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Procedia CIRP 100 (2021) 720–725

www.elsevier.com/locate/procedia

31st CIRP Design Conference 2021 (CIRP Design 2021)

Identifying an opportunistic method in design for manufacturing: an experimental study on successful a on the manufacturability and manufacturing effort of design concepts

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Abstract

The main objective of design for manufacturing (DfM) is to ensure and simplify the manufacturing of products to reduce manufacturing costs. The problem is that most of DfM methods address the limitations of manufacturing processes with providing design considerations to enable manufacturability, whereas successful approaches are missing to support engineers in emphasizing the unique capabilities and exploiting the potential of the manufacturing processes. Experimental studies are rare, which investigate how design engineers proceed when the design goal includes the main objectives of the DfM. Therefore, the aim of this research is to examine successful approaches of experienced engineers and inexperienced students during the consideration of DfM in the design process. The key performance indicators were manufacturability and manufacturing effort of the design concepts. A total of 27 participants took part in the experiment, from which 15 were Master's students majoring in mechanical engineering and 12 were design engineers from ten industrial companies in Germany. The results show, that 83% of the concepts could be manufactured. The distribution in the manufacturing effort shows that design engineers as well as students designed 45% of the concepts with a high manufacturing effort. Therefore, we analyzed successful approaches of design engineers, who cleverly optimized the design and still fulfilled the function. Furthermore, the successful approaches are implemented in an opportunistic method for DfM, adopted from additive manufacturing, which can be transferred to further manufacturing processes.

Keywords: design for manufacturing; gaze analytic; design methods

1. Introduction

The aim of design for manufacturing (DfM) in early product development is to simplify manufacturing of a product and thus reduce component and system manufacturing costs [1,2]. The consideration of manufacturing during design is highly challenging [3].

The problem is that most of DfM methods address the limitations of manufacturing processes with providing design considerations to enable manufacturability, whereas successful approaches are missing to support engineers in emphasizing the unique capabilities and exploiting the potential of the manufacturing processes.

To support the application of DfM methods in design and to enhance the skills of design engineers, researchers are constantly investigating in new design methods, tools and techniques to support DfM. Many methods have been developed and optimized to support the design engineer in considering manufacturing during design [4]. The range extends from checklists to catalogs [5], design guidelines [6–8], spreadsheet models [9], mixed product/process-based methodology [2] and decision support [10]. The purpose of engineering support is to raise awareness of manufacturing limitations, reduce the design time of a component, evaluate manufacturability and manage the necessary information in the tools used [11]. Several methods begin before the engineer develops a CAD model, namely when the engineer generates

10.1016/j.procir.2021.05.090

the very first concepts in the head or on a sheet of paper to test for manufacturability and to estimate the associated manufacturing effort.

In summary, the current DfM methods mainly support the design engineer in adapting the concept to the limitations of the manufacturing process and to its impact on many iterations in the design process [12]. A main benefit of DfM is to develop manufacturable concepts in order to reduce the manufacturing effort right at the beginning of the development process.

Experimental studies are rare, which investigate how design engineers proceed when the design goal includes the main objectives of the DfM: reduce the number of parts and manufacturing process steps. The studies carried out in the field of design for manufacturing and design cognition research consist of separate observations by inexperienced [13,14] or experienced engineers and also of a direct comparison between experienced and inexperienced engineers [8,15,16]. Inexperienced engineers benefited from the frequent use of a DfM method, while performing a design challenge in the detailed embodiment design [8]. However, engineers prefer to use their experience and intuition in knowledge and analogies from previous designs to adapt designs to new situations [17,18]. The findings offer insight in how the engineers proceed, but rarely show successful approaches to overcome the challenges. The findings of an interview study, which examined the challenges faced by design engineers in considering manufacturing in design [3], are four main challenges for design engineers:

- Know-How: Detailed and manufacturing-specific knowledge necessary but not sufficient
- Synthesis: Design engineers cannot create concepts that fully use the manufacturing potential in terms of costs
- Analysis: The feasibility of manufacturing is not assessed
- Evaluation: The dimension of cost drivers is unknown and optimisation in the early stages of design is difficult.

To overcome the challenges further support within design methods is necessary. The cognitive challenge of considering manufacturing in design could be especially shown during the synthesis. Further data of experimental studies are necessary, which examine how design engineers proceed. Nevertheless, the effort of the analysis of empirical research studies is immense. Ahmed [19] offers empirical research methods that can be used in industrial case studies as well as in experimental studies, e.g., document analysis, interviews, discourse analysis, observations, participant observation, and protocol analysis. For the analysis of successful approaches and strategies only the participant observation and protocol analysis can offer insight into explicit, implicit, or tacit knowledge [19]. The retrospective interview is suitable, in which the participants express their thoughts after performing the activity. For research on the successful approaches, the mentioned data analysis methods are qualitative.

In summary, experimental studies are rare, which investigate in how design engineers proceed when the design goal includes the main objectives of the DfM. The research is limited to the interaction with a DfM method. Investigations are necessary to give insight into successful approaches in emphasizing the unique capabilities and exploiting the potential of the manufacturing processes. Therefore, the aim of this research is to examine the successful approaches of experienced engineers and inexperienced students during the consideration of DfM in the design process.

2. Material and Methods

2.1. *Participants*

A total of 27 participants took part in the experiment, from which 15 were Master's students majoring in mechanical engineering and 12 were design engineers from ten industrial companies in Germany, all specialized in mechanical design with experience in designing sheet metal products. Table 1 shows the descriptive statistics of age and previous experience of all participants. Prior to the experimental study, the participants were asked to evaluate their previous experience in sheet metal design on a five-level Likert scale (0 = no experience, 4 = expert). The level of experience gained by engineers ($Md = 3, n = 12$) was significantly higher in comparison to that gained by students ($Md = 1, n = 15$). All participants provided written informed consent.

Table 1: Participants' characteristics

		Working Experience (years)			**Previous Experience(0-4)**
Group	n	Min	Max	Mean (sd)	Median
Engineer	12	1	20	7.4 (5.5)	3
Student	15	0	1	0.3 (0.5)	1

2.2. *Procedure*

Each participant attended individually and standardized conditions were applied. To ensure that all participants were provided with the same procedural requisites and information, the moderator´s influence was minimized by using the experiment software OpenSesame v.3.2.6, about which all relevant information was provided.

The participants were asked to work with a sheet metal method in which the content of the method was presented in a six-minute video. A video was chosen to present the training of basic considerations, limitations of sheet metal manufacturing, design and the details of the manufacturing process in a more motivating manner. The time for exploring the content was not limited.

After introducing the method, the participants began with the experiment, which consisted of four steps:

- Pre-survey for previous experience
- Task description
- Task processing
- Post survey for individual approaches

The aim of the task was to develop an optimized bracket angle from an economic point of view, as shown in Figure 1, Figure 2 and Figure 3. The task was to design the bracket angle using a classical manufacturing process that uses two machines with laser cutting and afterwards bending device. This manufacturing process offers possibilities to reduce the costs of the bracket angle. For this purpose, the recommendation in the task was to reduce the amount of parts, the process steps, and the amount of welding joints. The function of the component was to carry a load of 80 kg. The placement of drill holes and the material had to remain unchanged. The task for the participants was to create one or more concepts and to select one final concept after concept generation. The task had to be conducted using pen and paper only.

The moderator was responsible for introducing the experiment at the beginning and recording the whole procedure for analyzing the successful approaches. Recording began when a participant started the experiment and ended when the experiment was finished. The moderator tried to avoid communication with the participants, and questions to the task were not allowed during task processing.

2.3. *Metrics and Data analysis*

In order to identify successful approaches, the participants' concepts were evaluated with regard to manufacturability and manufacturing effort. Therefore, we examine the concepts of high-performer to identify the successful approaches.

The manufacturability and the decrease of the manufacturing effort were defined as goal of the design task. The concepts were qualitatively analyzed and evaluated by two experienced engineers of the industrial partner company. Concepts, which did not fulfil the expected function, were not further analyzed for manufacturing effort. The procedure for evaluating the concepts was: (i) evaluation of the functionality and the details of the design, (ii) evaluation of the manufacturability and (iii) categorization of the manufacturing effort. Two experienced engineers from the partner company evaluated the criteria as follows:

Function fulfilment: The credo behind every product is to fulfil the functions for which it was built. Therefore, in this study the fulfilment of function was chosen as the necessary criterion.

Manufacturability: Manufacturability was used as one evaluation criterion, as it is the reason for many iterations in the design process. These iterations exist mainly because the design is not suitable for the manufacturing process, hence the concept was manufacturable or not.

Manufacturing effort: This criterion can be divided into three groups based on the required cost. On the basis of a preliminary study, the authors asked service providers for suggestions regarding the costs of the most common concepts. Based on the costs, three categories were defined: from a (1) low manufacturing effort category to a (2) medium and a (3) high manufacturing effort for the reference product of the task description.

The participants were grouped in high and low performer based on the two evaluation criteria manufacturability and manufacturing effort. Engineers and students were divided into each high and low performer. For identification of the successful approaches to consider DfM during concept generation, the design concepts and the process of high performer were analysed.

Data Analysis: The metrics were determined for each participant. In order to test the differences between the groups, we used the Mann–Whitney U test. The normality distribution was checked using the Shapiro Wilk test. A p-value below .05 was considered to be statistically significant, and the effect size was calculated.

3. Results

The aim of this research was to examine the successful approaches of experienced engineers and inexperienced students during the consideration of DfM in the design process.

3.1. *Manufacturability and Manufacturing Effort*

The concepts from the task were available as sketches on paper. Two experienced engineers evaluated the 27 concepts, which participants selected as their final design concept. The distribution is as follows: 11% (3 of 27) of the concepts do not fulfill the function, as shown in Table 2. Furthermore, 17% (4 of 24) of the concepts were not manufacturable. Overall, students designed the concepts, which do not fulfill the function and were not manufacturable. Half of the students designed concepts, which were evaluated by the experts as not fulfilling the function or not manufacturable.

Table 2 Comparison of the engineers´ and students` design concepts with evaluation metric

Metric	Eng. & Stud.	Engineer	Student
	% (N)	% (N)	% (N)
No function fulfillment (N = 27 concepts)	11 % (3 of 27)	0	20 % (3 of 15)
No manufacturability (N = 24 concepts)	17 % (4 of 24)	0	33 % (4 of 12)
Manufacturing effort			
low	5 % (1)	8 % (1)	0
middle	50 % (10)	58 % (7)	38 % (3)
high	45 % (9)	34 % (4)	62 % (5)
	100 % (20)	100 % (12)	100 % (8)

Concepts with no manufacturability as examples are illustrated in Figure 1 closed profiles, which are not possible to manufacture with standard tools. Closed profiles (e.g. a triangular tube, see illustration) can not be manufactured using the die bending process, as the sheet metal will collide with the bending tool during the last bend. It is also not possible to bend a tab using this process. The die tool is clamped between the legs. Another problem is that the designs do not guarantee the overbending required for the dimensional accuracy of the angles. Overbending is necessary to compensate for the material-related springback of the sheet metal after the application of force has ended. This springback causes the real bending angle to increase unintentionally. In manufacturing, the inner angle must therefore be smaller than the required angle during the bending process.

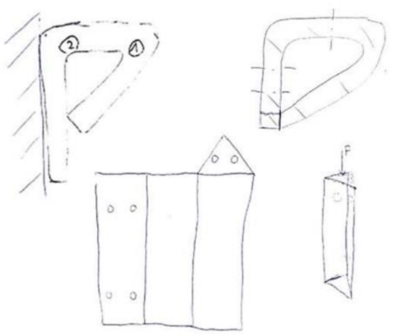

Figure 1 Example of concepts with poor manufacturability

The distribution in the manufacturing effort categories is similar to the overall evaluation. Engineers only designed 8% (1 of 12) of the concepts, which could be evaluated as low, 58 % (7 of 12) as medium and 34% (4 of 12) as high manufacturing effort. Students designed 62% (5 of 8) of the concepts with high manufacturing effort and 38% (3 of 8) with medium effort. Design engineers as well as students designed and selected concepts with an overall medium or high manufacturing effort. The high and low performer in each group of engineers and students were distributed based on the manufacturing effort.

3.2. *Characteristics of Successful Approaches*

Successful approaches in DfM are to simplify the manufacturing with the help of reducing the amount of parts and manufacturing steps. The results show that high-performing engineers have increased the number of bends and concurrently eliminated the welding joints in their concepts, whereas low-performing engineers did not. Successful strategies support to reduce the number of welds and increase the number of bends and therefore show a difference in manufacturing effort.

56% of the design engineers stated that they design with the help of DfM methods when optimizing a component. In contrast, only three students followed a methodical approach for the optimization. The challenges in optimizing the bracket angle that occurred in this experimental study were usually due to a lack of successful strategies.

Therefore, we analyzed successful strategies of design engineers, who cleverly optimized the design completely without welding joints and still fulfill the function. This reduces the number of parts and work processes. A design engineer with more than twenty years of experience, questioned the necessity of the welding joints. In the post-interviews the statement was: “Is this welding joint only for connection reasons or is it involved in the flow of force?” In Figure 2 two concepts of design engineers are presented, which can be regarded as one of the best solutions of the design task. The characteristic of this concept is the separation of contact surfaces and adding the contact surfaces as a bending bracket.

Separation of contact surfaces. The analysis of the approach resulted in four steps:

- Analysis of the initial situation. The design engineer should analyze how the components interact for function fulfilment and distinct functionally relevant and supportive surfaces with the system environment.
- Force flow analysis. Verify the functionally relevant force flow via the contact of components or surfaces and between the force application point and the force dissipation point.
- Reduce the amount of possible paths of force flow to minimum. Eliminate indirect connections (welding joints) and design direct connections (bending joints) to lead the force flow.
- Synthesis approach: split edges and surfaces of the unwinding transversely or vertically. This splits function relevant surfaces into two or three parts. These partial surfaces can then be moved to the welds and redesigned as bending edges.

Accordingly, the force flow now occurs from one function relevant component or surface to another via a direct connection. This principle, if applicable, allows the engineer to dispense with welds in his design.

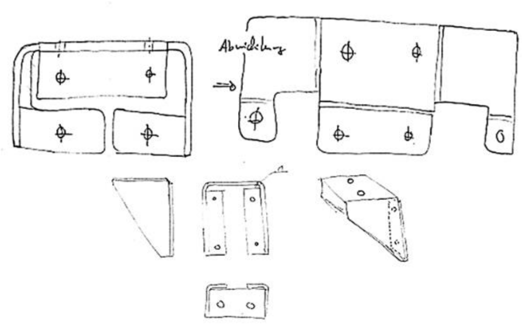

Figure 2 Example of concepts with good manufacturability and low manufacturing effort

4. Discussion

The results show that especially the students have problems to create concepts, which fulfill the function and can be manufactured with a low manufacturing effort. The participants did not consider the bending manufacturing process, the available bending tool, the overbending required to maintain the angular dimensions and possible collisions during the process. Only 67% of the students could design concepts, which could be manufactured. Even only 8% of the engineers were able to design low manufacturing effort concepts.

Furthermore, the current design method, as mentioned in the post-interview do not effectively support the engineer while considering manufacturing during design. The main objectives of DfM and the manufacturing possibilities in the context of sheet metal design (SMD) have resulted in restrictive design methods. The restrictive methods define the limitations of manufacturing processes, and provide design considerations to enable manufacturability [1]. Whereas, the successful approaches are implemented in an opportunistic method for DfM, adopted from additive manufacturing, which emphasize the unique capabilities of manufacturing processes [20].

Restrictive characteristic. These considerations help to enable manufacturability for engineers in the early stage of the design process. Table 3 presents the groups of restrictive limitations for sheet metal design: (R1) constraints that result from the manufacturing process. The design engineer must pay attention to the tolerances that are passed on with each bend, so that it is necessary to adapt the idea if necessary. Another set of constraints is collision due to design complexity (R2): as the complexity of a part increases, the part may also collide with itself, the tool or other machine parts. Under the group limitations concerning detail features (R3), constraints are collected that affect the detail design features. For example, the minimum bend radius increases with increasing material thickness. In addition, the engineer must also consider the materials to be used and their properties in the material characteristic restriction group (R4).

Table 3 Summary of restrictive sheet metal design concepts

	Design for sheet metal
R1	Limitations and inaccuracy due to manufacturing process
R2	Collision during manufacture due to design complexity
R3	Limitations concerning detail features
R4	Material characteristics

In summary, the results highlight that only 67% of students were able to design concepts, which consider the manufacturability. Furthermore, the manufacturing effort of the concepts has to be improved. These findings confirm those in the field of additive manufacturing, which showed that the restrictive method did not support to reduce the manufacturing effort of the design concepts of the students [13]. Although this is a more expected outcome, the results indicate the need for further development of the method. Taken together, these findings can be transferred to various manufacturing processes and contribute to the optimization of DfM methods.

A method has been developed to support sheet metal design. The method is published and can be accessed online here [23]. Therefore, we present four strategies in context of the sheet metal manufacturing process to exploit the potential of the manufacturing process, as shown in Table 4. One of the successful approaches and strategies is therefore, the surface separation, as shown in Figure 3. The strategy helps to simplify sheet metal components. For this purpose, surfaces of an existing sheet metal component are divided and combined with other surfaces. This stimulates creativity and creates new concepts. By splitting the surface, which is responsible for the force flow, here screwed to the wall, the bracket angle could be made from a single edge and only with bends to the desired shape. It can be assumed that this successful design is largely due to experience. The methodical strategy behind it, step by step from a welded construction to a single bending component can be transferred to the general sheet metal design process necessary to be implemented in a design method.

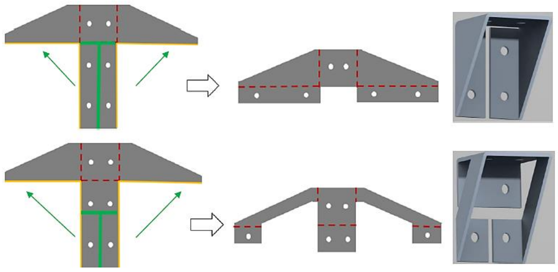

Figure 3 Synthesis step of the O1 opportunistic method: Surface separation

Table 4 Opportunistic strategies for sheet metal design

	Design for sheet metal
O1	Use manufacturing potential for part consolidation
O2	Inspiration in design potential for functional integration
O3	Lightweight design capabilities
O4	Savings for subsequent joining steps through smart joining techniques

First opportunistic strategy is the reduction of parts (O1), which is currently underutilized. In the group of (O2), the contact and channel approach, a method for concept generation based on abstraction, is included. The required component is reduced to its function and contact surfaces [21,22]. The group of (O3) summarizes methods of sheet metal design that are interesting for lightweight design. Savings can be achieved in (O4) with subsequent joining steps through smart joining techniques.

In summary, a method has been developed that can increase the capabilities of the restrictive methods of DfM with opportunistic approaches [23]. With the help of this opportunistic method, further training materials can be created, which provide support for necessary cognitive skills in conceptual development.

Limitations of the experimental study were, that the task was comparatively easy with only one function, a small amount of parts, and no complicated system. The cognitive ability of pre-thinking the bending sequence was minimized by mainly a maximum of three to five bends. Therefore, further research must explore the effect by transfer tasks, which are more complex. Another limitation could be the duration of the task, whereas no time limits were applied in this study. Therefore, future research needs to examine the effect of the duration of the design task on the quality of concepts.

5. Conclusion

The aim of the research presented in this paper was to investigate the successful approaches of experienced engineers and inexperienced students during the consideration of DfM in the design process. Not only students, but also experienced design engineers were mainly not able to design low manufacturing effort concepts. Hence, still challenges exist in the considering of manufacturing during design, especially for manufacturing effort and manufacturability. Therefore, we analyzed successful approaches of design engineers, who cleverly optimized the design and still fulfilled the function. Furthermore, the successful approaches, as for example the surface separation, are implemented in an opportunistic method for DfM, adopted from additive manufacturing, which can be transferred to further manufacturing processes.

In a further experimental study, it would be interesting to investigate in the comparison of restrictive and opportunistic methods.

Acknowledgements

In particular, the authors would like to express their appreciation to all those involved, without whose help this research would not have been possible, and to TRUMPF GmbH + Co KG, Ditzingen, Germany, for their support and funding of this project. The authors wish to thank various people for their contribution to this project; Mr. Dipl.-Ing. Jörg Heusel and Mr. Thomas Bronnhuber, for their valuable technical support on this project and especially Mr. M.Sc. Jonas Steiling for his patient guidance and for the many discussions on the content-related tasks and for his help in collecting the data. The research reported in this article was carried out with the agreement of all participants.

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