INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018
https://doi.org/10.21278/idc.2018.0193

DEFICITS IN THE SELECTION OF JOINING PROCESSES FOR CAR BODY DESIGN

E. Garrelts, D. Fabis, D. Roth, M. Werz, H. Binz and S. Weihe

Abstract

The number of different materials used in a single car body is growing, while the complexity involved in selecting joining processes in design is increasing. This paper will review the requirements for joining connections and for methods used to choose joining processes in car body design. Existing approaches will then be evaluated based on these requirements and the identified deficits discussed. Demonstration will be given that a new approach is needed: one which considers costs and different variants and which can estimate properties of joining processes for new material combinations.

Keywords: design support system, design for x (DfX), early design phase

1. Introduction

The use of multi-material designs for car bodies results in a number of possible material combinations, which cannot be handled by a single designer. For a car body with three materials, there are six possible material combinations, while there are as many as ten with four materials. 29 different materials are used in modern cars (Rumpelt and Günnel, 2017), which results in 435 possible material combinations. The number of different materials used in one car is still growing (Friedrich, 2017). In addition to different material combinations, there are geometrical and mechanical aspects to be considered**,** which make every joining connection unique. Since the solution set is large, it is not possible to predefine the most suitable joining process for each combination and joining situation. It is thus necessary to guide designers toward a suitable selection.

The approach of using different materials is called multi-material design (Reisgen et al., 2014; Schricker et al., 2015; Stambke et al., 2017). The goal of this strategy is to combine the advantages of all materials used to construct an optimized, lightweight product. This is one of many strategies applied to reduce weight (Friedrich, 2017). There is a strong interdependency between materials and joining processes. The chosen process has to consider material characteristics such as tensile strength and avoid corrosion or insufficient tightness. Not all materials can be combined without a separating layer. The joining process also influences the basic material properties. For instance, most types of aluminium lose strength or ductility when welded (DIN EN, 2014).

2. Problem statement and structure of the paper

The selection of joining processes in car body design is complex, as stated in the introduction. This paper aims to answer three questions in order to guide designers:

- What are the requirements for joining connections and selecting joining processes in car body design?
- How do existing methods support the designer in selecting joining processes?
- What are the deficits of the existing approaches?

The requirements for the joining connections in car body design are discussed in Section 2. As the number of different materials grows, so too does the number of required joining processes. There has recently been a great deal of progress made with welding techniques in particular (Werz and Seidenfuß, 2016). In addition to these new processes, it is possible to combine different joining processes, such as adhesive bonding and riveting. A selection method has to guide the designer and help address this complexity. The requirements for such selection methods for joining processes in car body design are discussed in Section 3. Different approaches have been presented to address the need to guide designers. The most common ones are discussed in Section 4, whereas in Section 5, the different approaches are compared to the requirements found in Sections 3 and 4, and deficits are discussed. The conclusion summarizes the findings and provides an overview of research that is still to be undertaken.

3. Requirements for joining connections in car body design

Due to the complex interaction between requirements such as material combinations, component preparation, shape, production costs and accuracy, the individual interdependencies have to be taken into account during the early phases of development in order to ensure joinability and realize a lightweight solution.

The typical groups of requirements for a joining-process selection problem are "Production process", "Material", "Geometry", "Function" and "Economy", as shown in Figure 1 (L'Eglise et al., 2001; LeBacq et al., 2002; Beck, 2013; Klein, 2013). Each group contains many requirements. A list of several requirements for joining connections in each group is shown in Table 1. The number of interacting requirements is vast, which only exacerbates the problem of selecting the right joining process. The joining of two or more parts has an influence both on the product and on the process (LeBacq et al., 2002).

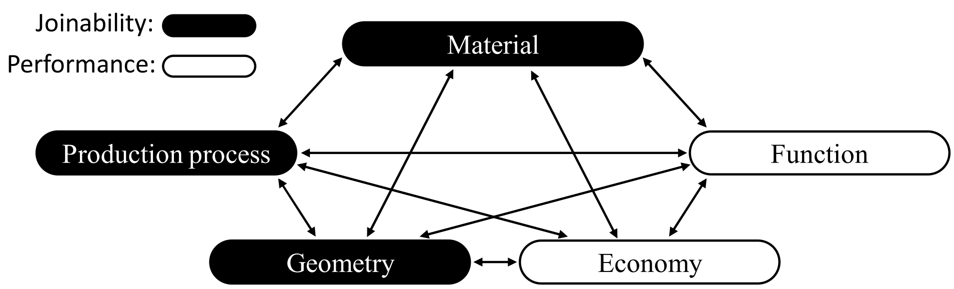

Figure 1. Requirements concerning joining processes

By definition, a joining connection is joinable if the partners to be connected (two or more) are able to be interconnected. This can be done by a process without an additional joining element, like in welding or clinching, or by a process with an additional joining element, like riveting or screwing (together). Besides the process, the main factor influencing joinability and the strength characteristics of a joint is the choice of the material (Beck, 2013).

The parts' materials must be joinable, either alone or in combination with other materials. Furthermore, other existing problems when using multi-material design have to be taken into account, such as differing thermal expansion or contact-corrosion properties (Prüß et al., 2010; Klein, 2013; Beck, 2013). The strength of the basic material should have a minimum value appropriate for the respective fatigue behavior or temperature-resistance (Beck, 2013; Klein, 2013). Surface properties are also important for joinability. Questions concerning whether or not the surface is critical must be answered (Beck, 2013). These are merely a few requirements besides many others, which cannot be listed exhaustively.

The second main factor influencing joinability is the joining process. The joining process must be feasible within the existing boundary conditions. Existing boundary conditions are – among others – duration, safety, thermal influence and automation (Beck, 2013). With regard to the duration, the process is restricted, e.g. in terms of the minimum time allowed before moving the joined component after the operation (Klein, 2013; Beck, 2013). Requirements and restrictions concerning safety are, for example, toxic emanation or flammability (Klein, 2013; Beck, 2013). Thermal influence can lead to local weakening of the mechanical properties of the material, as a further consequence of which the safety factors for calculating the dimensions must also increase. The mass consequently also increases (L'Eglise et al., 2001; LeBacq et al., 2002; DIN EN ISO, 2005). In order to satisfy the aspect of automation, evidence may be provided as to whether it is possible to alter the sequence in order to achieve synergy effects (L'Eglise et al., 2001; LeBacq et al., 2002; Beck, 2013). With regard to pressure, welding processes such as friction-stir welding result in improved strength characteristics in comparison to fusion welding processes due to the lack of solidification structure. There are also obvious restrictions with regard to accessibility (DVS/EFB, 2016).

Table 1. List of requirements for the join patch

Group	Group description	Grouped items
A	Material	Many joinable material combinations/handling multi-material strategy (Klein, 2016; DVS, 2016)
		Positive effect on corrosion-resistance (Klein, 2016)
		High realizable strength (Klein, 2016; DVS, 2016)
		Low joinable surface properties (LeBacq, 2002; L'Eglise, 2001)
		…
B	Production process	High availability of machines (LeBacq, 2002)
		High accessibility by the machine (LeBacq, 2002)
		Low minimum duration (Klein, 2016; LeBacq, 2002; L'Eglise, 2001)
		High safety of workers (LeBacq, 2002; L'Eglise, 2001)
		Low thermal influence on parts (DIN EN ISO 15609-1)
		High possibility of automation (LeBacq, 2002; L'Eglise, 2001)
		…
C	Geometry	Many compatible shapes (Klein, 2013; LeBacq et al., 2002; L'Eglise et al., 2001; DIN EN ISO 15609-1, 2005; Prüß et al., 2010)
		Processable connection type (point, line, area) (Prüß et al., 2010)
		Type of join patch (DIN EN ISO 15609-1, 2005)
		Varying thickness of pre-product (L'Eglise, 2001)
		…
D	Economy	Low production costs (Klein, 2016; L'Eglise, 2001)
		Low material costs (Klein, 2016; L'Eglise, 2001)
		High economies of scale (Klein, 2016; L'Eglise, 2001)
		Fast amortization of investment (Prüß et al., 2010)
		Low investment (Prüß et al., 2010)
		…
E	Function	Easy dismountability (LeBacq, 2002; L'Eglise, 2001)
		High/low thermal/electrical conductivity (LeBacq, 2002)
		High tightness (LeBacq, 2002; L'Eglise, 2001)
		High accuracy (LeBacq, 2002; L'Eglise, 2001)
		…

Geometry is another main influence on the joinability. The shape of the parts has to be compatible (L'Eglise et al., 2001; LeBacq et al., 2002; DIN EN ISO, 2005; Prüß et al., 2010; Klein, 2013). Consideration must be given to the type of connection, for example a point created using resistance spot welding or a line using MIG welding (Prüß et al., 2010). The type of joint constitutes another requirement (DIN EN ISO, 2005). These three main influences directly affect the joinability: If one or more main influences are not given, it is not technically possible to implement the considered joining process, which is of the utmost importance when selecting such a process. In addition to the factors influencing joinability, there are requirements in terms of the economy of the joining process and the function of a joint (Friedrich, 2017).

The economy of a joining process is described using requirements such as production costs, material costs, economies of scale or amortization of investment (L'Eglise et al., 2001; LeBacq et al., 2002; Klein, 2013). Here, the investment is irrespective of whether the required equipment is available or needs to be replaced (Prüß et al., 2010).

Requirements in terms of the function of a joint include dismountability, tightness, accuracy, conductivity and many more. Dismountability should be ensured, hence the repair and recycling possibilities being available (L'Eglise et al., 2001; LeBacq et al., 2002; Klein, 2013). With regard to tightness, there is sometimes a requirement that the joint should be waterproof (L'Eglise et al., 2001; LeBacq et al., 2002; Klein, 2013). The accuracy of a joint is important for fulfilling the tolerances (L'Eglise et al., 2001; LeBacq et al., 2002; Klein, 2013).

Looking ahead to the subsequent ranking process, the requirements for the joining processes should be adapted to the rating criteria of joining processes in terms of number and dimension. This is perfectly feasible using characteristics with only two possibilities. When using criteria with continuous characteristics, attention must be given to ensure that the rating scale has comparable gradation or that the values are in a normalized form (Prüß et al., 2010).

4. Requirements for methods for selecting a joining process

Just as joining processes demand specific attributes of the materials and geometries that should be joined, it is also necessary to specify requirements for the methods used. Without such defined requirements, it is not possible to assess whether a method provides the requisite support. Keller and Binz (2009) provide a review of general requirements for engineering-design methodologies and methods. The requirements are divided into eight groups, which are discussed in detail in Keller and Binz (2009). Table 2 shows the summary of the requirements specified by Keller and Binz (2009). In addition to the general requirements in the Groups A-E, G and H, there are specific requirements for a given task in Group F. The following paragraphs contain a review of the specific requirements regarding methods for selecting a joining process for car body design specified in Group F. In Table 2, Group F is further divided into three sub-groups.

The first group of requirements (Requirement management) considers the characteristics of a method's input data for selecting a joining process for car body design. All the individual requirements of the joining connection discussed in Section 2 must be taken into account. Only by doing so, can the designer find a fitting solution for the joining connection in question (LeBacq et al., 2002; Ashby et al., 2004). The requirements discussed are not necessarily expressible as exact values. A method for selecting a joining process must therefore be able to deal with uncertain criteria (Giachetti, 1998).

The second group of requirements (Implemented knowledge) concerns the method's implemented knowledge. The implemented knowledge must be complete in the sense that the important processes and materials are considered (LeBacq et al., 2002; Ashby et al., 2004; Rusitschka, 2017). It must also be able to be supplemented by new techniques and materials (Lae et al., 2002; Ashby et al., 2004; Prüß et al., 2010; Rusitschka, 2017). The information contained must be in sufficiently detailed (Rusitschka, 2017). Ashby et al. (2004) and LeBacq et al. (2002) state that the knowledge must be stored hierarchically. For companies using a method, it is necessary to be able to encapsulate knowledge and to have low maintenance effort (Rusitschka, 2017).

The third group of requirements (Results) considers the results of a method for selecting joining processes for car body design. The method should allow to compare alternative versions of one joining process. For example, the use of four M8 screws should be compared to the use of five M6 screws (Rusitschka, 2017). It is preferable that the method is also able to consider a combination of joining principles and thereby generate new ones (Prüß et al., 2010). Technically unfeasible solutions should not be shown among the results (LeBacq et al., 2002; Ashby et al., 2004). The solutions which are feasible should be rated according to the requirements the designer formulated (LeBacq et al., 2002; Ashby et al., 2004). In order to assist the designer in selecting the best possible solution, it is advantageous to give examples of the different solutions in case studies (Lae et al., 2002).

Table 2. Requirements for a joining-process selection method

Group	Group description		Grouped items
A	Revisability		Validation (Keller and Binz, 2009)
			Verification (Keller and Binz 2009)
B	Practical relevance & competitiveness		Innovativeness (Keller and Binz, 2009)
			Competitiveness (Keller and Binz, 2009)
C	Scientific soundness		Objectivity (Keller and Binz, 2009)
			Reliability (Keller and Binz, 2009)
			Validity (Keller and Binz, 2009)
D	Comprehensibility		Comprehensibility (Keller and Binz, 2009)
			Repeatability (Keller and Binz, 2009)
			Learnability (Keller and Binz, 2009)
			Applicability (Keller and Binz, 2009)
E	Usefulness		Effectivity (Keller and Binz, 2009)
			Efficiency (Keller and Binz, 2009)
F	Problem specificity	Requirement management	Consideration of individual requirements of the join patch (Ashby, 2004; LeBacq, 2002)
			Handling uncertain criteria (Giachetti, 1998)
		Implemented knowledge	Ability to encapsulate knowledge (Rusitschka, 2017)
			Complete/containing sufficient information (Ashby, 2004; LeBacq, 2002; Rusitschka, 2017)
			Containing sufficient detail (Rusitschka, 2017)
			Expandable with new technologies and materials (Ashby, 2004; Lae, 2002; Prüß et al., 2010; Rusitschka, 2017)
			Hierarchical storage (Ashby, 2004; LeBacq, 2002)
			Low maintenance effort (Rusitschka, 2017)
		Results	Comparing alternative versions (Rusitschka, 2017)
			Not showing technically infeasible solutions (LeBacq, 2002)
			Generating new joining principles by combination (Prüß et al., 2010)
			Help in selection of a process by showing examples (Lae, 2002)
			Rating solutions on their suitability (Ashby, 2004; LeBacq, 2002)
			Estimating properties of unknown combinations (Ashby, 2004; Lae, 2002; Prüß et al., 2010; Rusitschka, 2017)
G	Structure & compatibility		Handling complexity (Keller and Binz, 2009)
			Problem-solving cycle (Keller and Binz, 2009)
			Structuring (Keller and Binz, 2009)
			Compatibility (Keller and Binz, 2009)
H	Flexibility		Flexibility (Keller and Binz, 2009)

The use of multi-material strategies not only results in difficulties for the designer, but also for the material and joining-process specialist. Validating 435 different material combinations with different joining processes for a modern car is extremely time-consuming. In order to reduce this effort, an

estimation of properties for different processes in combination with different materials is needed (Lae et al., 2002; Ashby et al., 2004; Prüß et al., 2010; Rusitschka, 2017).
As mentioned in Section 1, the number of materials and joining processes used continues to grow. A modern approach should be computer-aided for this reason (Ashby et al., 2004). Two main components of such a computational approach are a set of databases containing sufficient data in accordance with Section 3 and an information system**,** which can handle all of this information in an appropriate manner, in accordance with Section 4 (Ashby et al., 2004).
The information can be stored in the database in several forms. Attributes such as tensile strength or density can be stored as numerical values. Non-numerical values contain attributes such as seawater-resistance and whether or not a joint is watertight. Another kind of attribute takes the form of specific information such as case studies or design rules. General support information contains elements, which are additionally required, such as supplier information und finite element modules. (Ashby et al., 2004)
Processes and materials can be stored in different databases. Data from different databases should be connected in form of links or rules to enable the selection of the best possible joining process considering the data in its entirety (Rusitschka, 2017).
It is necessary to have an interface between user and method. Since it comprises a connection between the user and underlying software, the interface is an important design support component. The interface guides the user through the formalization of the requirements.

5. Approaches for selecting joining processes

Having discussed the requirements for methods for selecting a joining process for car body design, the methods available to guide the designer are presented in the following section. These methods should be viewed as implementations of the requirements outlined above.
In the past, the designer was supported by tables. In these tables, different materials and processes are listed, and necessary information for a qualified selection is given. Examples for this kind of support can be found in Rampersad (1994), Houldcroft (1990) and Kalpakjian and Schmid (2001).
The existing modern and computer aided strategies for selection in engineering can be categorized according to the form of information used to formulate the selection strategy, as can be seen in Figure 2 (Ashby et al., 2004). The three different approaches are:

- Experts' knowledge/questionnaire-based
- Free search/based on quantitative data
- Analogy/based on previously completed tasks

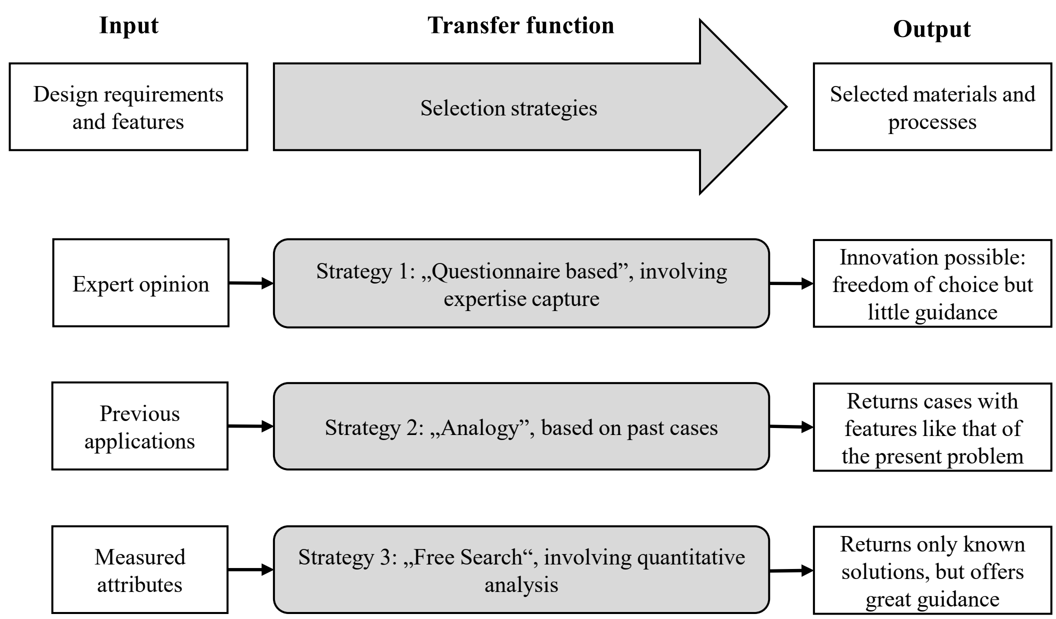

Figure 2. Different kinds of selection strategy (Ashby et al., 2004)

In order to apply the questionnaire-based strategy, the user is guided through an organized set of decisions, using integrated facilities to compensate for the lack of information on the part of the user. The aim of the strategy is to represent an expert by asking specific questions with answer options, each of which constitutes a possible answer for the expert. A prerequisite for this strategy is an in-depth interview of experts on every joining process. As a result of the answer provided, another question is asked until an unqualified answer – i.e. a solution – is reached (Ashby et al., 2004). Figure 3 shows the principle.

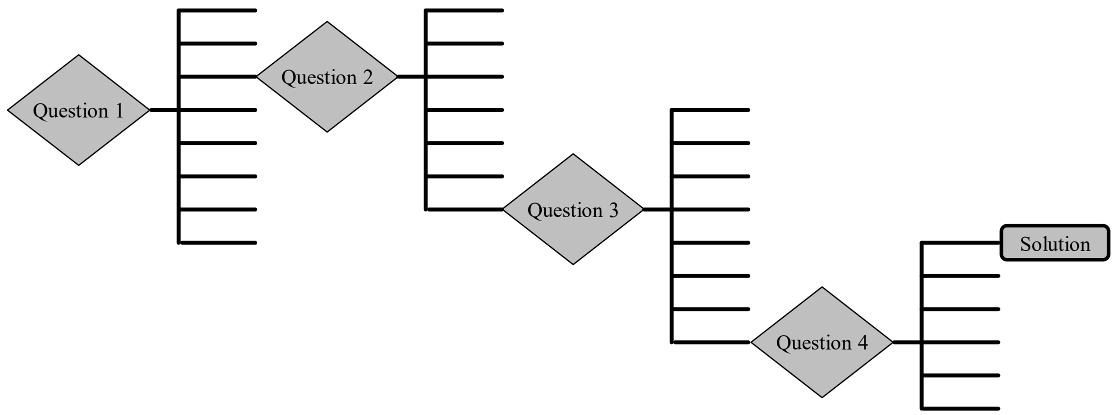

Figure 3. Principle of questionnaire-based strategy

Herein lies a disadvantage. Every question must be answered and no question can be omitted. This is time-consuming. Another disadvantage is the fact that a questionnaire-based strategy brings difficulties with it in terms of creation and maintenance. The incorporation of new materials and processes is also not possible because these did not exist when the expert was consulted (Ashby et al., 2004). Due to these disadvantages, the "expert knowledge/questionnaire-based" approaches will be omitted in subsequent considerations.

The approach based on analogies or previously completed tasks has its foundation in empirical experience. The structure of this approach is similar to that in Figure 2. Here, the input is a problem, which has to be translated into a set of requirements. With the help of a transfer function, existing cases are identified and compared to the current problem. When there is sufficient conformity with the requirements, the transmission of this solution from the past to the current problem is controlled (Ashby et al., 2004). One prerequisite for this kind of selection strategy is a database with a number of case studies. In order to identify a suitable solution in this database, it is necessary to define the 'distance' between requirement sets (Lae et al., 2002).

The general procedure of a selection strategy for joining processes with “Free Search” can be condensed into four main steps (Ashby et al., 2004; Jahan et al., 2010):

1. Translating requirements into specifications and performance metrics
2. Screening the solutions that are not suitable
3. Ranking the remaining solutions
4. Finding supporting information and choosing the best option

In the first step, the designer must consider the requirements and constraints regarding the join patch. Both need to be converted into specifications that refer to a joining process. For example, the designer needs to derive the required strength of a joint from the strength requirement of the whole product or system. Selection always starts with a set of possible solutions.

With the specifications found in step one, the designer must then eliminate the unsuitable options in the second step. For example, the joining processes with strength values below the specification must be neglected. In the third step, the remaining solution options have to be ranked according to their suitability for the task. The ranking may consider different attributes such as cost, weight, processing time or others discussed in Section 3. The final step of selecting an alternative is to look for supporting information. The designer has to consider further weaknesses in the processes and decide which joining process is the best possible one for the joining connection in question.

Measurable data is crucial for a free-search approach. The four basic steps of a selection strategy are conducted based on the function of the joint, requirements and goals to be optimized. The prerequisite in this case is the description of which requirement needs to be maximized or minimized.
A competitive software solution for free-search material selection is the CES software package (Ashby et al., 2004). The support in the selection of materials is guided and ordered according to the process described above. In addition to a material database, a joining process database is implemented. Based on the choice of material it is indicated, which joining methods can be used. Hereby a statement is made, whether the respective joining method can be used with multi-material. It is not shown which materials can be combined with one another. The possible joining methods are shown in the form of a detailed list. Information about the process is given, for e.g. relative costs. However, there is no guidance for an implemented joining process selection. Materials are only linked to appropriate processes, and a ranking mechanism for joining processes is not implemented.
One further free-search approach is the selection of joining processes within the MAMPS software as described by Giachetti (1998). The software includes three different modules with different tasks. With the help of product profile requirements, the first module has the task of identifying the most suitable material, whereas the second should find the most suitable joining process. After these tasks are processed, the third module joins the upstream modules. The result is a characteristic value, which describes the conformity between the requirements and the material, in addition to the process. The fact that the compatibility of the process and material with the requirements can be described with a fuzzy logic is particularly noteworthy: This makes it adaptable to imprecise and linguistic data (Giachetti, 1998). A Disadvantage is that there is no economic comparison implemented. In addition to the approaches, which follow a single strategy there are some, which include advantages of different approaches.
The approach, proposed by LeBacq (2002) combines the "Questionaire Based Approach" and a "Free Search Approach". Here, the user is guided with a questionnaire. Thus, the inputs are the answers to a given questionnaire. The result of this questionnaire is not one favorable joining process, as in an expert system, but rather a set of requirements. The following screening and ranking process is still a free-search approach so as not to neglect innovative or new processes. The designer receives a list of suitable procedures including a rating. Each process is characterised by three evaluations. Those represent the technical agreement, the ability of the company to use the process and the perception of the process in the industrial field of the application. The user has the possibility to weight the evaluations. The screening and ranking are carried out with the aid of a fuzzy logic. The guidance ensures that no important information is missing. Economic comparison is missing.
A further approach named ASTEK is presented by (Lae et al., 2002). It is a combination of a questionnaire based, free search and an approach based on analogies. To get the necessary information to select a joining method, an expert questionnaire is used. Here, a hierarchically structured database is needed. The data becomes more detailed during the selection progresses. In the software, the user answers four type of questions. These are structured in questions about the geometry of the joint, materials to be joined, required functions from the joint and joining production conditions. The answers to the questionnaire describe the requirements on the joining method. When the questionnaire is filled, a transcription of the technical requirements becomes available. First, technically impossible processes are excluded. Then a global technical evaluation ranks the remaining processes. Fuzzy logic is implemented allowing the choice of processes depending on the importance of each criterion. Afterwards further information is given by a number of reference cases stored in the database, which are similar to the case under investigation. The reference cases are selected with the help of a screening and are ranked. Some information that is not constituted by answering the questionnaire, but which is stored in form of text for a reference case study, can be given by suggestions for the new case study. Within this approach no economic comparison is given.
Another mixed approach is described by Rusitschka (2017). In the (developed) software tool, solvable connections can be selected. The approach of Rusitschka uses a menu-based interface which is implemented in a CAD system. The designer defines the location of the connection and the parts to be joined directly in the system. The combination of different approaches is realized within a modular construction. Each module compares requirements with the capabilities of joining processes featuring

different methods and algorithms. The modules have no relationship among each other, which reduces the complexity. One of the modules compares the existing problem with previously solved ones. In another module different potential solutions can be dimensioned with design rules, which are implemented. The designer gets an overview of the possible solutions and can choose the most economical one. Further advantages are simple maintenance and extensibility of the system (Rusitschka, 2017). The tool is developed in an industrial company for inside use. Also it does not handle welding techniques.

6. Deficits of approaches

The last sections identified requirements for selecting joining processes and described the main approaches that try to guide the designer through the difficulties of selection. Some of the identified requirements are not addressed by any of the approaches. This section outlines the main deficits that were identified. In Table 3, these findings are summarized.

Table 3. Evaluation of the approaches for selecting joining processes in car body design

○ Not fulfilled ◐ Partly fulfilled ● Fulfilled	CETIM (LeBacq et al., 2002) Questionaire/ Free search	ASTEK (Lae et al., 2002) Mixture of all	CES (Ashby et al., 2004) Free search	MAMPS (Giachetti, 1998) Free search	Rusitschka (Rusitschka, 2016) Free search/ Analogy
Possibility to handle multi-material (Section 3, Table 1)	●	●	◐	◐	●
Consideration of costs (Section 3, Table 1)	○	○	◐	○	●
Guided selection of joining processes/ Comprehensibility (Section 4, Table 2)	●	●	○	●	●
Expandable by new technologies and materials (Section 4, Table 2)	◐	◐	●	◐	◐
Consideration of different variants (Section 4, Table 2)	○	○	○	○	●
Not showing technical not feasible solutions / Screening (Section 4, Table 2)	●	●	○	●	●
Rate solutions on their suitability / Ranking (Section 4, Table 2)	●	●	○	●	●
Estimate properties of unknown combinations (Section 4, Table 2)	○	○	○	○	○
Availability of the software	○	○	●	○	○

As stated in the introduction, one challenge for the selection of joining processes for car body design is the use of multi-material strategies. It is thus necessary for a support method to be able to deal with multi-material strategies. All considered approaches are a helpful tool with regard to multiple materials, although the quality of the support provided varies. CES (Ashby et al., 2004) provides information on

whether a process is able to handle different materials or not, but no specification is given as to which materials may be combined.
A further important point in design in general is the consideration of costs. In the case of joining, this includes all costs arising during the production of a joint. These include production costs, costs for tools, and investment, as discussed in Section 3. Only Rusitschka (2017) considers costs in their entirety. Ashby et al. (2004) provide information about economy in the form of relative values, which may also help in certain situations.
As discussed in Section 4, and in detail in Keller and Binz (2009), it is preferable that a method is comprehensible to the designer. A selection of joining processes for car body design necessitates assistance, however. Since the CES software package focuses on material selection, it does not provide clear guidance.
Due to research and development in the areas of materials and joining processes, a growing database is needed for the appropriate selection of joining processes in car body design (Section 3). There are different ways to expand databases. The easiest way, involving the addition of numerical information to databases, is supported by CES. The extension of databases is more complex for other approaches. Some joining processes are able to fulfil the requirements in different variants. One example given in Section 4 is the use of different patterns of screws. In the comparison of the different approaches, it is found that only the approach proposed by Rusitschka (2017) can facilitate this functionality.
As discussed earlier, the screening and ranking algorithms are a crucial part of a support tool. In terms of joining processes for car body design, it is important to pursue rule-based screening in form of formulas to exclude processes. The subsequent ranking needs to compare the remaining possible processes in accordance with the user's requirements. Although these aspects are covered in a thought-out manner for the material selection, the CES software has deficits in these two areas for selecting joining processes. In CES, the compatibility of the material and process combinations needs to be manually identified. A ranking of solutions for choosing the best possible process is also lacking in CES, while other approaches fulfil this requirement.
To fulfill the two steps of screening and ranking, it is crucial to have information about the combinations of processes and materials in question. Since there is an enormous number of possibilities, measurement of all data would be extremely laborious, if not impossible. A module for estimating these values based on similar combinations could significantly reduce the required size of the underlying database and thereby the effort involved. None of the selection support tools has such a module implemented.
Although not explicitly listed in the requirements above, availability is crucial in order for an approach or method to be used. At present, the only commercially available software is the CES software package. Other software packages are only implemented within companies (Rusitschka, 2017; CETIM; ASTEK; MAMPS). Thus an access to the software packages is not available for scientific community. The conclusions found in this paper are mainly drawn from available publications and conversations with scientists from corresponding institutes in these instances.

7. Conclusion

This paper found a set of requirements for a method for the selection of joining processes for car body design. The set is divisible in requirements concerning the method itself, which are concluded in Table 2, and requirements concerning the joined parts, concluded in Table 1.
Furthermore, the existing approaches to the problem are described and compared to the found requirements.
Within the free-search strategy, it is possible to generate innovative, specific solutions, yet it is challenging to describe the requirements to be maximized or minimized.
Questionnaire-based strategies offer the user guidance through a set of decisions, which is the replication of experts' answers, therefore the result represents the experts' experience and knowledge. The prerequisite for this strategy is an in-depth interview of experts with regard to every joining process. This kind of strategy is used for the translation of data sets in the interface into a form that is compatible with the respective requirements.

An analogy-based approach compares the current problem with solutions from the past. If there is sufficient compatibility, the solution from the past is adopted. This is a fast means of finding a solution, yet new materials and joining processes can only be considered with great effort.

The strategies examined in this paper are a suitable way of assisting designers in selecting material und joining processes during the product-development process. Nevertheless, there are significant deficits concerning requirements in the selection of joining processes in car body design, which are concluded in Table 3.

The existing deficits demonstrate that there is a great need for a new approach for selecting joining processes in car body design that fulfills all requirements and is available for a wide community.

A new approach to the problem should therefore:

- Be able to support multi-material strategies
- Include new materials and joining processes, or it should be easy to implement them
- Include economic factors
- Consider different geometric variants of a joining connection
- Estimate unknown values

References

Ashby, M.F., Bréchet, Y.J.M., Cebon, D. and Salvo, L. (2004), "Selection strategies for materials and processes", *Materials and Design*, Vol. 25 No. 1, pp. 51–67.

Beck, F.U. (2013), Verbindungstechnik strukturell tragender CFK-Al-Mischverbindungen im Automobilbau, PhD thesis, University of Stuttgart.

DIN EN (2014), DIN EN 1999-1-1: Eurocode 9: Desing of aluminium structures - Part 1-1: General structural rules, European Committee for Standardization, Brussels.

DIN EN ISO (2005), DIN EN ISO 15609-1 Specification and qualification of welding procedures for metallic materials - Welding procedure specification - Part1: Arc welding (ISO 15609-1:2004), Beuth, Berlin.

DVS/EFB (2016), Fügeverfahren für die Mischbauweise (DVS 3451), DVS Media GmbH, Düsseldorf

Friedrich, H.E. (2017), *Leichtbau in der Fahrzeugtechnik*, Springer Fachmedien Wiesbaden, Wiesbaden. https://doi.org/10.1007/978-3-8348-2110-2

Giachetti, R.E. (1998), "A decision support system for material and manufacturing process selection", *Journal of Intelligent Manufacturing*, Vol. 9 No. 3, pp. 265–276.

Houldcroft, P.T. (1990), *Which process?: An introduction to welding and related processes and a guide to their selection*, Abington, Cambridge, U.K.

Jahan, A., Ismail, M.Y., Sapuan, S.M. and Mustapha, F. (2010), "Material screening and choosing methods – A review", *Materials and Design*, Vol. 31 No. 2, pp. 696–705.

Kalpakjian, S. and Schmid, S.R. (2001), *Manufacturing engineering and technology*, Prentice Hall, Upper Saddle River, New Jersey.

Keller, A. and Binz, H. (2009), "Requirements on engineering design methodologies", *Proceedings of ICED 09, 17th International Conference on Engineering Design, Vol. 2, Design Theory and Research Methodology, Palo Alto, CA, USA, June 24-27, 2009*, pp. 203-214.

Klein, B. (2013), *Leichtbau-Konstruktion: Berechnungsgrundlagen und Gestaltung*. Springer Fachmedien Wiesbaden, Wiesbaden. https://doi.org/10.1007/978-3-658-02272-3

Lae, L., Brechet, Y., LeBacq, C., Jeggy, T. and Salvo, L. (2002), "Knowledge-Based Systems for Selecting Joining Processes", *Advanced Engineering Materials*, Vol. 4 No. 6, pp. 403–407.

LeBacq, C., Brechet, Y., Shercliff, H.R., Jeggy, T. and Salvo, L. (2002), "Selection of joining methods in mechanical design", *Material and Design*, Vol. 23 No. 4, pp. 405–416.

L'Eglise, T., De Lit, P., Fouda, P., Rekiek, B., Raucent, B. and Delchambre, A. (2001), "A Multicriteria Decision-aid System for Joining Process Selection", *International Symposium on Assembly and Task Planning, ISATP, Fukuoka, Japan*.

Werz, M. and Seidenfuß, M. (2016), "High-Strength Friction Stir Welds for Joining Aluminium and Steel with Dissimilar Sheet Thickness", *11th International Friction Stir Welding Symposium, May 17-19, 2016, Cambridge, UK.*

Prüß, H., Stechert, C. and Vietor, T. (2010), "Methodik zur Auswahl von Fügetechnologien in Multimaterialsystemen", *Proceedings of the 21st Symposium on Design for X, September 23-24, 2010, Buchholz/Hamburg, Germany.*

Rampersad, H.K. (1994), *Integrated and simultaneous design for robotic assembly*, Wiley, Chichester.

Reisgen, U., Schiebahn, A. and Schönberger, J. (2014), "Innovative Fügeverfahren für hybride Verbunde aus Metall und Kunststoff", *Lightweight Design*, Vol. 7 No. 3, pp. 12–17.

Rumpelt, T. and Günnel, T. (2017), Leichtbau im Audi A8: „Das Maximale erreicht". [online] Automobil Industrie. Available at: https://www.automobil-industrie.vogel.de/leichtbau-im-audi-a8-das-maximale-erreicht-a-603318/

Rusitschka, F. (2017), Methodik zur Auswahl von lösbaren Verbindungen in der variantenreichen Serienfertigung, PhD thesis, University of Stuttgart.

Schricker, K. Stambke, M. and Bergmann, J.P. (2015), "Experimental investigations and modeling of the melting layer in polymer-metal hybrid structures", *Welding in the World*, Vol.59 No.3, pp. 407–412.

Stambke, M., Schricker, K., Bergmann, J.P. and Weiß, A. (2017), "Laser-based joining of metal-thermoplastic tailored welded blanks", *Welding in the World*, Vol. 61 No. 3, pp. 563–573.

Enno Garrelts, Academic Assistant
University of Stuttgart, IKTD
Pfaffenwaldring 9, 70569 Stuttgart, Germany
Email: enno.garrelts@iktd.uni-stuttgart.de