work, an algorithm to design welded profile connections automatically has been developed and implemented (chapter 6).

2. A FORMALIZED AND STRUCTURED PRODUCT DESCRIPTION BY PROPERTIES
A formalized and structured product description by properties is the basic requirement regarding to an automated product development using an algorithm-based approach. Properties are (mostly verbal) descriptions of objects that allow the identification and differentiation of a product. A property consists of an attribute (e.g. “length”) and a value (e.g. “1000 mm”) from an attribute-specific set of values [1].

2.1 Dependent and independent properties

The description of technical systems by properties is important for product development in many ways. It is the starting point for various methods and the basis of the classification part of design catalogues. The potential, advantages and relevance of a property based product description were often analyzed and explained in the past. Thereby, the product properties were classified according to different criteria. Hubka classifies product properties according to the noticeability (e.g. internal and external properties) [2]. The distinction between internal and external properties was the starting point for further studies and classifications.

A classification of product properties according to a possible direct determination by the designer seems to be a highly targeted approach as basis for an automation of the design process. On the one hand, product properties that are directly determined by the developer are called independent properties. On the other hand, the product properties that designer cannot determine directly are called dependent properties. Their values depend on the determination of the independent properties. Designer only can influence them by determining the independent properties in the right way. [3]

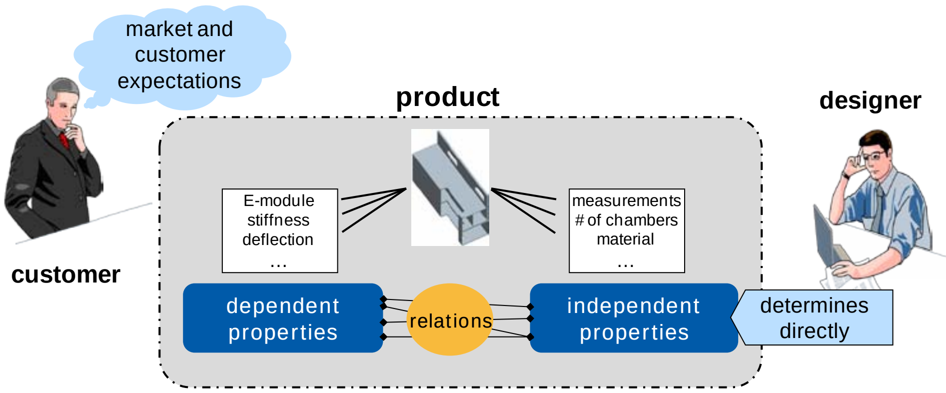

Figure 1. Dependent and independent product properties

The knowledge of the independent properties and their influence on the dependent properties is of particular importance during the design process. The independent properties act as a kind of ‘setscrews’. The implementation of the desired product will only be successful if the developer knows the relevant independent properties and their effect to the respective dependent properties. Network-structures called property-networks (figure 2) are predestined to represent these dependencies.

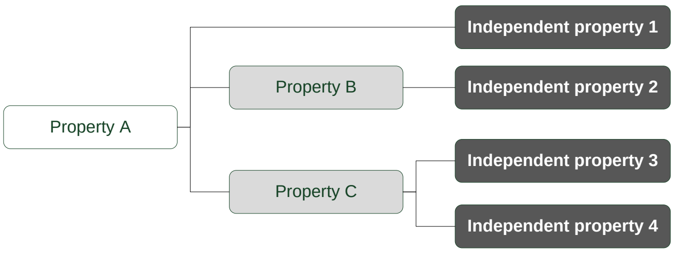

Figure 2. Property-network

The classification according to independent and dependent properties is a highly targeted approach for an automated product development process because the independent properties are used as optimization variables.

2.2 Product and process properties

Properties of the usage process are interpreted erroneously in many cases as product properties during the analysis of a product [3]. Doing so, properties that describe the usage process are allocated to the product, for example the external load or thermal effects.

These properties indeed fulfill the formal requirements of a product property (attribute and value), but the value is not directly or indirectly determined by the designer. The values of these properties is defined solely by the usage process. It is therefore particularly important to separate between product and (usage) process properties.

Furthermore, there is an additional important group of product properties that appears during the usage process. This additional group of product properties is also dependent on the (usage) process properties (e.g. deflection, internal forces or heat transfer). These dependent properties can be influenced and changed by the selection of independent product properties. Because of their dependencies on the usage process properties, they are named as process-related product properties. For example, the deflection of a beam (process-related product property) can be influenced by the independent product properties cross section design and material. At the same time, the deflection also depends on the external load (usage process property).

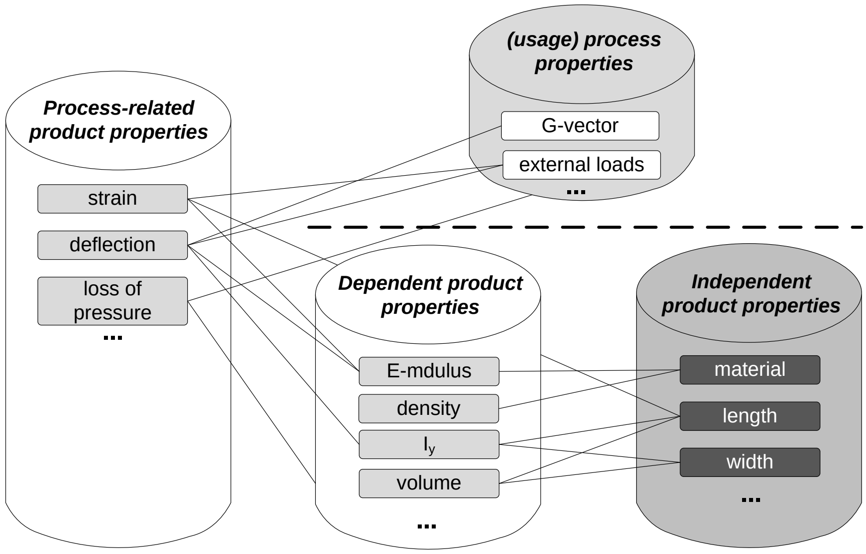

Figure 3. Relationship between product properties and (usage) process properties

3. ANALYSIS OF THE PRODUCT CREATION PROCESS REGARDING TO PRODUCT PROPERTIES

The analysis of the product creation process regarding to product properties shows that a differentiation corresponding to the progress of the process is necessary.

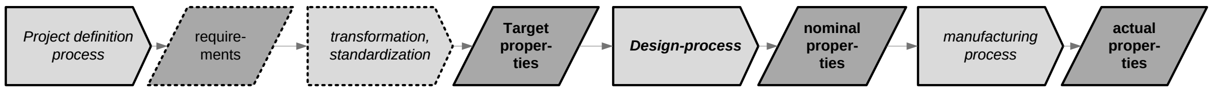

Figure 4. Product creation process

The requirements regarding to the product are recorded and documented during the project definition process. Customer and market expectations are included in these requirements containing required and desired product properties. Consequently, they are defined as target properties.

A formal description by product and process properties is a precondition for an automation of the product development process. Verbalized requirements have to be standardized and transformed into target properties with adequate tools (e.g. digital thesauri) [4].

In this context, note that an interval requirement is transformed into a target property with a set of values. This apparently contradicts the above property definition (a property consists of an attribute and one value). This definition has to be extended for target properties and must allow set and ranges of values. This extension is unproblematic, because target properties only describe how the product should be. Thus the values are tolerated alternatives.

The next step of the product creation process is the design process. During this process the independent product properties are determined in such way that the target properties are achieved or observed. The basis for designing a product is an extensive knowledge of the relations and dependencies between the dependent and independent properties. The results are the determined nominal properties that are needed to produce the product. It is known that the properties of the real product are more or less different than the nominal properties because of uncertainties and inaccuracies of the production. That is the reason why geometrical product properties are added with

tolerances of shape, position and dimension. These tolerances are a kind of set of values that is acceptable from the designer's point of view.
After the production process the real product can be described and identified by its actual properties. Exactly one value is allocated to each actual attribute. The customer is now able to compare the product with the market and customer expectations by the actual properties.

4. PROFILE-STRUCTURES OUT OF LINEAR FLOW SPLIT COMPONENTS

The targeted automation of the product development process is especially for technical products that are manufactured using the novel manufacturing technologies linear flow splitting and linear bend splitting. The analysis of assemblies out of linear flow split components shows a high object complexity. Hence, products are divided into defined form design elements to reduce this complexity.

4.1 Linear flow split components and profile-structures

Linear flow splitting is a massive forming process for the production of bifurcated profiles in integral style. Bifurcated sheet profiles allow implementing desired functions without consuming much space or material. Compared to plane components with the same mass they are much more resilient. In addition, closed cross-sections show heavy torsional stiffness. The bifurcations allow designing multi-chambered profiles. The chambers can be used to integrate different sub-functions, e.g. creation of insulating hollow space, cable ducts, gas conduction, liquids or compressed air. So far, bifurcated sheet metal profiles were mainly produced in differential style, e.g. by gluing, welding or similar procedures. Manufacturing those parts in integral style by linear flow splitting has different advantages. It enables to produce very thin-walled profiles. Due to the lack of or the small number of connecting pieces the profiles have less weak spots. A high accuracy can be achieved through transforming the semi-finished part at ambient temperature. Bifurcated sheet metal profiles are lighter. They have a lower disposition to corrosion and a higher thermal conductivity. [5]
The initial material is a sheet metal plan. It is transformed at ambient temperature by a specific tooling system which consists of obtuse angled splitting rolls and supporting rolls. In discreet steps, the fixed tool system forms the translatory moved work piece to a profile with the final geometry. The further processing of the linear flow split sheet metal by roll forming and bending procedures presents the opportunity to produce multi-chambered profiles with new cross-sections from sheet metal (figure 2). Numerous new possibilities for chambered profiles to optimize lightweight design arise when anew using linear flow splitting at the end of the flange and forming new flanges. [6]

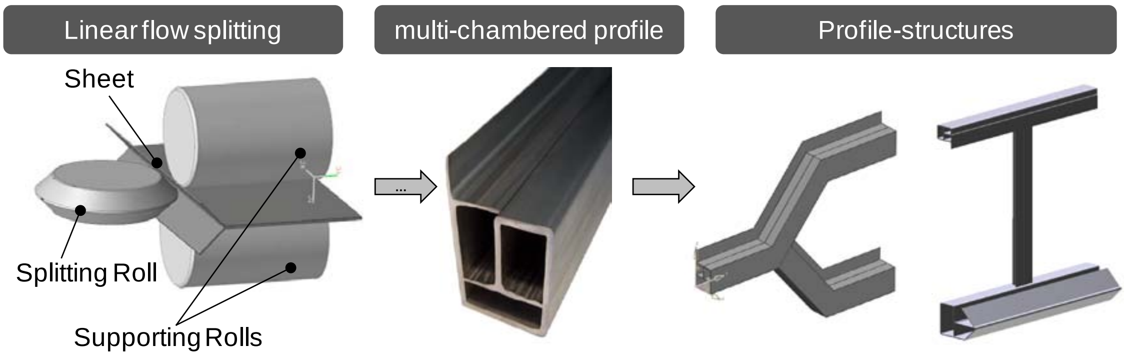

Figure 5. Manufacturing multi-chambered profiles and profile-structures by linear flow splitting and further roll forming and bending procedures

The level of bifurcation of the components can be increased by linear bend splitting. Flanges are created from the center of the plate using appropriate rolls and high pressure.
A very flexible application is given through the use of multi-chambered profiles in profile-structures. In this contribution, assemblies out of linear flow split components are focused that are characterized by a secure connection between the individual components. This secure connection does not permit any movements between the components. Examples of profile-structures are given in figure 5. The chambers of the profiles can be used additionally to conduit material (fluids, compressed air, cables etc.).

4.2 Reducing the object complexity by dividing into design elements

An analysis of profile-structures has shown that the number of relevant properties is very huge and that the relations and dependencies between the properties are very complex. The profile-structures are divided into defined form design elements to manage and reduce the object complexity. This division in so called profile-elements and nodes is consistent with the basic structure-topology of the assembly [7]. The straight profile-elements are connected by nodes. The division in profile-elements is design and also technology independent. This means that one profile can be modeled out of different profile-elements and nodes (structure-topological) (figure 6).

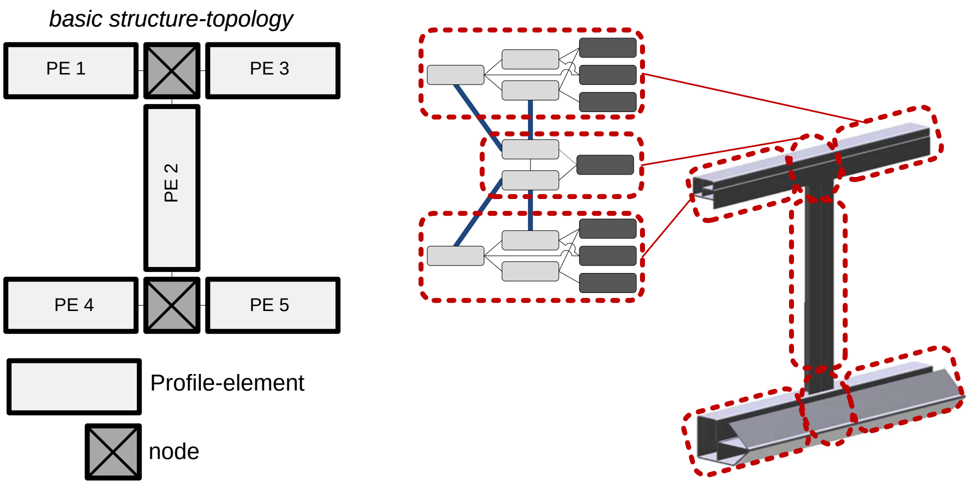

Figure 6. Division into design elements

The division allows describing each form design element with his properties separately. The relations and dependencies can be represented in generally valid and project-independent property-network-modules. The form design elements of the assemblies are connected and also the properties of the individual elements are connected. Therefore the property-network-modules are merged to a superordinate property-network, which describes the assembly by its properties. The concept to divide into design elements is the basis of the formalized description of profile-structures.

5. DESIGN PROCESS AUTOMATION

Design process automation requires identification and conditioning of relevant input and developing adequate algorithms according to the selected approach.

5.1 Input for an automated design process

Target properties are the initial point of the design process as proven by the analysis of the product creation process. They also give restrictions and objectives for a mathematical optimization. The second important inputs are the relations between the properties as represented in property-networks. However, the challenge is the identification and preparation of these complex relations as well as the implementation in a mathematical optimization.

During the manual design process, designers come back to certain other sources of information, e.g. basic rules of embodiment design, principles of embodiment design and guidelines for embodiment design. These are instructions and accordingly superordinate principles. Do not follow them might lead to disadvantages, errors, damages, accidents or non-practical solutions. [8]

The rules, principles and guidelines for embodiment design are often used by intuition. However, to adopt them appropriately a designer needs to have experience and technical understanding since they are sometimes phrased abstractly. To integrate them appropriately in an automated development, they need to be transformed and assigned to certain product properties. Then they can be used as objectives or restrictions for a mathematical model of optimization.

Table 1. Transformation of rules, principles and guidelines for embodiment design

rule, principle, guideline for embodiment design	comments	objectives/constraints
„simplicity“	realize solution with little components	minimize number of components
principle of uniform strength	constant utilization of material strength	stresses = const.

Several aspects of restrictions of manufacturing have to be taken into consideration when starting the design process. In the linear flow splitting process, the number of forming mills, the maximum splitting depth per forming mill, the role's surface pressure and the roll geometry can have system-dependent limitations and predefinitions. Keeping in mind the constraints of the design process, the relations between the manufacturing process properties and the product properties (according to the independent product properties) need to be analyzed. The maximum length of flanges will be limited by the number of forming mills and the splitting depth per forming mill. These relations can also be represented in property-networks. Therefore restrictions of the manufacturing process can be transformed and they can be displayed in terms of independent product properties in an automated design process. As a result of the complexity of these relations, their analysis and optimization is currently being researched in several projects. In regards to the systematic of properties, there are parallels and analogies about the analysis of the using process.

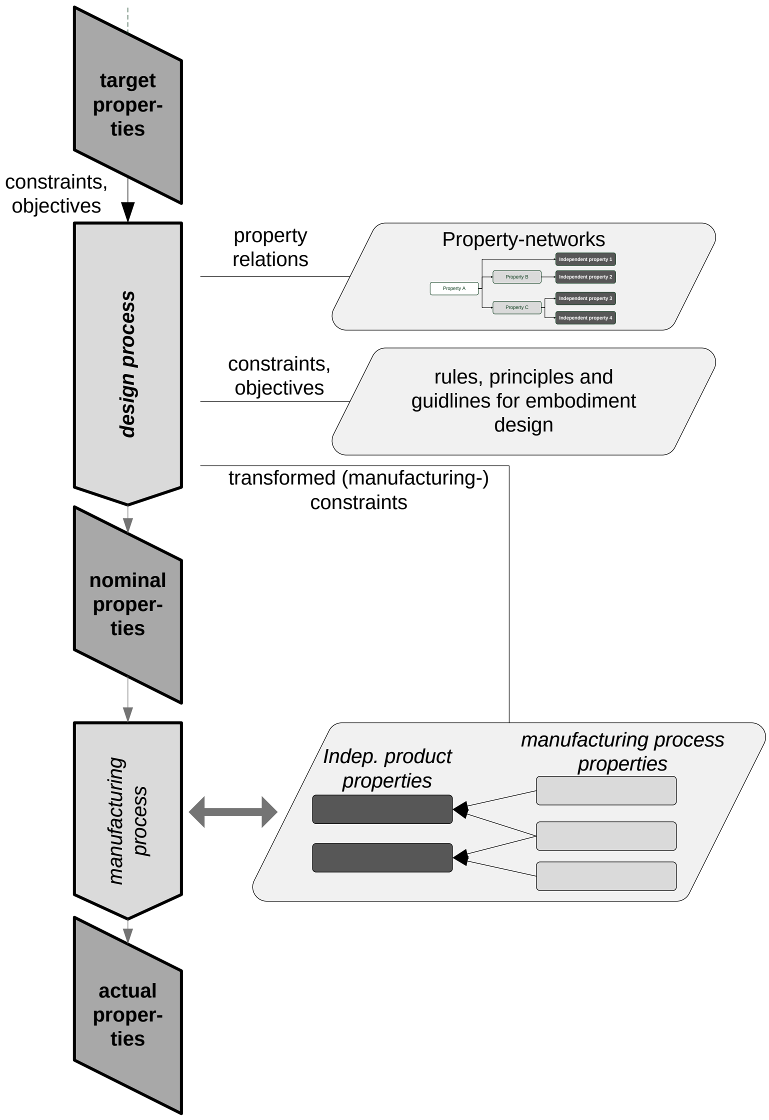

Figure 7. Inputs for the automated design process

5.2 Optimization algorithms

Developing algorithms is a key factor in the automation of the product development process. To some extent, the analysis of properties (product and process properties) and the development of optimization algorithms (complete, accurate, precise phrasing of process regulation) can be done simultaneously. The actual approach begins with the determination of the topology (structure-topology and cross-sectional topology). Geometry and technology are defined based on the topology. Several approaches to optimize the structure-topology and the cross sections of the profile-elements have been developed and partially integrated into a mathematical optimization model [7]. The actual main research is the analysis and development of algorithms for the optimization of designing nodes. An example is explained in chapter 6.

6. OPTIMIZED DESIGN OF WELDED NODES

To explain how an algorithm can optimize the design (respectively the properties) of nodes, a node that connects three profile elements is examined. To give a simple and demonstrative example, the angles between the profile elements are 90° and 180°. The external dimensions of the profile-elements' cross sections are even. This simplified example does not constrain the general validity of the approach. A further target property related to the node is that the contact form of the connections is adhesive bond (welded connections). The profile elements can be welded only from outside along the lateral surface area due to the limited accessibility. In general the design of the node can vary considering the mentioned specifications. Figure 8 shows an extract of possible designs. The welding seams are marked in black.

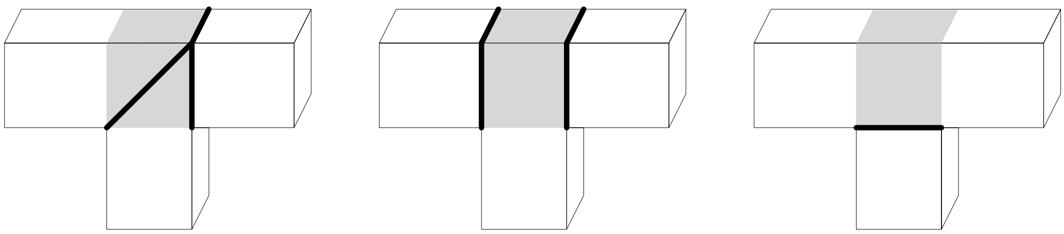

Figure 8. Different designs of welded nodes

Following independent product properties have to be optimal defined as part of the automated design of a node:

- Design of the pairs of effective areas of the welded joints
- Number and design of the welding seams
- Size of welding seams

The design of the welding seams requires the observance of the distribution of forces. Welding seams are not to be put in highly exposed areas. [9]. The stresses in the welding seams may not exceed the allowable stresses of the material. The stresses of the welding seams are a safety relevant property and the exceeding of the allowable stresses will result in a failure. The objective of the optimization is to minimize the maximum stresses. Simultaneously, the welding seams are made only as thick as the strength of the connection requires.

The stresses inside the node depend on the external loads of the profile structure during the usage process. These and additional relevant process properties are defined during the product definition process and documented as target properties. The design of the nodes can be handled as shown in figure 9.

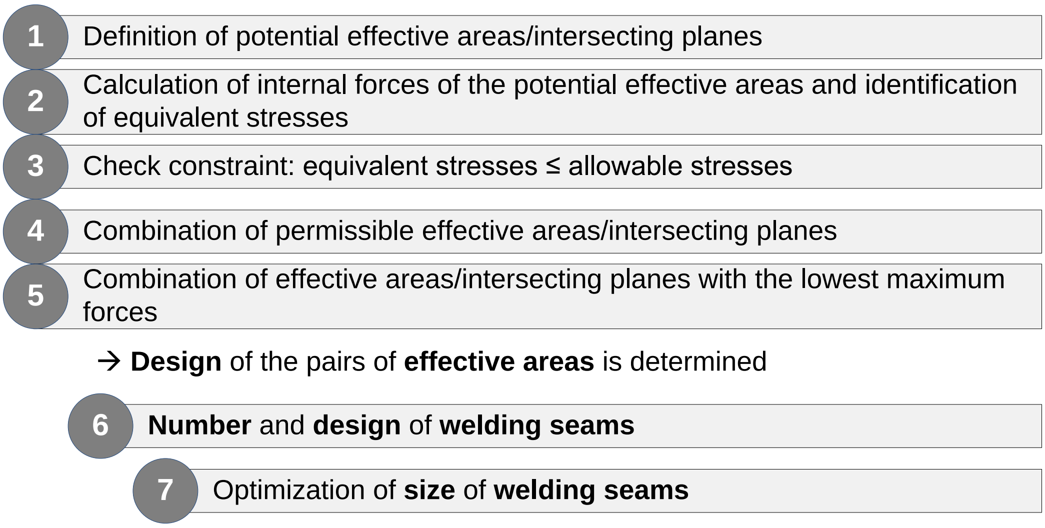

Figure 9. Algorithm to design welded nodes

The result is an optimized design of the node in regards to the external loads. The integration of additional objectives and constraints (e.g. regarding to manufacturing) is possible and may require a different weight of the objectives. The steps are described as follows in detail.

Step 1: Determination of potential effective areas / intersecting planes

There are different possibilities to cut and weld profiles as shown in figure 10 above. The example shows five intersecting planes that are potential effective areas for welded joints. More potential effective areas exist in common situations if the angel between the profile elements is not 90°.

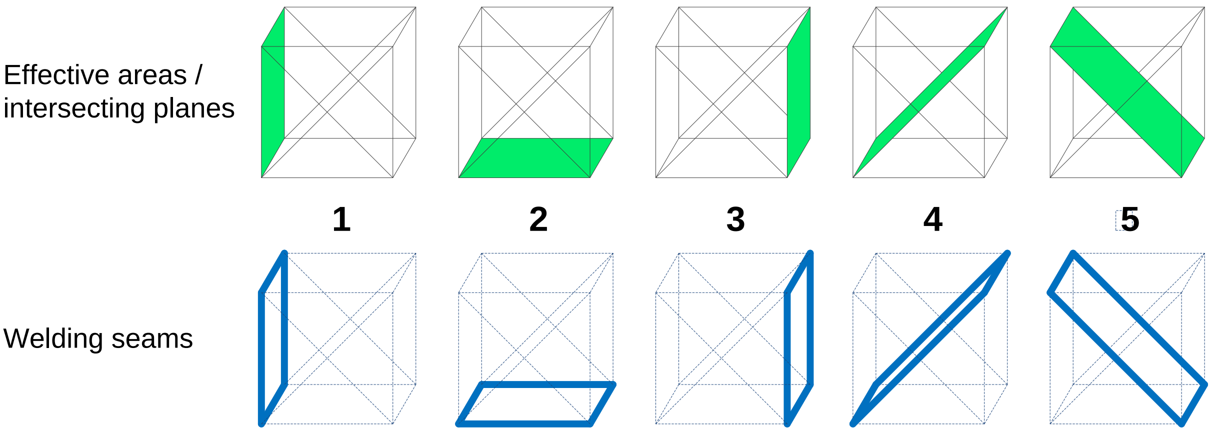

Figure 10. Effective areas/intersecting planes and welding seams

Step 2: Calculation of internal forces of the potential effective areas and identification of equivalent stresses

The internal forces and moments (normal and transverse forces, bending and torsional moments) of the potential effective areas are calculated according to the external forces acting on the profile structure and nodes. The equivalent stress intensity is calculated for all four potential welding seams due to the fact that all profile elements can be welded along their four lateral surface areas (figure 10 below)

Step 3: Check constraint: equivalent stresses ≤ allowable stresses

The calculated equivalent stresses are compared to the allowable stresses. The intersecting planes will be rejected if the equivalent stress is higher than the allowable stresses.

Step 4: Combination of permissible effective areas / intersecting planes

Permissible effective areas / intersecting planes are combined. The connection of all three profile elements must be ensured. Figure 11 shows the combination of the example described above.

Combination 1 has one effective area. Profile element 1(the left one) and profile element 3 (the right one) can be assembled based on a continuous profile. This does not mean that this combination is regarding to the stresses and welding seams always the optimum solution.

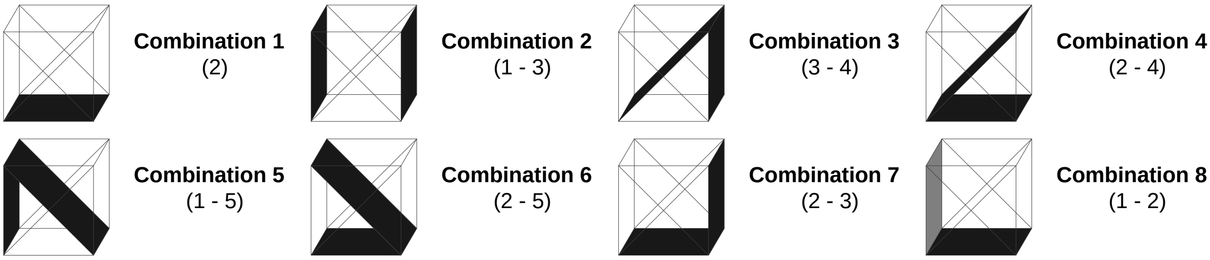

Figure 11. Combination of permissible effective areas / intersecting planes

Step 5: Selection of combination of effective areas / intersecting planes with the lowest maximum stresses

The selection of combination of effective areas / intersecting planes with the lowest maximum equivalent stresses is done based on the available information and results. This determines the design of the effective areas / intersecting planes as an independent product property.
The solution depends mainly on the external forces. Figure 12 shows some example nodes that were optimized for different external forces using the described algorithm. In example 1, the ends of the profile element 1 and profile element 3 are loaded by transverse forces. The welding seams are under pressure. This solution is not optimal for example 3. In this load case the welding seams (of solution 1) would be stressed by shear. Hence, the automation provides the displayed optimal solution; a solution that is not always visible at a first glance.

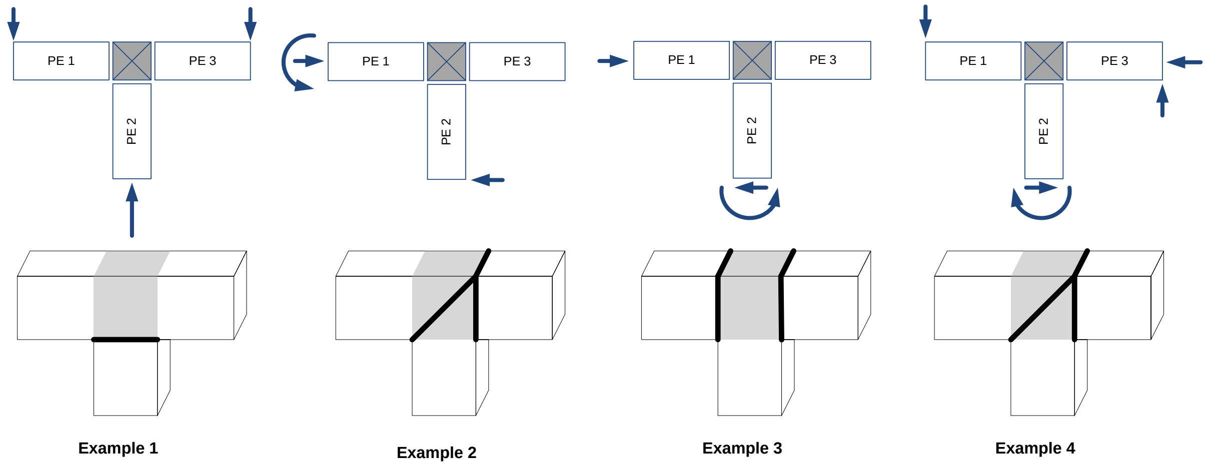

Figure 12. Examples of automatically designed nodes

Step 6: Number and design of welding seams

Depending on the load case, a revolving welding seam is not always necessary. For this reason it has to be checked along which lateral surface areas the profile-elements are welded. The decision depends on the internal forces and moments. This approach allows the simplification of the design of the nodes based on the rules of embodiment design. Especially, a compatibility matrix was created for this purpose. It shows what kind of forces and moments can be transferred to the profile cross section depending on the design of the welded joints.
The compatibility matrix is based among others on the basic rules of embodiment design. It contains the principle of uniform strength and the principle of force transmission. In addition it is based on further comprehensive studies of adhesive bonded connections. An automated determination of the possible design of the welding seams can be generated based on the input of the later appearing stresses.

image	Name	normal force F_x	transverse force F_y	transverse force F_z	torsional moment M_x	bending moment M_y	bending moment M_z
	image 1-1	0	0	0	0	0	0
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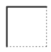
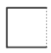
	image 2-1	0	0	0	0	0	0
	image 3-2	0	1	0	0	1	1
	image 4-1	1	1	1	1	1	1
...	...	...	...	...	...	...	...

Figure 13. Extraction of the compatibility matrix

Step 7: Optimization of size of welding seams

The welding seams have only to be as strong as the strength of the connection needs it [9]. Safety factors are included in calculating the optimum welding seams depth according to the basic rule ‘safety’. A smaller size of the welding seam (independent product property) requires inducing less thermal energy and reduces the risk of undesired errors in shape during the welding process. The knowledge of relations between independent product properties and manufacturing process properties are used and transformed to the objective ‘minimize the size of welding seams’. The independent product properties of the node are determined as the result of this algorithm.

7. SUMMARY AND CONCLUSION

This contribution includes a concept for a formalized and structured description of products as basis for an automated design process of profile-structures. The independent properties act as a kind of setscrews and they are also used as optimization variables in mathematical procedures. Further explanations show that a separation between product properties and process properties is very important.

The inputs of an automated design process have been identified by analyzing the product creation process. Rules, principles and guidelines for embodiment design can be transformed and included in addition to target properties and the relations between independent and dependent properties.

The object complexity is a great challenge by designing profile-structures out of linear flow split components. Dividing them into defined design elements is a helpful possibility to manage and reduce this complexity.

The developed algorithm shows how the relevant independent properties of a welded node can be identified and determined automatically.

In the next step further algorithms to design non-welded nodes have to be developed. The nodes and the relations of their properties have to be analyzed and the independent properties have to be identified. Furthermore the individual algorithms have to be linked and integrated in the existing approaches and procedures to get one mathematical procedure for designing and optimizing profile-structures. This tool can support designers by their daily work enormously.

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