ON THE DEVELOPMENT OF VISUALISATION CONCEPTS AS TOOLS IN PRODUCT DESIGN

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Abstract

Visualisations as tools for product design are very useful in supporting engineers in their tasks. Product design is a complex task and features interdisciplinarity and communication across departments. Visualisations can help to increase product design performance under these challenges.
The integrated PKT-approach for developing modular product families, Radikal Forenkling via Design or Complexity Management by DSMs and Node-Link-Graphs are just a few examples of methods for product design that utilize visualisations as important tools for design support. Much research has been done in order to develop such visualisation concepts and on how these can be used in engineering design.
In this paper however the focus lies on how design researchers proceed when developing a visualisation concept meant as a tool for engineering design, what problems they encountered and what need for support they have for the development of the visualisations. Fourteen cases of PhD projects at three universities have been analysed by document study and interviews. The results build a foundation for a future support that can help to develop effective visualisation concepts as tools in product design.

Keywords: Visualisation, Product modelling, Design methods, Human behaviour in design, Research methodologies and methods

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1 INTRODUCTION

1.1 Research Object

Visualisations as tools for product design provide very useful support for engineers. Mortensen states that visualisations are "an obvious strength in any design tool or method" and that "very little research has gone into the visualisation of modular architecture concepts" (Mortensen et al., 2008, p. 220). Krause et al. put visualisation as the central strategy in the integrated PKT-approach to enable teamwork in workshops and problem analysis (Krause et al., 2013). Beyond visualising product structures, visualisations often show additional factors, such as requirements and production concepts. Many product development methods have visualisations as major tools within their procedures to assist analysis, communication and solution finding. DSM-based methods (Eppinger and Browning, 2012) and Radical Simplification (Mortensen, 2012) are examples. Figure 1 portrays their general look and use.

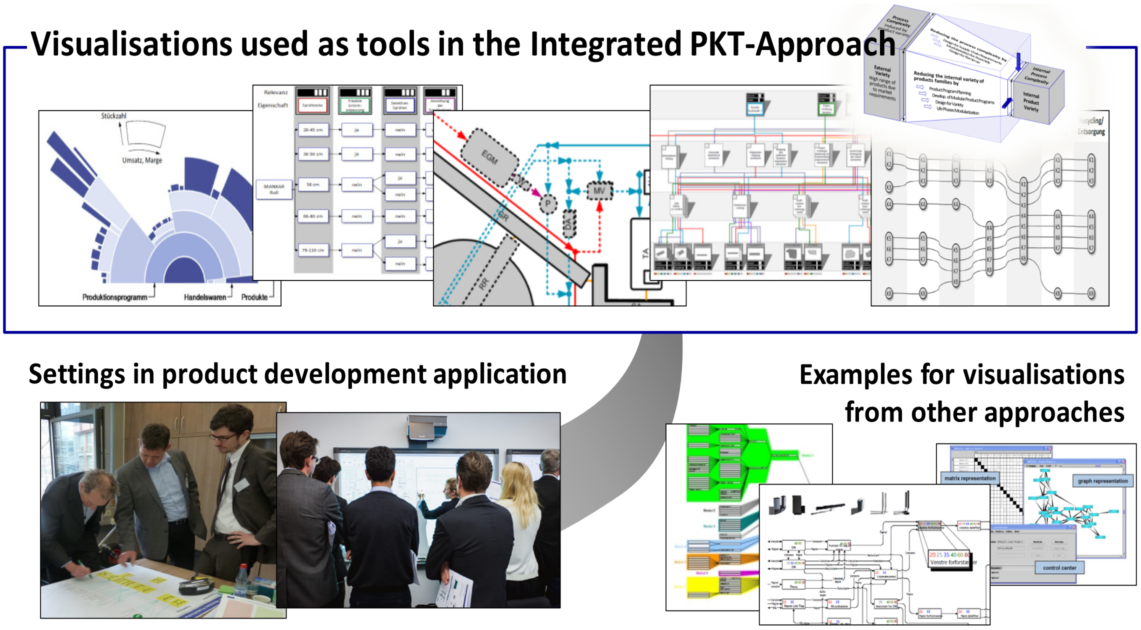

Figure 1. Examples of visualisations as tools in product design (Krause et al., 2013; Bruun and Mortensen, 2012; Lindemann et al., 2009)

In this paper, a visualisation is understood as a simplified, abstract and static graphical representation of products and their families, programs, structures and properties or behaviours for the purpose of supporting product design. A more detailed disambiguation of visualisation and other main terms is given in Section 2.1.

The researchers who developed these methods adopted, adapted or designed visual tools and incorporated them into their proposed methodical proceedings. People developing and improving product design methods are often researchers, consultants, process developers and even product developers themselves. The visual tools have a great impact on the applicability and acceptance of the methods since they are important user interfaces and a major representation of the specific method. A visualisation might not suit engineer expectations or conventions because of its graphical design and coding. It might jeopardize the whole application of an engineering method that could have been a helpful methodical approach. Previous studies have shown that even small differences in the graphical design of a visualization used as a tool in engineering design have a significant impact on its performance in product design practice (Gebhardt et al., 2014).

The aim of this work is to identify and describe how design researchers proceed when developing a visualisation concept meant as a tool for engineering design, the problems they encounter and the need for support they have for future development of visualisations.

1.2 Research Objective

By literature study and interviews in industry the main influencing factors on the design of the visualizations in practice have been analysed (Gebhardt et al., 2014). This paper now presents a continuative study on the following research questions:

1. How did people proceed when designing concepts for visualizations?
2. Did they include the influencing factors that had been identified in previous work (listed in Section 2.5, ref. to Gebhardt et al., 2014)?
3. Which needs exist to support the development of a concept for a visualisation as a tool in product design?

The aim of this work is to derive the needs, requirements and conditions to develop future support to guide method developers through the process of designing a visualisation concept that will provide an efficient tool in engineering design methods.

The research questions and approach are shown in Figure 3.

2 LITERATURE REVIEW AND PREVIOUS CONTRIBUTIONS

2.1 Clarification

In engineering, **visualisations** are mainly referred to as visual representations of products and product data. Research in information visualisation defines the term as a creative process of establishing a graphical representation (Schumann and Müller, 2000), (de Lange, 2006). Social science is more oriented towards representations as boundary objects (Dick, 2006), i.e. objects that members of different groups (e.g. company departments) can use to interact and communicate (Star and Griesemer, 1989). Boundary objects are understood by all participating groups and contain all relevant information.

For this work, the term **visualisation** is defined as a simplified, abstract and static graphical representation of products and their families, programs, structures, properties or behaviour to aid product design. The scope is limited to modular product families. As shown in previous work, the terms used with visualisations are not consistent while meanings remain standard (Gebhardt et al., 2014). Therefore, the following working definitions were made.

A **visualisation concept** is the schematic idea of a visual coding of a visualisation that is a purpose-oriented visual support for particular steps in engineering. It consists of one or more visual principles and techniques. A **visual principle** is a general type of visualisation, e.g. a matrix, a node-link, a rendering, a bar plot or a sketch. A **visual technique** is a visual coding that is used for an entity of data or information, e.g. colour, position, shape, size, text or icons.

2.2 General Fundamentals on Data and Information Visualisation

The research field of Data and Information Visualisation provides fundamental knowledge about how to use visual representations as tools in a product design context. Important work in this field has been presented in (Ware, 2004), (Bertin, 2010), (Tufte, 2001), (Spence, 2007), (Shneiderman 1996), (Schumann and Müller, 2000), (Lengler and Eppler, 2007), and (Duarte, op. 2008). They integrate fundamentals of human sight and perception, visual processing, interpretation of colour, shapes, patterns, icons, gestures, data and graph types, graphical coding, validity of visualisation and interaction with visualisations. Importantly, some of these authors created guidelines and rules for designing visualisation concepts.

2.3 Product Visualisations used in developing modular Product Families

Many methods that support product design incorporate visualisations. Each method proposes visualisation concepts guiding representation of product data and further aspects.

Examples are (Tjalve et al., 1979), (Kusiak and Huang, 1996), (Sahin et al., 2007), (Harlou, 2006), (Mortensen et al., 2008; Mortensen, 2012), the Interface Diagram by (Bruun and Mortensen, 2012), the Integrated PKT-Approach (Krause et al., 2013), the DRed software (Bracewell and Wallace, 2003), the Design Structure Matrix (Eppinger and Browning, 2012), LOOMEO (Lindemann et al., 2009), the 3D-MECHGRAPH (Diehl, 2010) and SOLEY (Kissel, 2014).

2.4 Research Work on how to visualize

Because of the potentials of visualisations as tools in product design, many authors analysed their **functionality within this context**. (Römer et al., 2002) analysed the use of sketches and physical models in early design stages, and reveal their prominence in providing external information storage and external aids for e.g. solution finding, testing and communication. Maier et al. describe the role and effectiveness of product models and modelling as used in design - recognizing visualisations as models (Maier et al., 2014). Dick studies the use of visualisations in solution finding in practice and experiments and derives a description model of aims, activities and visualisations ("models") used in product design (Dick, 2006). Henderson describes the role of visual representations and computer graphics in design engineering (Henderson, 1999). Other authors provide **guidelines on how to design visualisation concepts**. Tjalve provides a work sheet collection style book that guides the designer through choice and design of drawings and illustration, and embeds these steps into design activities (Tjalve et al., 1979). Waßmann offers a systematic approach to choose visualisations for mechatronic systems (Waßmann, 2013). Lengler and Eppler do the same for a management perspective, using a "Periodic Table of Visualization Methods for Management" (Lengler and Eppler, 2007). Yoon proposes six graphical forms of visualisations in information management for technology planning (Yoon, 2010).

Bracewell and Wallace developed the DRed software (Design Rationale editor) at Cambridge Engineering Design Centre, which allows designers to record their design rationale (Bracewell and Wallace, 2003). The Soley software aims for graphical pattern recognition in product data (Maximilian Philipp Kissel, 2014).

2.5 Authors' previous Work

Previous research activities by the authors at the Institute for Product Development and Mechanical Engineering Design led to the research objectives of this study, as presented in Section 1.2 and Figure 3.

2.5.1 The integrated PKT-approach for developing modular Product Families

The integrated PKT-approach has been under continuous development at the Hamburg University of Technology since 2006 and is constantly tested, improved and expanded by researchers at the Institute for Product Development and Mechanical Engineering Design (Krause et al., 2013). It incorporates visualisations into individual method steps to provide tools for analysis, communication, solution finding and evaluation.

Evaluation of the support that the integrated PKT-approach provides to development of modular product families has been undertaken using ten industrial case studies (Eilmus et al., 2012). The results described the application of the approach in practice and revealed needs for improvement in the use of visualisations. The study data from applications in practice was then compared to literature and the theoretical approach, and analysed more specifically for product models and knowledge transfer (Gebhardt et al., 2012). The results indicated a need for better understanding of how visualisations can be developed and used for the design of modular product families.

2.5.2 A Framework for Visualisations as tools in Product Design

Based on literature review, the important **factors that influence a visualisation concept** for successful use of visual representations in product design have been summarized. Figure 2 shows the results, using Beckmann's notation for process visualisation (Beckmann and Krause, 2013). The factors from these domains need to be taken into account when developing a visualisation concept that aims to support a particular step or task in product design.

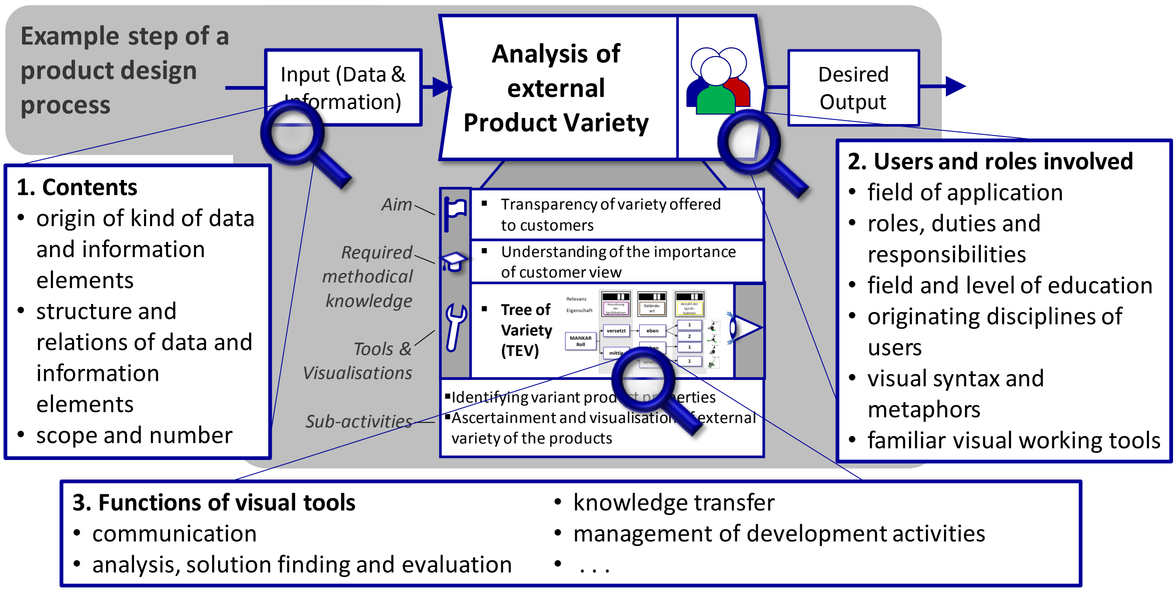

Figure 2. Properties (1,2,3) of a product design activity relevant to designing the visualisation concept (centre) used as a tool in this activity (Gebhardt et al., 2014), (Beckmann and Krause, 2013)

2.5.3 Industry Study on Visualisations in Industry

The **current use and applicability of visualisations in industrial practice** was examined using interviews of industry representatives (Gebhardt et al., 2014) and (Beckmann et al., 2014). Twelve engineers, from seven companies and two consultancies, were interviewed. The study showed that application of visualisations in industry is comparatively rare and mostly simple, e.g. structured lists, simple data graphs, sketches and CAD. The supportiveness of a visualisation as a tool in product development strongly depends on:

- A common language and work customs in the company, involved user vocabulary and understanding, suitability for management presentations
- The visual appearance of the product and parts at the centre of the visual representation for better understanding and creativity
- Easy understanding and 'uncluttered' image, with variety of visualisations kept to a minimum
- Automation of visualisation and further use of results
- Guidance for the designers, minimising possible errors and misunderstandings
- Facilitation of a broad overview of product structures as well as details
- Communication between company departments supported by visualisation concepts displaying information from more data domains.

The important influencing factors on a visualisation concept, as presented in Section 2.5.2, were verified by the study. The use of visualisations in industry, and practitioner responses and opinions about visualisations proposed by methods from research on how to develop modular product families led to the research questions posed in Section 1.2.

3 RESEARCH APPROACH

A suitable study group was defined, followed by the search and selection of case studies in which visualisations had been developed. Six finished and eight ongoing research projects were found, and one researcher from each was interviewed. Nine publications from these projects were gathered or requested from the authors. After document analysis, the study group was interviewed and data were consolidated and analysed. The research approach is summarized in Figure 3. Research questions and data collected are shown with numbering symbols that will be used in this text.

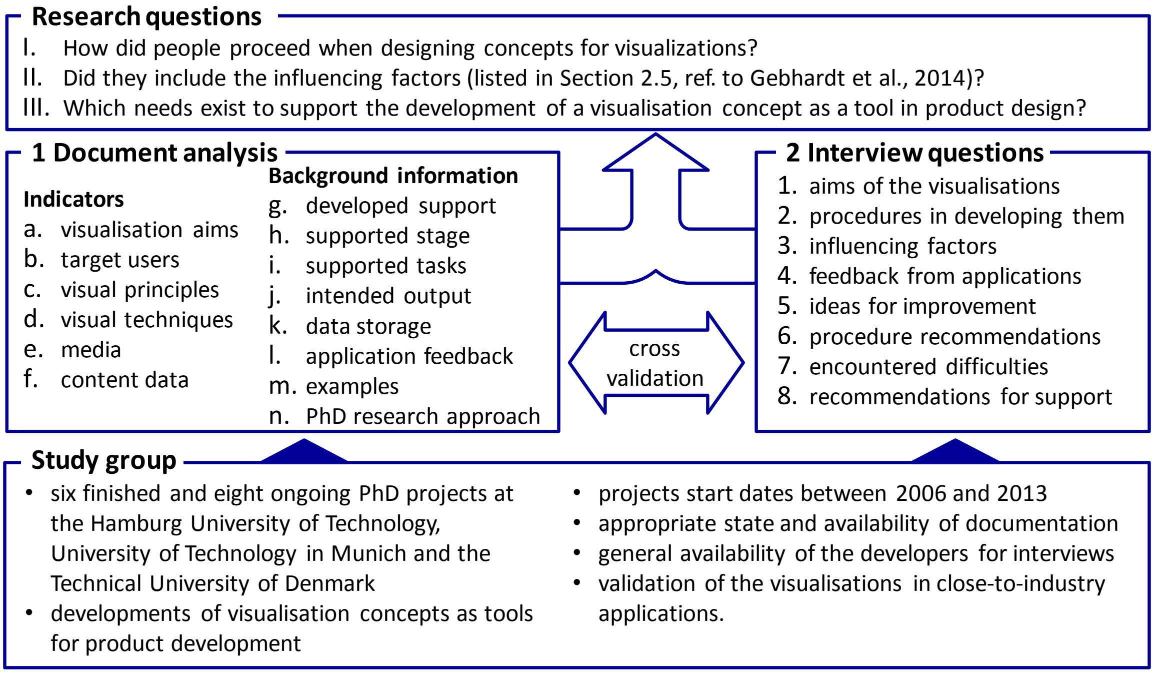

Figure 3. Overview of the research approach

3.1 Document Acquisition and Analysis and Interview Study

Document analysis provided sufficient background information on the case studies and validation by multiple data sources. Indicators are shown in part 1 of Figure 3 on the left. The numbering from Figure 3 will be used in this text. Interviewees have been contacted to assure completeness of the data. Because of the pre-existing familiarity of interviewees and researchers along with sound background knowledge, the **study method of interviewing** promises efficient data acquisition without imprecision. The study group is described in Figure 3. A scheme of semi-structured interviews was used to acquire necessary data while covering the case-specific answers in detail in unstructured questioning. A short interview outline was given to the interviewees beforehand for preparation. Due to the low number of available participants, a pilot interview was constrained to internal peer testing, which is discussed to be sufficient by Blessing and Chakrabarti (Blessing and Chakrabarti, 2009). In some cases, two researchers took notes during the 45 to 75-minute interviews. Notes were compared with deviations noted and discussed. Deviations were only minor disparities. Answers were categorized by content and sorted by frequency of occurrence. The answers were sent to the interviewees for verification: Only minor corrections were requested, with no significant impact on data validity.

4 RESULTS

4.1 Document Analysis

The interviewees stated that their aims in using visualisations were to provide an overview (5 times); identify relations across domains (twice); support decision making (twice); provide a suitable level of abstraction; support solution finding and product analysis (once each). Intended users of visualisations were product development (6 times), marketing & product planning (4 times), supply-chain management (twice), heads of company departments/management board, sales, production management and one external vendor (once each). The data used in the visualisations were components, variety, connecting flows, functions, working principles, manufacturing costs, production process, and capabilities of the production system. The principles used in the visualisations were spread widely across the possible options in the literature, for example, the node-link diagram (sometimes tree-structured), process diagram, roadmap, bar diagram, line diagram, pie charts, matrices and sketches. Some multi-principle visualisations could be found and node-link diagrams were a slight majority among the principles used. Coding techniques (or visual techniques) were widespread as

well, and included shapes and contours, grey shading, line types, line colours, icons, pictures, text, pictures and CAD renderings.
Media used for representations was mostly MS Office (7 times), Java Tools and all but one visualisation concept were primarily designed for display on large-format posters.

4.2 Interview Study

The summarized results of the interviews are shown in Figure 4, with the numbering referring to the interview questions in part 2 of Figure 3.

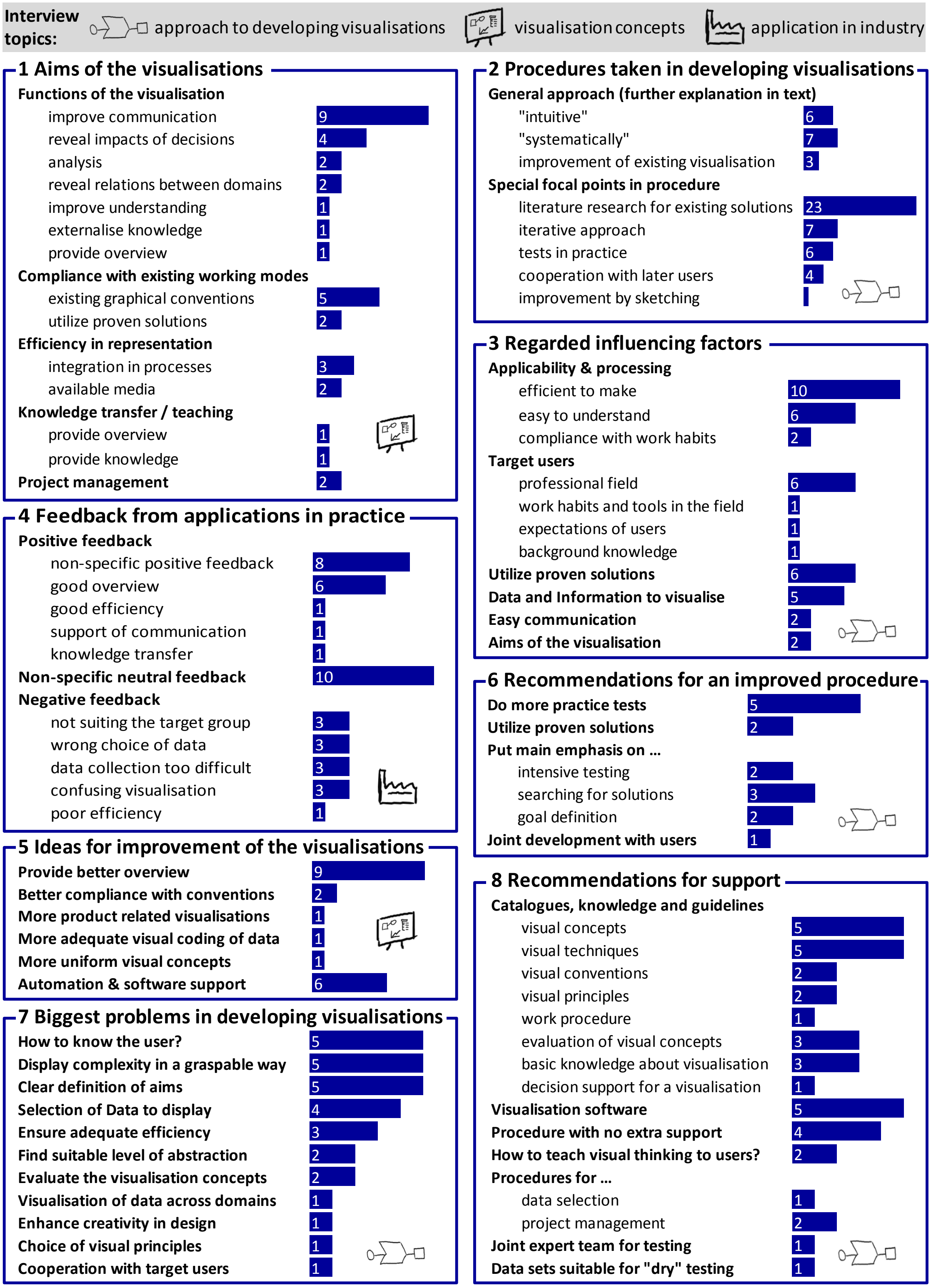

Figure 4. Results to the interview questions (numbering refers to part 2 in Figure 3)

4.3 Data Bias Compensation in the Interview Study

When influencing factors were stated as being important when defining a visualisation concept, the answers given show a significant interdependency (No. 3 in Figure 4). A visualisation being "easy to understand" might be the result of sound integration of "user needs", and "orientation on existing solutions" might represent "user behaviour" well.

To compensate, analysis was performed qualitatively. In answers on the potential to improve visualisation concepts (question 5 in Figure 4), a slight bias is assumed since the interviewees might be in favour of their own developments.

5 DISCUSSION

5.1 Research Question I - Procedures in Designing Visualization Concepts

Generally, there were two procedures followed in developing a visualisation concept, with two cases not matching this classification. **The "intuitive" approaches** started with creative solution finding, mostly sketches, and shortfalls were revealed. The concepts were improved and enhanced by researching alternatives.

The "systematic" approaches followed the steps of defining goals, researching the state-of-the-art, concept synthesis, trial and improvement. Larger iterations of this general scheme were sometimes carried out.

5.2 Research Question II - Regarded Influencing Factors

The factors that were of special concern during the development of visualisation concepts were gathered from document analyses (indicators a, b and f) and interview questions 1 and 3. Figure 5 shows a summary categorized by the influencing factors (left, ref. to Figure 2). At a broad level, nearly all categories are covered. Only the available visual principles and techniques are underemphasized. The actions taken by the interviewees don't cover many influencing factors and solutions available in literature, indicating promising potential for improved development of visualisation concepts.

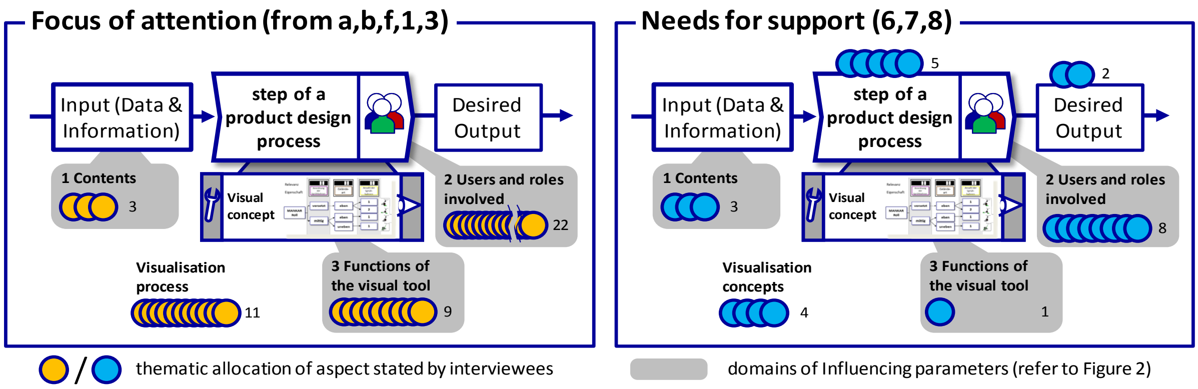

Figure 5. Allocation of interview results to influencing factor categories (ref. to Figure 2)

5.3 Research Question III - Needs for Support

All interviewees stated that they would take a same 'general approach', even though these were quite different (correlation of interview question 2 and 8). Suggestions were only made concerning individual steps in the approaches. The initial situations people had experienced showed significant diversity and the differences in general approaches might be due to personal preferences. No correlations could be found between approaches and aims (indicator 'a' and interview question 1), contents (f) and feedback from industry (l, 4). People who developed a design support consisting of a visualisation only to a lesser degree than other kinds of support tended towards a "systematic" approach (g, 2). Visualisations constitute only one possible kind of product design support (Blessing and Chakrabarti, 2009). Thus a support for developing a visualisation concept should be easy to integrate into all the usual approaches that people prefer when developing design support.

Despite stating that intense literature research was important, people still asked for support with general knowledge about visualisation: Topics included visual principles and techniques, heuristic support in decisions on when to use visualisation as a tool for product design, choosing the data to include, and evaluating a visualisation concept as a tool for product design. An assumed need for support in developing a visualisation concept as a tool in product design is supported by the fact that available literature is mostly focussed on sub-topics and is barely applicable to most situations (Section 2.4).

6 CONCLUSIONS AND OUTLOOK

Approaches to developing a visualisation concept to support product design activities are individual, ranging from spontaneous and intuitive, to systematic and methodical. The visualisation is only one alternative solution in design support besides guidelines, checklists, software, etc. Therefore, support for the development of visualisation concepts should be designed as a loose framework that is usable in all kinds of approaches.

Overall people regard a wide range of relevant influencing factors when developing a visualisation concept. On the other hand, they often do not base their solutions on thorough knowledge of how a visualisation does act as a tool in product design activities. There is a need for more profound general knowledge on visualisation solutions, such as visual principles and techniques, applicability, visual conventions and human cognition. Literature lacks sufficient and comprehensive support. There is good potential to improve access to knowledge necessary for the field of design research to facilitate understanding of the function of visualisations as tools in product design and the development of visualisation concepts in future. The case studies investigated are PhD projects at three universities in Germany and Denmark. The research group differs from the desired target group as visualisations as tools in engineering design are not developed exclusively in PhD projects. Thus integrating knowledge from other fields, such as human-machine-interface design and communication design, will be vital to increasing applicability to different areas of visualisation development.

The Institute for Product Development and Mechanical Engineering Design is currently compiling the support needed for developing visualisation concepts into catalogues of visual principles and techniques, application examples, guidelines for the development of visualisation concepts, evaluation and an adaptable procedures compendium. The focus will be on establishing a consolidated procedure that guides method developers through the process of designing a visualisation concept that will provide an efficient tool in engineering design methods. The results presented in this paper will contribute the requirements and framework.

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