Approach for the Reliable and Virtual Design of Mechanical Joints in an Uncertain Environment

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Abstract

The demand for lightweight assemblies necessitates appropiate joining processes, such as cold forming processes enabling multi-material joints. The absence of universally applicable approaches for the design of mechanical joints makes their initial design iterative and time-consuming. Machine learning based approaches already partly solve this problem, but the impact of uncertainties, is usually neglected. Thus, this contribution proposes the concept of a novel computer-aided approach, supporting the initial design of clinch joints, taking into account uncertainties and varying conditions utilizing numerical simulations, data-driven methods and ontologies. This aims for a high-quality joint design demonstrated using an application scenario where a hat profile and a sheet are joined.

Keywords

Mechanical Joining, Clinching, Machine Learning, Finite Element Method, Uncertainties

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1. Motivation

The growing demand for lightweight designs and multi-material assemblies requires efficient joining processes [1]. Clinching, categorized as “joining by forming” in DIN 8593-5, is a mechanical joining process, that is becoming increasingly important in lightweight design, since the cold-forming process is a suitable method to join two or more [2] dissimilar overlapping sheets in contrast to established joining techniques such as welding [3]. However, the lack of universally applicable analytical approaches for the design of mechanical joints renders the task highly iterative and time-consuming by utilizing numerical analyses and experiments to ensure the required clinch joint properties [4]. Motivated by this hurdle, machine-learning based approaches emerged, demonstrating their potential to accelerate the process of predicting and optimizing the nominal clinch joint properties using data from numerical simulations [5, 6]. This is currently limited to simple joining tasks assuming similar sheet thicknesses and materials to be joined. Moreover, inevitable uncertainties that may arise in the process chain, such as variations of the tool geometry or material properties, that affect the joint quality are mostly neglected. However initial studies, show that their consideration plays a crucial role in the reliable prediction of joint properties [2].

2. State of the art

The following is a brief overview of the clinch joining process, the resulting clinch joint properties and the conventional and machine-learning based approach of designing mechanical joints.

2.1. Clinch joining process and joint characteristics

By clinching, the joint of metal sheets, tubes or profile parts is achieved exclusively through local cold forming without using auxiliary joining parts [7], as illustrated in Figure 1 on the left-hand side. Initially, the sheets are positioned and fixed in place. Then, the sheets are displaced from the sheet plane by an orthogonal force exerted by the punch. Subsequently, the sheets are deformed by spreading or a form of transverse extrusion [8]. The material displaced in the radial direction thus forms a geometric interlock between the two sheets [9]. In addition to the resulting form closure, residual compressive stresses are also formed, which lead to an additional frictional connection. Finally, the punch is lifted and the sheets can be removed [10].

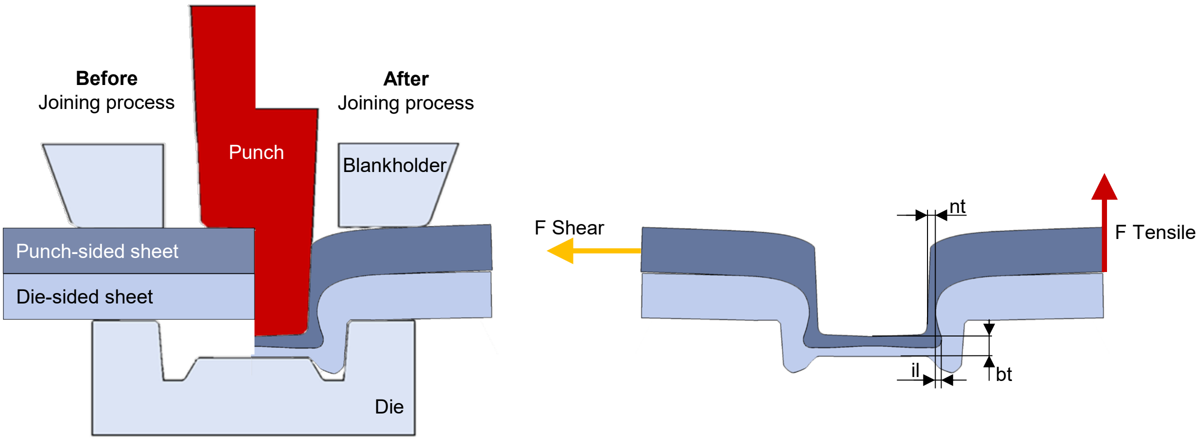

Figure 1: The clinching process (left) [2] and geometrical-characteristics and load capacity of the clinch joint (right) [11]

The use of clinch joints is applicable to the joining of dissimilar materials and sheet thicknesses, while the plastic formability of the sheets is a fundamental requirement and the joining point must be accessible on both sides [8]. Another advantage is the potential for production without the necessity for explicit finishing treatment, whereas clinching is less suitable for the use on visible surfaces due to the pattern formation on the surface [12]. Therefore, clinch joints are employed in a multitude of applications, those pertaining to household electronics, ventilation and air condition technology, and the automotive industry [10]. The quality of a clinch joint is mainly characterized by its shear- and tensile-load capacities, which are furthermore influenced by the geometrical properties interlock (il), neck thickness (nt) and bottom thickness (bt), as illustrated on the right side in Figure 1 [13].

2.2. Design of clinch joints

In general the design process is comprised of two stages, the initial design of the tool geometry and the subsequent analysis of the resulting clinch point [4]. The design of the clinch joining point and the selection of the tool geometry necessitates an understanding of the relationships between the tool geometry and the properties of the resulting clinch joint. In [13] an analytical method is proposed to calculate the required neck thickness and interlock for the desired shear and tensile-load capacities directly in relation to the punch diameter and the angle between the two sheets. The volume equilibrium between the material displaced by the punch and the die cavity allows then for the selection of an appropriate tool geometry [14]. Subsequently, the resulting joint properties formed by the selected tool geometries are validated through numerical analyses [13]. To gain insight into the relationship between the tool geometry and the resulting characteristics of the clinch joint and to ensure a sufficient initial design, the influence of nominal tool design parameters is studied in [15, 16]. In [17] the influence of pre-straining of the sheets has been investigated using finite element (FE) models. Although analytical methods could be implemented in the early stages of the product development process, existing analytical methods for the design of mechanical joints lack universal applicability [4]. That renders the design process highly iterative and time-consuming, because numerical analyses and experiments need to be utilized to ensure the required clinch joint properties [4].

To overcome this drawback, metamodel-based methods are used to generate a high quality initial joint design. In [18] a data-based approach is proposed, that utilizes metamodels, to predict and optimize the inherent clinch joint properties. These metamodels are trained and evaluated on numerical data [19]. Therefore, a 2D rotational symmetric FE model of the clinching process is employed, comprising similar aluminum sheets (EN AW-6014 T4) and an automatic analysis of the joining force and the geometric clinch joint properties, is used to generate a database [20]. The predictive metamodels are then implemented in an assistance system with the additional incorporation of manufacturing knowledge, such as the accessibility for the clinching tool [18]. An additional link to an CAD system enables the automatic generation of a suitable tool design [18].

However, this design method only focuses on the nominal clinch joint properties under static loads, while uncertainties of the tool geometry or material properties, such as manufacturing tolerances, are not taken into account [18]. Thus, in [2] the uncertainty of the clinch joint properties is examined by the use of a Gaussian process regression model, in conjunction with supplementary numerical simulations involving varying input parameters. The transferability of metamodels to predict the clinch joint geometry when minor variations of the tool geometry are considered is confirmed in [21]. This paves the way for the use of metamodels for the data- and knowledge-based design of clinch joints, taking into account a wider range of uncertainties.

3. Research problem and research goal

Existing design methods do not consider all pertinent, inherent uncertainties within the process chain, as they primarily concentrate on nominal designs and do not incorporate multi-material connections [6]. However, the consideration of these uncertainties is essential to obtain realistic clinch joint properties predictions [2] and thus enable a robust design of clinch joints. To overvome the current hurdles, the following research question has to be answered:

> *How can a reliable and virtual design of mechanical joints in an uncertain environment be realized?*

In order to fully exploit the potential for lightweight design and avoid extensive iterations, a concept of a versatile computer-aided approach for the design of clinch joints in an uncertain environment is proposed. This includes that the approach should be applicable under varying conditions, such as different loads, multi-material joints and various sheet thicknesses, while accounting for uncertainties that may arise in the process chain, such as manufacturing tolerances of the punch and the die.

4. Methods and procedures

On the one hand, this approach requires the development of a versatile process simulation chain, that is able to map the uncertainties to the resulting joint characteristics. This data is then used to evaluate the applicability and extensibility of already promising metamodels trained on nominal data. By considering alternative metamodel approaches, like Bayesian networks, the ideal combination of metamodels for the efficient prediction of real joint properties is investigated. On the other hand, the aimed realistic prediction goes beyond data-based approaches and requires formalizing knowledge about complex interrelations that cannot be mapped in the process simulation chain. Therefore, an ontology will be developed based on literature study and expert interviews. Both aspects will be unified in one approach that can be used to design a mechanical joint with its nominal properties and realistic uncertainties.

4.1. Concept overview

The approach is categorized into three steps, the data generation, the metamodeling and the initial design for a new joining task, as illustrated in Figure 2. Firstly, the users must ascertain, whether a database exists for the desired joining task and the necessary input parameters. In the absence of an existing database, one must be created. Therefore, they utilize an ontology to identify necessary simulation models. Subsequently, appropriate metamodels, which align with the desired target values and input parameters are selected, trained and saved to the backend. If existing metamodels can be used or have been created, the users utilize the ontology, to select adequate metamodels based on the requirements and boundary conditions from the backend to predict the clinch joint properties. These are then used to generate a range of design alternatives. By incorporating additional manufacturing knowledge and robust design (RD) recommendations from the ontology, the users are then able to select the most suitable design alternative. The ontology framework is separated in two ontologies. One ontology is dedicated to the data generation and metamodeling, while the other is focused on the initial design. This separation allows for clear delineation of responsibilities and enhances the complexity. This approach guarantees that the designed joint fulfills the specific requirements and constraints and ensures a high-quality preliminary design by considering additional process knowledge and robust design recommendations.

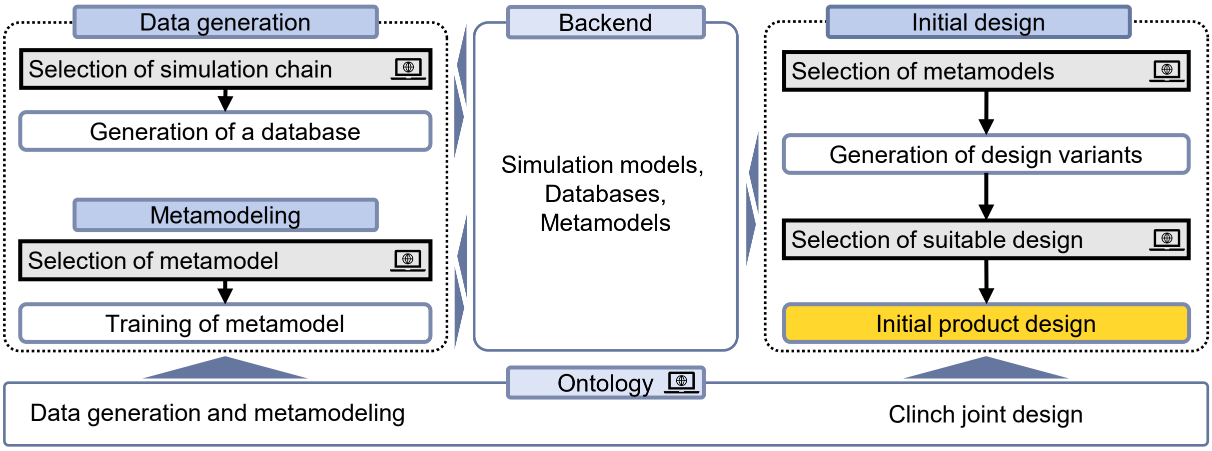

Figure 2: Overview of the process for data generation and metamodeling and initial design for a new joining task

4.2. Data generation and metamodeling

In the event that no existing metamodels are available, or no databases exist, for instance, if the clinch joint is to be created using a novel joining process, a new database and new metamodels must be generated. The ontology enables the users to identify the requisite simulation models, which are specific for the desired target values and have been incorporated into a process simulation chain. In addition, the users can select simulation models with the required material models and the associated flow curves. For example, a material model for simulations with or without material failure [22]. Thereby the simulation chain is used to map the input parameters to the resulting target variables. The approach employed for querying the ontology is illustrated in Figure 3, which depicts the selection of a suitable simulation chain for the given target variables. The user input is then translated into a machine-readable query, to obtain the necessary simulation models for geometric load capacity properties of the clinch joint.

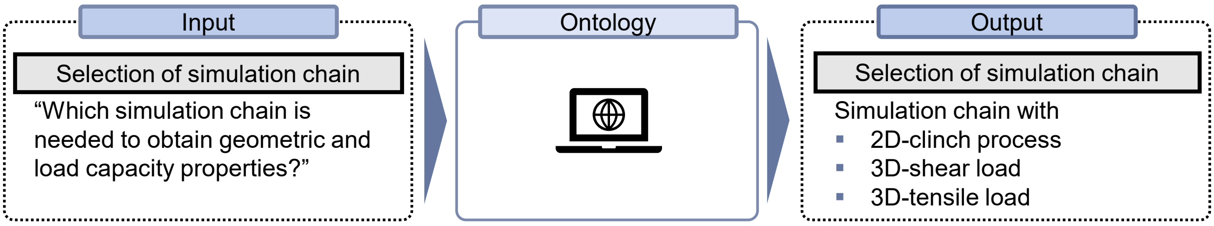

Figure 3: Usage of the ontology with an example query in the selection of the requisite simulation chain

Furthermore, the users are able to identify the pertinent parameters, that influence the target variables and therefore must be considered in the simulation models. For example, the punch diameter shows a strong influence on the joining force, but no influence on the neck thickness [23]. Subsequently, the users select the necessary process simulation chain, which is either already stored in the backend, or must be created, parameterized and validated by a FE specialist, which is not part of the described approach. In this contribution, the existing simulation models from [11, 24] are utilized. The users can check with the help of the ontology, if all relevant input parameters, such as the punch diameter and the die are defined. Therefore, they query the ontology, which parameters need to be defined in this simulation chain and compare them with those already defined. In addition, the users can query the ontology to identify suitable intervals and expected variations of unknown input parameters that are depictable in the process chain. By way of an example for relevant input parameters and suitable intervals, and variations of the punch diameter and the die depth are chosen, as illustrated in Figure 4.

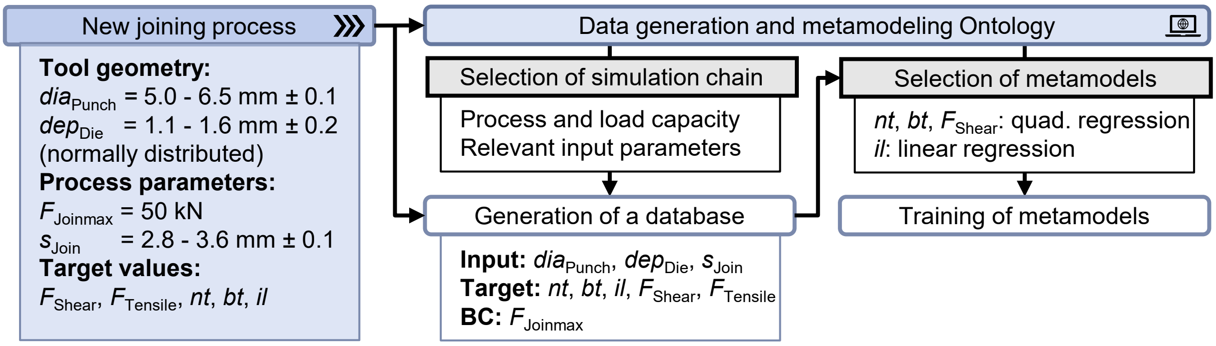

Figure 4: The data generation and metamodel training substep with knowledge from the ontology

The maximum joining force serves as a boundary condition. Simulations exceeding this value can be directly sorted out and are not included in the database. The data generation is demonstrated by an example of a parameterized numerical process simulation chain in LS-Opt with LS-Dyna simulation models for a clinching process with shear- and tensile-load capacity tests and analyses, to obtain the required geometric and load capacity characteristics, as illustrated in Figure 5. Therefore, a two-dimensional (2D) rotational symmetric simulation model of the clinching process [24] is used to estimate the geometric characteristics of the clinch joint, including neck thickness, interlock and bottom thickness, similar to [25]. In order to reduce the time required for calculations, a 2D simulation model is employed, which simplifies the clinching process by postulating rotational symmetry [24]. In addition, the joining force can be evaluated through a cross section in LS-Dyna. A three-dimensional (3D) simulation model is necessary for the analyses of shear- and tensile-load capacities of a clinch joint, to be able to take into account non-axisymmetric deformations [17]. The stress and strain data from the 2D forming process is mapped to a 90° respectively a 180° rotated clinch joint and imported to the numerical load capacity simulations. The resulting shear- and tensile-forces are likewise analyzed through a cross section and the maximum values are exported.

Subsequently, the process simulation chain can be employed to simulate multiple clinch joints, thereby facilitating the generation of a comprehensive database, while the data generation and metamodeling ontology supports the users in creating a design of experiment (DoE) that is suitable to the specific task, e.g., by suggesting to select a wide or a small parameter interval, according to the expected distribution.

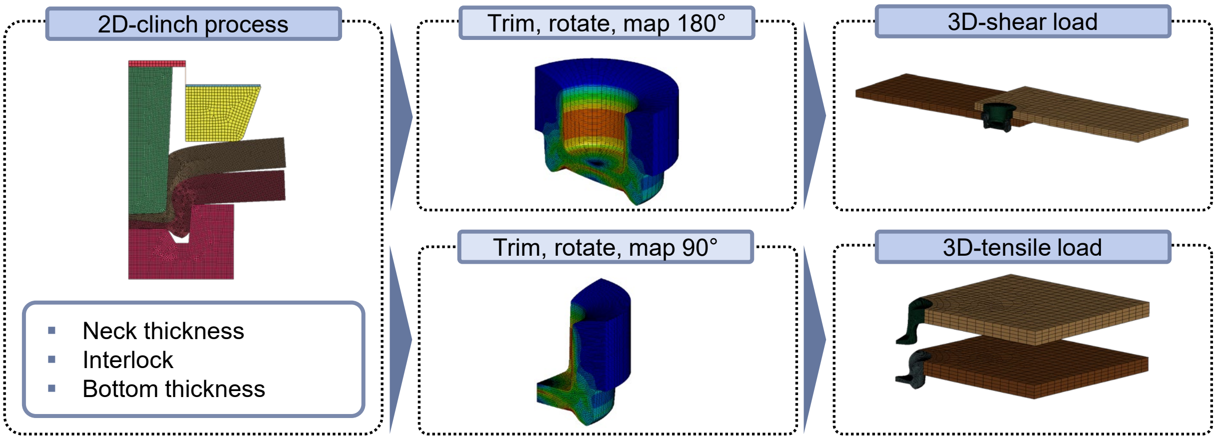

Figure 5: Overview of the process simulation chain for generating a database with geometrical characteristics and static load capacities

Afterwards, the database contains the considered parameters and the identified target values. The used parameter intervals are saved to the design ontology. A supplementary sensitivity analysis may be employed to further reduce the number of input parameters, by eliminating parameters with a small influence on the target variables, to optimize the metamodeling process.

Subsequently, the generated database can be used to train metamodels. The users select adequate metamodels for the specific target values, input parameters and design objectives, based on knowledge from the ontology. For example, a quadratic regression model (qrm) can be selected for predicting the bottom thickness, the shear-load capacity and the joining force and a linear regression model (lrm) for the neck thickness [23], or metamodels, that are able to provide an uncertainty of the prediction, such as Gaussian process regression model [2], Bayesian neural networks or an ensemble of metamodels [26] when uncertainties are taken into account.

4.3. Initial design for a new joining task

The application of the design process, illustrated in Figure 6, is described using an exemplary application scenario involving the joining of a hat profile and a sheet. The users start with a set of requirements for the clinch joint, such as the corrosion resistance, the shear strength and the used sheet materials. Furthermore, it is essential to define additional parameters with the expected variations such as the usable tool geometry, the sheet thicknesses and process parameters. With the help of the clinch joint design ontology, the users can additionally identify safe process intervals for parameters that cannot be implemented in the process simulation chain, such as tool wear and lubrication condition of the sheet surfaces. This knowledge allows the users to enhance the process reliability and avoid potential issues, even if a direct simulation is not possible.

Subsequently, the users select, with help of the ontology, suitable metamodels for the prediction of the clinch joint properties. In contrast to the selection of suitable metamodels in the data generation and metamodeling substep, the users can select a combination of metamodels, according to the required target variables. Subsequently, the metamodels provide a desired number of suitable clinch joints manufacturable with the given tool geometry and process parameters.

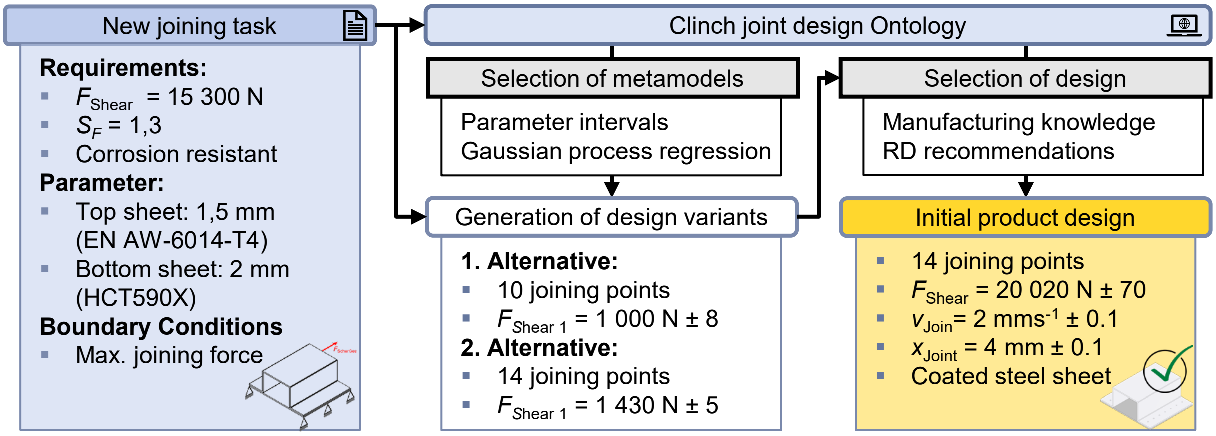

Figure 6: The design process with knowledge from the ontology

In general uncertainties that influence the prediction of the clinch joint properties can be classified in three categories, the *uncertainties of the simulation models*, *the uncertainties of the metamodels* and *the uncertainties of the input parameters*. As the validation of the simulation models is achieved by comparing the results of the target variables derived from the simulation with the corresponding experimental results, the *uncertainty of the simulation models* can be determined [24]. As example, the utilized simulation model of the clinching process calculates a bottom thickness of 0.72 mm, while the experimental results vary between 0.67 mm and 0.72 mm [24]. Therfore the uncertainty of the simulation model with this specific parameter combination equals +0.00 mm and - 0.05 mm. If the simulation models are validated with several parameter combinations the uncertainty can be interpolated. The *uncertainty of the metamodel* results from its approximation to the simulation data. and can be calculated directly by various methods, such as the use of a Gaussian process regression model [2]. Theoretically the metamodel uncertainty can be reduced by improving the model architecture [26]. The influence of the *uncertainties of the input parameters* on the clinch joint properties can be approximated for example, by the use of a metamodel [27]. For example in [27] a DoE is created with uniformly or Gaussian distributed input parameters and the resulting distributions of the target variables are predicted with the metamodel. Finally, the total uncertainties of the clinch joint properties can then be calculated by adding the uncertainties caused by the *input parameters* to the *uncertainty of the metamodel* [2] and the *uncertainty of the simulations*. This approach enables a reliable design, since it ensures that all possible uncertainties are considered and the users can identify the best- and worst-case clinch joint properties.

Manufacturing knowledge and robust design recommendations help in the last step to select the most suitable alternative. For example, manufacturing costs can be reduced by selecting the alternative with fewer joints, or the alternative with the least total variation in order to achieve the most robust assembly. Another robust design recommendation could be to select the alternative that is least susceptible to variations of the tool geometry that could result from wear. Thus, this approach allows to select a design that leads to less sensitive joints. Problematic properties such as susceptibility to contact corrosion due to the materials used is taken into account and a solution to this e.g., a coating of the steel sheet, is recommended with knowledge stored in the ontology. The final weighting of the recommendations and the selection of the most appropriate alternative are conducted by the users. For example, alternative 2 as the more robust option, or alternative 1 for a more reasonable number of joints, as illustrated in Figure 6. Subsequently, an algorithm is used to export a CAD-model of the clinch point and the assembly, analogous to [18].

5. Conclusion and outlook

The proposed conceptual approach enables a data and knowledge-based design of mechanical joints in an uncertain environment. Thus, the approach can be applied for multi-material joints, different loads and various sheet thickness, while considering variations of the tool geometry, the material properties and process parameters. The approach focuses on the investigation of clinch joints and the interactions and consequences of the varations of the input parameters and therefore allows for a reliable clinch joint design, since arising uncertainties can be taken into account. In combination with manufacturing knowledge and robust design recommendations in the design stage, this ensures a high-quality initial design.

In future research activities, the proposed approach will be implemented into an assistance system. A main aspect will be to investigate the suitability of several metamodels to predict the realistic clinch joint properties of multi material joints. Consequently, a comprehensive database will be constructed, comprising a variety of geometrical, material and process input parameters, along with an analysis of the geometrical and static and cyclic load capacity of the clinch joint properties. Another aspect will be to investigate several metamodeling techniques to consider uncertainties of the input parameters. Therefore, different methods will be investigated, to identify the most suitable method for the specific target variable.

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