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Data-driven support for CAD parts modelling based on automated estimated production planning – approach and user research

Martin Erler [1], Sebastian Langula [1], Christian Wölfel [1,✉], Julia Schneider [1], Christiane Kunath [1] and Michael Königs [2]

[1] Technische Universität Dresden, Germany, [2] FVP Aachen, Germany

✉ christian.woelfel@tu-dresden.de

Abstract

We present a data-driven approach to support decision-making in CAD modelling and to improve design for manufacturing. Based on automated estimated production planning, information is provided on possible design actions and their impact. A study was conducted on perspectives on and visualizations in CAD modelling. Requirements for a user interface of the described support system were identified. The results serve as basis for further research and development on the interaction of engineering designers with data-driven decision-making support in CAD modelling.

Keywords: design for x (DfX), data-driven design support, decision making

1. Introduction

Designers play a special role in the product development process, as up to 85% of all follow-up costs are determined during the design phase (Ehrlenspiel and Meerkamm, 2017). For example, recognising a design that is not suitable for production at an early stage can reduce the costs for the entire product with little effort. Although Design for manufacturing design is taught as one of the basics in mechanical engineering studies, the actual requirements in this regard in real operations are significantly more extensive and complex. In addition, manufacturing technologies and processes are constantly evolving. The acquisition and application of process knowledge in particular places high demands on a person's planning skills. The previously linear planning approach is increasingly being replaced by an iterative approach with a growing number of alternative manufacturing processes. This expands the necessary manufacturing knowledge by numerous dimensions, as the focus is no longer just on the application of a specific process, but must also take into account the consideration of how this part can be manufactured most efficiently. This requires extensive knowledge of all relevant manufacturing processes. In addition, the growing number of manufacturing processes increases this problem (Deneka et al. 2010). The existing company processes – in particular the classic CAD-CAM chain – no longer fulfil these requirements (Matta et al., 2010). Large companies with global value chains began to counteract these developments years ago. However, the measures selected for this purpose are generally not available to SMEs.

The CNC machining of parts, the feasibility, achievable quality and associated costs, for example, do not only depend on the component geometry and production features. Rather, there is a field of tension between component geometries, production features, specific machines and tools, materials as well as production quality and costs (Yeo et al., 2021). This often requires time-consuming production planning by highly qualified and experienced personnel. Despite digital systems, the processes currently in use are often time-consuming to parameterise and configure manually. The specialisation of specialist areas leads to constantly increasing demands on skills (Mandolini et al., 2020). Companies and development teams must fulfil these requirements in order to remain competitive. However, the typical design engineer in an SME is often employed as a generalist and cannot fulfil this role. As a result, there is a risk that the smaller batch sizes typical of SMEs will become increasingly uneconomical. The intrinsic advantage of SMEs – their flexibility and cost-effectiveness even with small batch sizes (Zhou, Chen and Xie, 2007) – is in danger of being lost due to a design that is not production-orientated and the associated increased production costs.

2. Theory

2.1. Data-based solution approach

In order to equalise this impending competitive disadvantage, a process is to be developed that enables designers to carry out the design in a production-ready manner. To this end, the technological foundations for a data-based assistance are being developed. This provides information on the impact of design decisions on the production-process based on automated work preparation. This information is processed and visualised in such a way that the designer can assess the possible actions and their effects in combination with the design requirements for the component and find a solution that is more suitable for production.

Algorithms for predictive production planning of CNC components already exist for forecasting production costs (Niazi et al., 2006). Many of the algorithms used work on the basis of surface models and only roughly calculate production costs using the chip volume (Al-wswasi et al., 2018) or estimate the efforts by comparing the designed part with similar ones from a database (Zhang et al., 2009). However, these approaches have technological limitations in terms of its fidelity to the actual manufacturing process, with corresponding consequences for planning based on it or lead to excessive efforts on maintaining a database, which then still can only be used to interpolate. New parts with cannot be evaluated, if no similar part is found. A promising approach addresses the problem by determining manufacturing costs comprehensively on the basis of data. This includes both the CAD data of the component geometry and the parameters of the machines, tools and materials (Langula, Erler and Brosius, 2023; Erler, Koch and Brosius 2023; Erler, 2018).

By using discrete data models, production-related machining features are recognised and the associated planning data calculated. The basis for this is formed by real machining tools and their actual possible engagement kinematics. This results in realistic production areas and operations. Subsequent operation sequence planning, taking into account the clamping required for the respective work step and the machine tools suitable for production, automatically creates a production plan and provides the data required for downstream processes, such as main and auxiliary times, tool lists or production resources. This approach can be applied to all kind of cnc parts regardless of shape, size or material. In particular, the challenge of variant evaluation, which has rarely been considered to date, is to be addressed. The underlying model enables not only the mapping of technical and technological restrictions, but also an economic evaluation of different work sequences. The expert manufacturing knowledge otherwise provided by the planner can be applied digitally and thus made accessible to optimisation methods and heuristics. For example, the selection of the operation sequence plan can be pareto-optimal and situation-specific.

The automation of production planning offers considerable potential for improving the competitiveness of companies. The significant reduction in the efforts of estimating production cost through automation is accompanied by more accurate planning through the use of a standardised basis (Li et al. 2018). Compared to established processes, the following advantages that feature important properties of robust production systems (Stricker and Lanza, 2014) can be concluded for automated production planning:

- High accuracy of the data basis
- Reproducibility of the results
- Transferability of the calculation procedure through standardisation of the
- planning process

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- Decoupled from typical human fluctuations in work quality
- Work planning and determination of planned times
- Automatic documentation
- Implementing and interacting with the information in the design process.

A suitable user interface must be developed in order to incorporate the described approach into the workflows and working environments of designers. This should provide the designers with the relevant information they need to make design decisions regarding the component geometry. The aim is not just to address basic manufacturability. Rather, the aim is to offer an assistance system that provides data-based, real-time analyses of the status of the component geometry with regard to production quality and costs. The data of the component geometry is processed with that of the material, machine tool and tools in a learning algorithm. The approach provides a preliminary production plan. Costs and quality can be estimated in conjunction with this. Component geometry can be set in relation to the resulting production features.

In addition, situation-specific recommendations for action and support measures, which are provided in close relation to the current planning task, harbour enormous potential for making day-to-day work in interdisciplinary teams smoother and the entire product development process more efficient and reactive. In this context, the approach pursued here has the following advantages:

- First-Time-Right: The ability to evaluate design and planning decisions in advance enables the proactive avoidance of planning errors and time-consuming iterations throughout the product development process.
- Utilisation of existing capacities: The properties of different production resources such as machines, devices and tools can be taken into account during the design phase.
- Transparency: Thanks to a continuously expanding knowledge base, cause-and-effect relationships can be learnt with little effort and taken into account in future planning.
- Direct industrial applicability: The project will generate new findings on evaluation and analysis methods, in particular for the a priori determination of production times and production costs. At the end of the project, these will be prepared in the form of a guideline and made available to a broad community of interested parties
- Not a system for experts: The intuitive presentation and utilisation of recommended actions in CAD and CAM software demonstrators are suitable for quickly training untrained personnel. This is important in the context of demographic change and the rural-urban migration of potential junior staff, which SMEs have to deal with, especially in rural regions.
- Intuitive operability: It should be possible to provide the effects in parallel to planning and in the planning tool provided for this purpose. To this end, new visualisation and user guidance concepts are being developed that represent unique international selling points and are also provided in the form of guidelines. These should enable SME software houses in particular to adopt the concepts developed in their system landscapes.

The project can make a significant contribution to meeting the ever-increasing pressure on staff qualifications. The planned methodology will enable the designer to effectively influence the design in terms of manufacturability during the design process. At the same time, the central formalisation and provision of technical manufacturing knowledge offers considerable savings potential for training and further education – a cost factor that should not be underestimated, especially for SMEs.

The requirements, parameters and consequences of component design are not only diverse, but complex in many respects: they are numerous and often opaque to the designer, they are interlinked, sometimes contradictory, and they are dynamic in that they can change depending on the manufacturing process and system, but also depending on any manipulation of the component geometry. From the designer's point of view, however, the component geometry is initially defined by the technical function, interfaces, force flows, etc. – manufacturing aspects are only part of all requirements here (Bender and Gericke, 2021). The goals, competences, experiences, mental models and conventions of the designers must therefore be taken into account when designing the user interface of the new assistance system (Cross, 2004; Casakin and Badke-Schaub, 2015) if it is to be used successfully (cf. e.g. DIN, 2018; DIN 2020).

In order to be able to use the underlying approach to assist the designer, the information must be categorised, related, prioritised and, on this basis, prepared and presented in a cognitively and physiologically ergonomic manner. On the one hand, classic software ergonomics requirements (see DIN EN ISO 9241, in particular parts 11, 110; DIN, 2018; DIN, 2020), but also the conventions of established CAD user interfaces and designers' mental models. In addition, non-instrumental aspects of user interaction should be designed with equal attention, as they directly influence motivation and acceptance, which in turn ensures the quality of the designers' work results (Wölfel and Krzywinski, 2019; Thüring and Mahlke, 2007).

In order to design the user interface appropriately, requirements and solution approaches are collected and evaluated in an iterative process with practising designers as part of empirical user research.

The fundamentals and requirements for human-technology interaction in CAD systems are analysed with a special focus on conventions and trends in visual communication in PEP. This is associated with an in-depth determination, systematisation and evaluation of general and special requirements on the basis of standards, norms and guidelines specific to the technical system and the target group (designers with at least five years of professional experience). In addition, typical specialist knowledge, mental models and procedures in design (design problem solving) are considered and included in the analysis and determination of requirements.

The information to be communicated in the user interface is transferred into a system that ensures the ergonomic and reliable communication of possibilities and consequences of individual decisions and options for action (e.g. quality losses or cost drivers on the component). The basis for the development of the user interface is a user-centred systematisation, categorisation, prioritisation and presentation of information for adaptive visual communication.

A scalable, specific principle solution for information communication for typical CAD systems is derived and developed on the basis of the requirements identified and the conceptualised system for the visual communication of processed information. Based on the principle solution, individual elements are developed for the complete representation of typical use cases for test tasks for different scenarios of production possibilities.

3. Methods

An online survey was conducted to identify basic requirements for such a solution.

3.1. Design

The survey was divided into two main parts: individual perspectives on CAD modelling in engineering design and use and understanding of visualizations in CAD software. For perspectives on CAD modelling it was aimed to collect information on the basic understanding of consequences in manufacturing. Questions were designed to find out, what construction employees look out for that might affect the process of manufacturing and what they mostly ignore in the construction process. With these questions it was intended to gain insight on where an assistance system should give more or less feedback or where it could and should focus on. Answers were collected in percentages or 6-Level Likert Scales. For the Visualizations in CAD software part, possible graphic components of an assistance system where designed. It was aimed to screen possible components of an assistance system and how possible users think it would suit the systems aims. They were then rated regarding familiarity, visual appeal and informational value on a 6-Level Likert Scale. In addition to that, the following demographic variables were collected: professional experience, field of work, company size, manufacturing experience.

3.2. Sample

The sample consisted of N = 7 participants. They were specifically chosen as experts in CAD modelling with complementing expertise in design for manufacturing. This specific sample was selected, because it was necessary to probe where problems can arise in the manufacturing process with CAD models. Employees in development departments are not necessarily aware of such problems and would not be able to give sufficient inside. The participants were acquired within companies who are involved in the

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project. They did not receive additional compensation for their participation. Most of them (72 %) work in engineering service companies. The other 28 % were contract manufacturers or the "others" category. The company sizes ranged between 10 and over 150 employees, although 72 % of the participants worked in a medium-sized company with 10–49 employees. All participants were male and had a mean professional experience in CAD constructions of 11 years (SD = 8.23, min = 1 year; max = 20 years). 14 % of them have experience only in redesign, 29 % only in new product development, whereas the majority of 57 % have experience in both.

3.3. Materials

For the visualization part of the survey, stimulus material was designed. It consisted of different data visualizations each containing specific system information which could have an impact on manufacturability. A total of seven visualizations were created containing the following representation types: combi chart circle and bar, bar chart, 3D Graph, network chart, tree chart, component with information labelling. All used visualizations can be reviewed in figures 1 to 3.

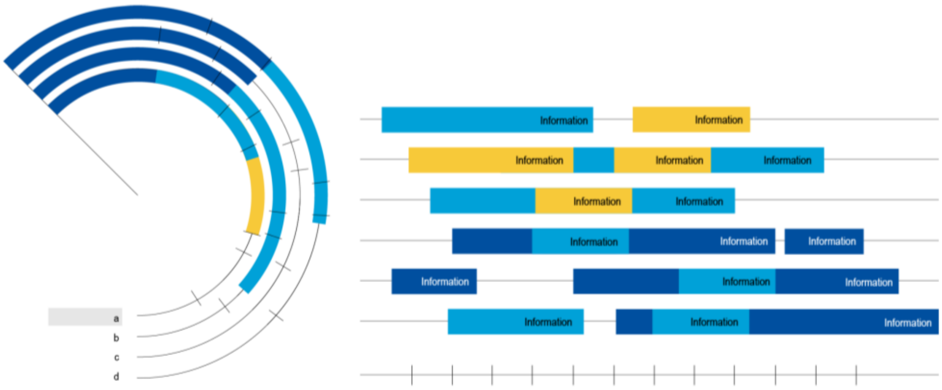

Figure 1. Left: combination bar and pie chart; Right: bar chart

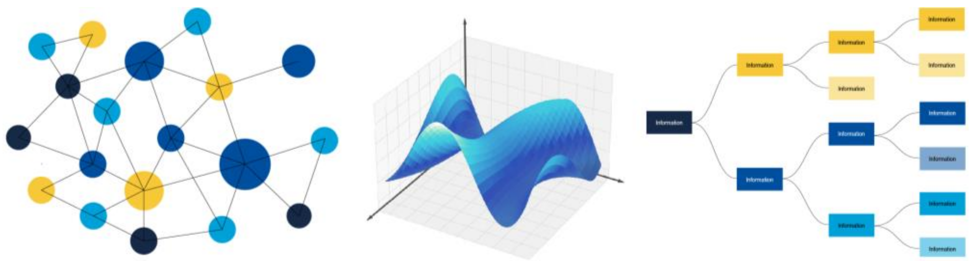

Figure 2. Left: network chart; Middle: 3D graph; Right: tree chart

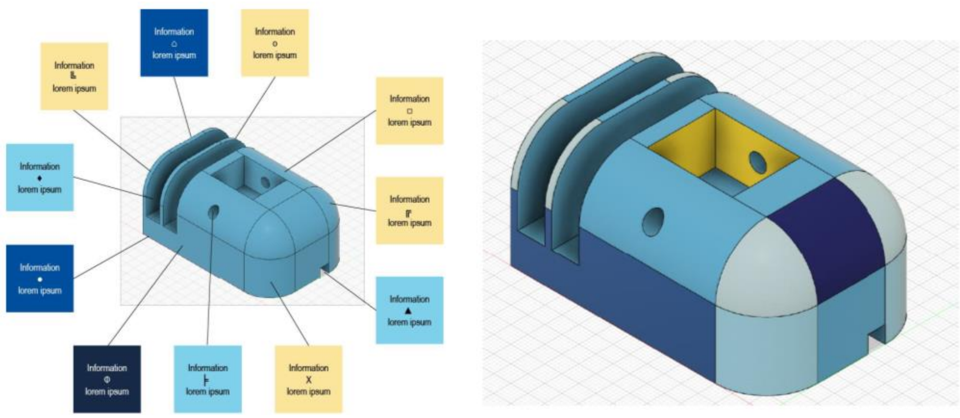

Figure 3. Left: component with information labels; Right: Component with colour coding

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3.4. Procedure

The online survey was conducted using SosciSurvey. Participants completed the questionnaire using their work Laptops in their work surroundings. They received background information about the project aims and partners. They were instructed to answer all questions considering the context topic context milling of metal materials. Then questions regarding part 1: individual perspectives on CAD modelling. After that, the visualizations with respective questions were presented at random to prevent any sequence effects. At the end, the demographic questions were answered. Participants were also given the chance to give additional feedback to the project. The whole survey took about 10 to 15 minutes to complete.

4. Results

4.1. Perspectives on CAD modelling

For individual perspectives on CAD modelling it was aimed to collect information on the basic understanding of consequences in manufacturing. Questions were designed to find out, what construction employees look out for that might affect the process of manufacturing and what they mostly ignore in the construction process. Results show, that participants only have an average of 36.00% (SD = 16.41) of the components geometry in mind when they start modelling it in CAD (figure 4). They also think, that their modelling decisions influence follow-up costs to a large degree (mean = 78.14%; SD = 12.54; figure 4).

The experts were also asked about their awareness of certain parameters during their modelling process. All of those parameters all can be reviewed in figure 5. Low values arise for the manufacturing time (mean = 3.00; SD = .53) and cost (mean = 3.57; SD = 1.29), as well as the negative form (mean = 3.57; SD = 1.18). Middling values where found for tool change (mean = 4.41; SD = 1.64) and complexity (mean = 4.43; SD = .90). The highest ratings could be revealed for functional (mean = 5.86; SD = .35) and manufacturing requirements (mean = 5.43; SD = .73), manufacturing quality (mean = 5.00; SD = 1.31), as well as material (mean = 5.43; SD = .49).

In figure 6 the ratings to what degree participants pay attention, how certain modelling decisions influence manufacturing parameters, are presented. The questions referred to necessity of respanning (mean = 4.71; SD = 1.03), suitability to material (mean = 5.43; SD = .49) and manufacturing machine (mean = 4.71; SD = 1.16), as well as accessibility to the tool (mean = 4.71; SD = .88). All reached middling to high values larger than 4, with the highest rating for the suitability to material.

The last question of part 1 was asked to identify whether or not participants think, that it would help users with their CAD models, if production planning information would be available. The rating on that question received middling to high rating with a mean = 4.86 (SD = 0.64; figure 7).

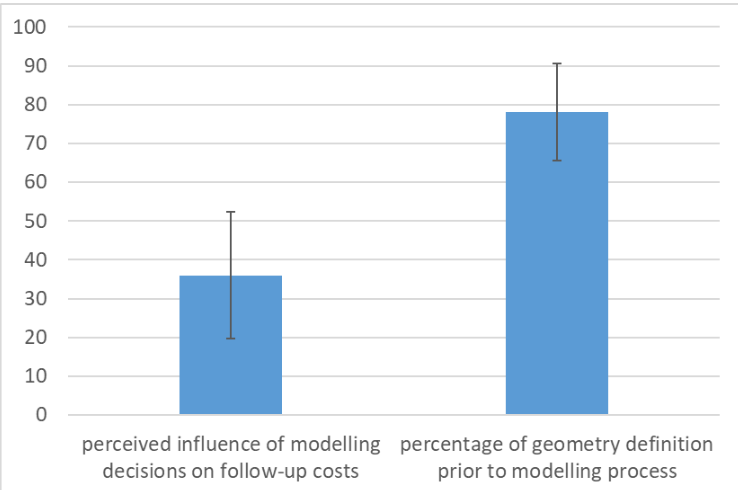

Figure 4. Left: Perceived influence of modelling decisions on follow-up costs; Right: Percentage of geometry definition prior to modelling process. N = 7, error bars = standard deviation

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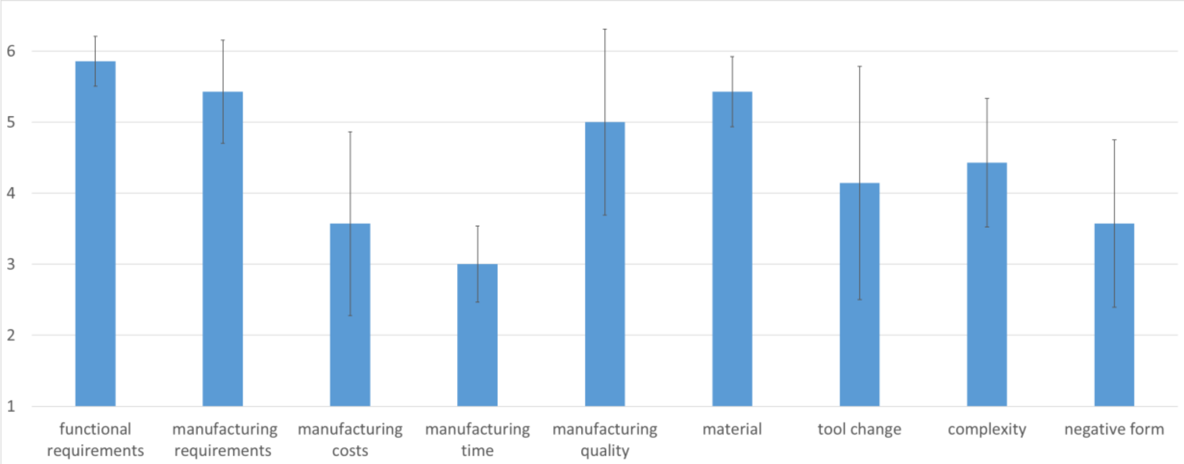

Figure 5. Awareness about different parameters during CAD modelling process; N = 7; error bars = standard deviation

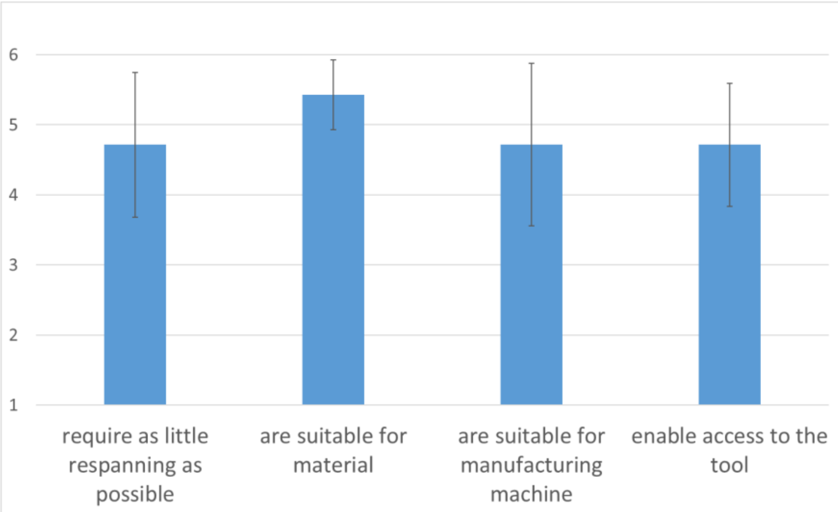

Figure 6. Modelling decisions influence on manufacturing parameters; N = 7; error bars = standard deviation

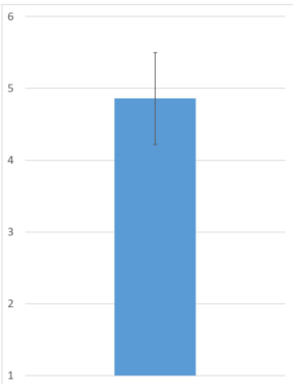

Figure 7. Helpfulness of accessible production planning information; N = 7; error bars = standard deviation

4.2. Visualizations

For the second part of the survey, participants rated different visualizations regarding familiarity, visual appeal and informational value. In figure 8 ratings of the visualization types are presented alongside

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each other for comparability. For familiarity, all visualizations were rated between 3.5 and 5 indicating that no visualization is completely new to the participants. However, highest ratings were achieved for tree charts (mean = 5.00; SD = .53) and the component with information labelling (mean = 4.86; SD = 1.73). The visualization with the lowest familiarity is the 3D graph (mean = 3.86; SD = 1.81). Interestingly, the highest rating in visual appeal were achieved for the most familiar visualizations: tree chart (mean = 4.71; SD = .45) and the component with information labelling (mean = 5.29; SD = .45). The lowest rating was the 3D graph (mean = 2.43; SD = 1.05). Middling values were found for the network chart (mean = 3.14; SD = 1.25), the combination of bar and pie chart (mean = 3.29; SD = 1.28), bar chart (mean = 3.57; SD = .73) and the component with colour coding (mean = 3.86; SD = 1.55). For information value highest ratings were given again to tree chart (mean = 4.86; SD = .99) and the components with information labels (mean = 5.43; SD = .49). All the other visualization received middling values for this variable.

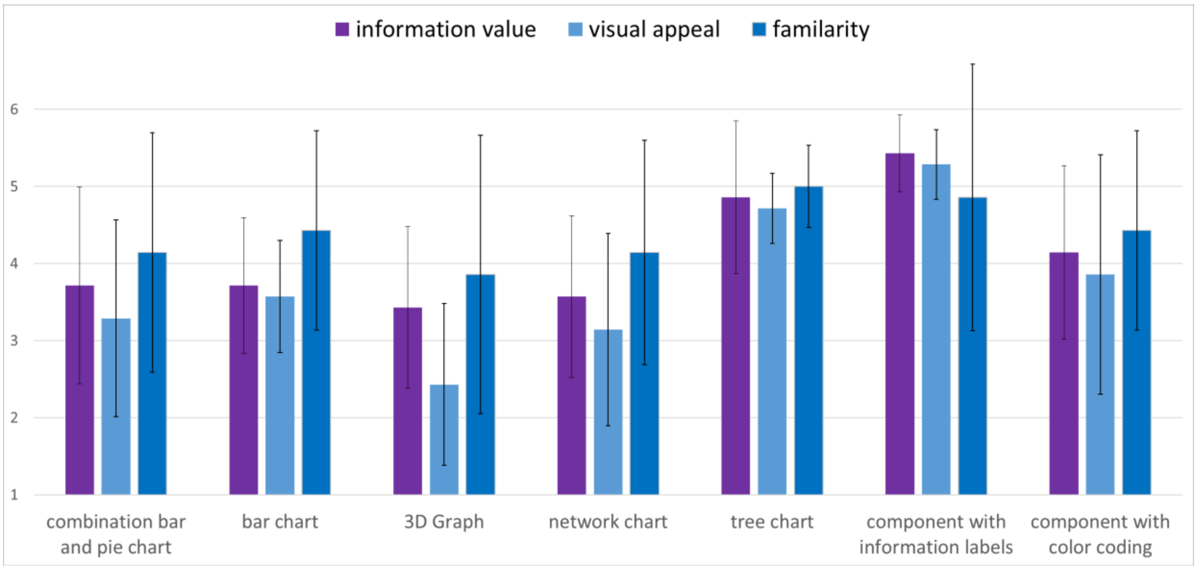

Figure 8. Information value, visual appeal and familiarity of all visualizations; N = 7, error bars = standard deviation

5. Discussion

5.1. Perspectives on CAD modelling

Results show, that participants believe they have a great deal of influence on manufacturing and that they can model for manufacturing. They also think, that their modelling decisions influence follow-up costs to a large degree. However, when asked more precisely about parameters like costs and time, it becomes clear that they are not able to estimate this accurately. An assistance system could and should provide useful information on these factors to enhance insight into these two variables. For some of the parameters the standard deviation is also rather high, indicating that the participants are not always of one opinion for possible parameters of a CAD assistance system. For example, the awareness during CAD modelling about tool change in production ranges between all possible options 1 and 6. This indicates, that some of the experts do think about tool change while modelling, some don't. Similarly high standard deviations were revealed for manufacturing costs, quality and negative form. All differences are also presented visually in figures 4 to 8 using error bars. Similar observations were conducted for the modelling decisions on necessity of rechunking and the fit to the machine specifications. Hence, an assistance system should include information about these conflicting opinions with possibilities of personalization. However, future research should provide data on whether a self-assessed high rating on a parameter, for example tool change, really lead to a CAD model that is better adapted to tool change or not. It should also be possible to adapt the system to factors that are specifically important for a certain project if needed. Overall, results indicate, that the least need for support is

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required for the parameters of functional requirements and material as well as modelling decisions on suitability of the model to the material.

At the end of part 1 a question was posed to identify whether or not participants think, that it would help users with their CAD models, if production planning information would be available. This ultimately contributes to the question, of whether or not an assistance system would be wanted or helpful in the context examined. The rating on that question received middling to high rating. The low standard deviation indicates unity amongst the participants regarding the need of such an assistant system.

5.2. Visualizations

The most prominent result for the second part of the survey is, that the tree chart and the component with information labels were rated highest on all three of the variables familiarity, visual appeal and information value. It was found that if visual appeal ratings are low, it does not necessarily mean, that participants think their information value is low. For the next evaluation in the present project, visualizations should not be excluded because of a lesser visual appeal if the information it transfers is high. Overall however, the component with information labels should be preferred over the component with colour coding. Also it appears that experts in CAD modelling prefer clear, unambiguous presentation methods that can be grasped at first glance. Accordingly, three-dimensional graphs should be avoided for the system.

6. Discussion and outlook

The results are far from being representative for engineering designers and CAD modelling professionals across branches, company sizes or regions. The sample of the study is just large enough to allow for descriptive statistics. A much larger sample as well as an adopted study design would be needed to provide significant results that can be generalized to broader CAD modelling cases. However, the results may give guidance for the development of principal solutions for an expert user interface that assists engineering designers during part modelling in CAD systems. One core finding is that all CAD modellers considered themselves to be paying regard to design for production. However, from a production engineering perspective, the CAD modellers consider general technology-specific manufacturability (e. g. for milling). But they do less consider underlying aspects of production planning such as necessary tool changes or resulting cost or quality issues. This gives guidance on the further development of a respective assistive system for the said target group.

There is common sense among many usability experts on the value of evaluations with small samples, most often referring to Nielsen (2001, cf. Virzi 1992). While Nielsen's position that '5 users' is enough may only be valid for specific settings (e. g. homogenous user groups, cf. Caulton, 2001) and non-standardized measurements, it is widely followed as it mirrors practical experiences of usability experts in corporate settings. However, in scientific terms sample sizes must be well considered or even calculated based on study designs G-power analysis. Study described here aimed at informing decisions in a systematic development of an assistance system for CAD modellers. In further research and development on the implementation, visualisation and interaction in engineering CAD modelling, more refined mock-ups and prototypes will be evaluated in more rigorous empirical settings. Based on the current state of the research, different user interface designs are designed that will be evaluated in another online expert assessments with more refined stimuli as well as based on a larger number of participants. This will allow for further elaboration of the user interface that is planned to be assessed in a quasi-experimental setup, where professional CAD modellers conduct standardized tasks using a click dummy of the assistive system. The implementation of standardized usability and user experience evaluation scales will allow for a reliable study design and robust findings. However, the expected results will only be valid for the investigated case, while generalizations will need to be discussed.

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