INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

VISUAL REPRESENTATION FOR DEVELOPING MODULAR PRODUCT FAMILIES – LITERATURE REVIEW AND USE IN PRACTICE

N. Gebhardt, G. Beckmann and D. Krause

Keywords: visualisation, product families, modularity

1. Introduction and motivation

Stronger market competition and differing customer demands often force companies to diversify their products. A good strategy for keeping the internal variety of product components and processes low is the systematic utilisation of modules for the configuration of product variants. Furthermore, modularization can provide benefits in all product life phases. Implications for product development are manifold, e.g. [Lindemann 2009], [Mortensen and Harlou 2012], and include the integration of many company departments. To support product development in these challenges several methods aim to give a systematic approach. The integrated PKT-Approach for developing modular Product Families (mPF) is one of these approaches (Figure 1) [Krause et al. 2013a]. Other approaches are summarized and compared in [Jiao et al. 2007], [Krause and Ripperda 2013] and [Simpson 2013].
Many of these methods incorporate visual representations (examples in Figure 2 and Figure 3). Mortensen states visualisations as "sound to consider as part of a strong methodology for product architecture development" [Mortensen et al. 2008]. They can give a visual overview of modularity or variety and differ in level of abstraction [Sahin et al. 2007]. Beyond product structures many integrate important influencing factors, such as requirements or production concepts.

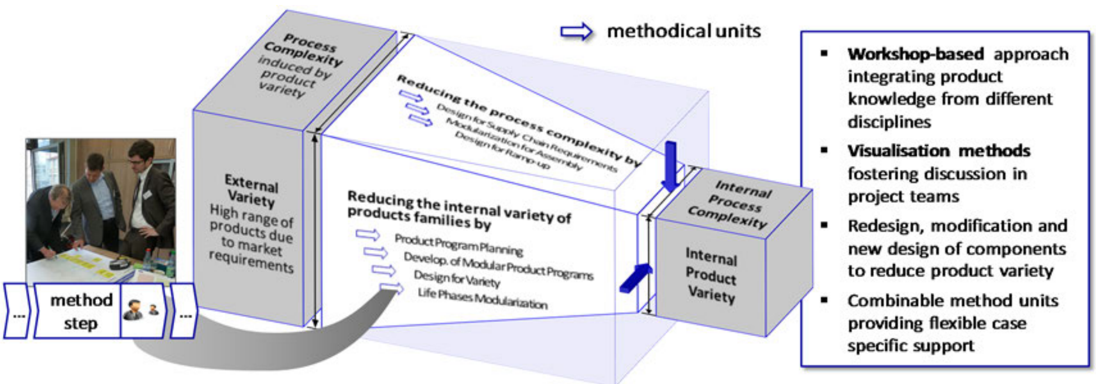

Figure 1. Conceptual overview of the integrated PKT-approach for developing modular product families and its strategic characteristics [Krause et al. 2013a]

The integrated PKT-Approach for developing modular Product Families aims to achieve external product variety for the market with small internal variety of components and processes within the company [Krause et al. 2013a]. It seeks four strategic aspects, listed in Figure 1. The visualisations incorporated into the individual methods provide the main tools for analysis, communication, solution finding and idea evaluation. Figure 2 gives an example using the Module Interface Graph (MIG) for definition and communication of module boundaries. The MIG is an abstract overview of product family components, their variety and connecting flows [Blees 2011].

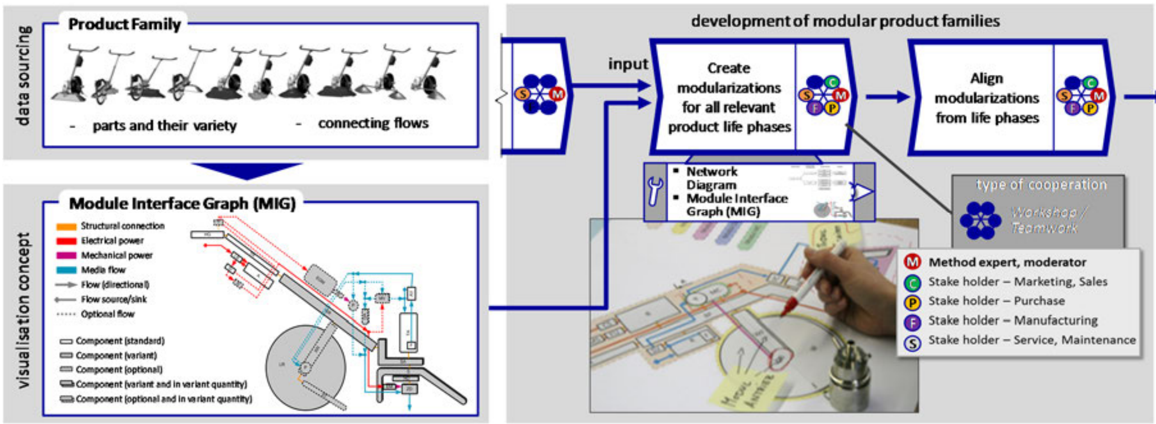

Figure 2. The context of a visual representation as a tool for developing modular product families; example of the Module Interface Graph (MIG), cf. [Blees 2011], [Beckmann and Krause 2013]

Many projects in industry have demonstrated good applicability and effectiveness of the visualisations, e.g. [Dick 2006], [Eilmus et al. 2012]. However, experiences indicate rare use of visual tools. Designers seem to usually tackle the challenge without special processes, methods or tools [Gebhardt et al. 2012]. Detailed relations and mechanisms of how visualisations are used in the development of modular product families (mPF) are hard to find in literature. The visual design of product data representations leads to difficulties in their application for product development.
The aim of this work is to contribute to the overview of the

- **Use of visual representations** for developing mPF in practice
- **Influencing parameters** of the success such visualisations as tools in development and
- To summon **criteria for a future assessment** of existing visual concepts.

The resulting questions are:

1. Which visualisations are applied in industry for developing mPF?
2. What is considered to be supportive, and what is not?
3. What are the implications for the design of visualisation concepts?

Another question arises: How do people proceed when defining the visual concepts of representations? This fourth question is part of a study not presented in this paper but will be published shortly.
Section 2 and 3 present the terminology and fundamentals of visualisation, modular product families (mPF) and methodical support for their development. Section 4 presents and categorizes visual representations as tools for developing modular product families. Literature from the field of information visualisation provides insights into the functionalities and design of visual concepts. Results of an interview study based on questions 1 and 2 are presented in Section 5 to provide an overview of product development practice.

2. Definition of visualisation conception in this work

In **engineering**, visualisations are mainly referred to as visual representations of products. Research in **information visualisation** defines the term as a creative process of transferring data and information into a graphical representation with a defined explanative or explorative purpose of discovering structures and relations or of presentation and communication [Schumann and Müller 2000], [de Lange 2006]. Some authors stress that the term 'visualisation' should not be used to refer to what is seen on a display or printed [Spence 2007]. This is in contrast to everyday language. An online survey of six participants of the Design Society Summer School of Engineering Design Research 2013 – all of different nationality – showed this ambiguity in languages as well. **Social science** is more oriented towards representations as boundary objects [Dick 2006], which provides a good basis for explaining their functions in product development: Members of different groups (e.g. company departments) use boundary objects to interact and communicate [Star and Griesemer 1989]. Boundary objects are understood by all participating groups and contain all relevant information. Since boundary objects are relevant to differing social groups their design and contents are a potential cause of conflicts.

For this work the term visualisation is defined as simplified and abstract graphical representation of products, product families and/or product programs, their structures, and properties or behaviour for the purpose of supporting product development. As mentioned above, the scope is limited to modular product families.

3. Modularity and product variety

Modularity describes the extent to which a product structure is modular. Blees summarizes results from Salvador into five basic characteristics, all being gradual and constituting modularity, namely [Salvador 2007], [Blees 2011] commonality (use of modules in several products), combinability (use of modules for configuration of product) function binding, interface standardisation and decoupling. Modularity can be utilized as a measure to support technical requirements and strategic aims.

Product variety arises when a product is manufactured for an identical main function or purpose but with variant alterations of its' properties [Franke 2002]. External variety of offered products can lead to higher sales, if placed correctly. Internal variety of product components and processes originates mainly from external variety.

Designing mPFs adds complexity and multidisciplinarity. Additional and exceptional knowledge of influencing factors, design options and outcomes is needed. At the same time modules devoted to products in many sections of the company's portfolio need to be managed [Andreasen et al. 2004]. A number of approaches for supporting the development of modular product structures can be found in literature. Methods differ in focus, fields of application, considered influencing factors, supported phase(s) of the design process and types of tools provided [Krause and Ripperda 2013]. Literature shows the following needs for methodical support for the development of modular product families [Mortensen et al. 2008], [Pedersen 2010], [Gebhardt et al. 2012]:

- Better methodical knowledge and skills
- Interfaces between available tools and existing PDM systems
- Ways of integrating company departments other than development
- Assessment of consequences of changes in product architectures on all product life phases

4. Visual representations for developing modular product families

	Visualisation	Define Market Segments	Market Attack Plan	Customers Needs	System Requirements Definition	Functional Requirements	Component Alternatives	Generic System Architecture	Module Boundary Definition	Architecture Roadmapping	Commonality Assignment	Architecute Module Sizing	Architecture Downselection	main purpose	visual principle
integrated PKT-approach	TeV	○	○	●	◐	○	○	○	○	○	○	○	○	define external variety	node-link-diagram (tree)
	MIG	○	○	○	○	○	◐	●	●	○	○	●	○	overview of components, variety and connecting flows	combined node-link & chart
	VAM	○	○	◐	◐	◐	◐	○	◐	○	◐	○	○	allocation of external and internal variety	node-link-diagram
	MPC	○	○	○	○	○	○	○	◐	○	○	◐	○	alignment of modularization requirements	node-link-diagram
	PSM	●	◐	○	○	○	○	○	○	○	○	○	○	planning of product programs	combined pie chart & Treemap (Sunburst)
	CAP	○	○	○	○	○	○	◐	◐	○	●	○	○	assignment of carry-over components	node-link-diagram
	CoC	○	○	○	○	○	○	◐	◐	◐	●	○	○	assignment of carry-over components	combined matrice & node-link
	...														
other approaches	DSM	○	○	○	○	○	○	◐	●	○	○	●	○	module-definition by couplings	matrix (Clustering)
	MIM (MFD)	○	○	◐	○	○	○	◐	●	◐	●	●	○	module-definition by module drivers	matrix (Clustering)
	PFMP	◐	◐	●	○	●	●	●	●	◐	●	○	○	allign product structure (customer, engineering, parts)	node-link-diagram & lists
	MOSFLEPS	○	○	○	○	○	○	○	●	○	○	●	○	module-definition by couplings	matrix (Clustering) & 3D node-link-diagram
	...														

○ not/weakly applicable ◐ supporting ● well applicable

Figure 3. Selection of visual representations for developing modular product families and their applicability for steps in a modular platform design process, cf. [Otto et al. 2013]; refer to [Krause et al. 2013a] for compared visualisations

Methodical approaches supporting the development of modular product families often incorporate particular visual representations as tools within their methodical steps. Figure 3 shows the applicability of visual representations using a generic set of twelve design activities derived from literature in modularity and product platforms, according to [Otto et al. 2013]. The visualisation concepts in Figure 3 represent a selection from possible visualisations as tools in the design process of developing mPFs.

4.1 Background from research fields of visualisation

Literature from the field of visualisation illustrates the general advantages of visual representations. [Spence 2007] summarizes them as giving users a global system overview, thus reducing complexity and fostering system understanding while providing focused views on specific aspects. The huge capacity of human visual perception and the unique usefulness for interdisciplinary communication and creative work add to these benefits. Fields of research relevant to visualisation are scientific visualisation, information visualisation or visual analytics [Waßmann 2013], as illustrated in Figure 4.

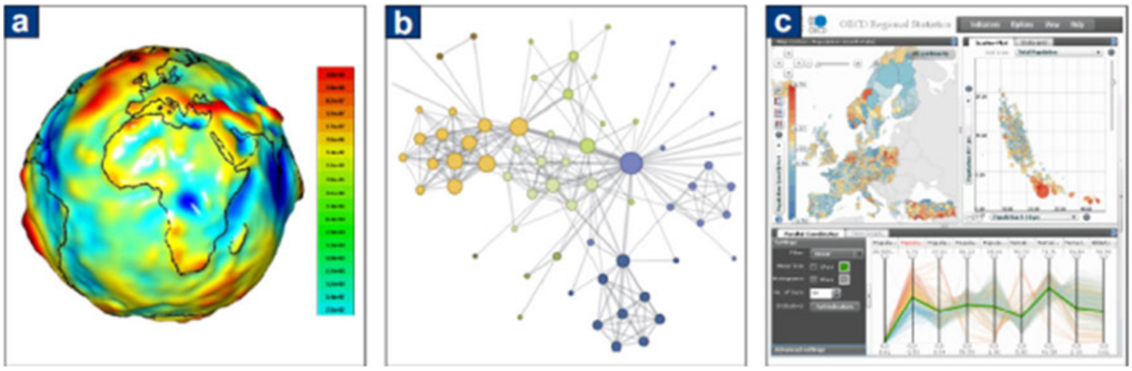

Figure 4. Examples of a) scientific visualisation, b) information visualisation and c) visual analytics [Waßmann 2013]

The research fields of information visualisations and scientific visualisation primarily understand visualisation as a process of transferring information into a graphical representation under certain conditions and aims. Input factors that are important to integrate into this process are presented in Section 4.3. Two main types of functions are "visual thinking" and "visual communication". The former encompasses solving tasks by visualisations as tools, and the latter using visualisations as boundary objects (Section 2). [Henderson 1999] emphasizes the meaning of visualisations for the transfer of tacit knowledge between interacting participants. Even though every viewer may have their own interpretations based on unique preconditions, many elements of a visual representation can rely on widely shared understandings and even on pre-attentive cognition [Ware 2008].
Designers usually possess good skills in interpreting visual representations [Schumann and Müller 2000]. Visualisations as tools can be considered as knowledge resources for the product development which supports the designers in decision-making by interpretation [Lindemann 2009]. [Maier et al. 2013] refer to the quality of a product model as the degree to which it informs gainful decision-making and counts visual product representations in such models.

4.2 Influencing parameters and parameters of visual representations

This section provides aggregated classifications of visualisation from literature. Four main fields of main parameters can be found in the literature, as shown in Figure 5.

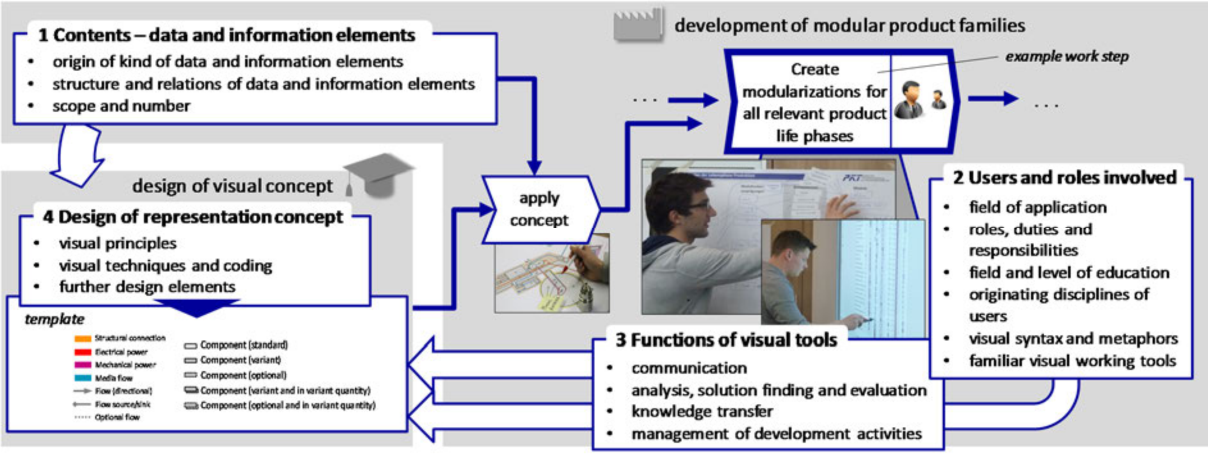

Figure 5. Influencing parameters (1-3) on the visual concept of a representation (4) used as tool in the development of modular product families

1. Contents of visual representations: data, information, structure and relations

The content (data and information elements) of a visual representation is specified by the development task it is meant to support. The structure and relations of the data and information elements is of great importance – firstly, because they enable deeper insights into influencing factors and the effects of design decision and secondly, because visual representations are particularly suitable for revealing exactly this relational information [Lengler and Eppler 2007]. Important parameters of the contents to be visualized are:

- **Origin** of data and information elements [Mortensen et al. 2008]
  - domain (e.g. product, process, organization, knowledge)
  - life phase (e.g. market, design, production)
- **Type** of data and information elements [Buur 1990], [Shneiderman 1996]
  - property type (e.g., parts, functions, design costs, concepts, people)
  - data type (quantitative or qualitative; 1, 2 and 3-dimensional data; temporal data; multi-dimensional data)
  - concreteness and level of detail
- **Structure** and **relations** of data and information elements (unrelated, sequential, relational, hierarchy, network data) [Shneiderman 1996], [Schumann and Müller 2000]
- **Scope and number** of elements and relations [Lengler and Eppler 2007]

2. Users and roles involved

The user of visual representations in the process of product development can be the designer, a group of colleagues within a project (who might even be 'non-specialists'), and 'outsiders' from management or other departments, such as manufacturing, marketing, etc. [Buur 1990].

Integrating the needs and characteristics of user groups involved in the visual design of these is important for the success of the visual tools. Interestingly enough, a significant number of authors emphasize this importance, but measures in the design of visual representations (and procedures in their designing) are rare. Even though every viewer may have their own interpretations based on unique preconditions, many elements of a visual representation can rely on widely shared understandings and even on pre-attentive cognition [Ware 2008]. Important aspects about the user of visual representations are:

- The field of **application** (e.g., management, engineering etc.) [Lengler and Eppler 2007]
- Their **roles, duties and responsibilities** [Dick 2006], [Spence 2007]
- The originating **discipline of users** [Lengler and Eppler 2007], field and level of **education** and the corresponding visual syntax and metaphors [Schumann and Müller 2000]
- Their **familiar working tools**, especially in the visual domain [Schumann and Müller 2000].

3. Functions of visual representations as tools in development of modular product families

Based on experiences in industry, there are core areas of application for visual representations in the development of modular product families:

- **Communication** of concepts, ideas, and decisions outwards from a team can be effectively enhanced by visual representations. Time for explanation and experts involved of the shown contents might be limited. Retaining customized visualisation principles is important here to ensure correct interpretation and acceptance.
- The use of visual representations as **tools for development tasks** applies to individuals or small teams. They provide information flexible to the design situation, support ideation, can be used to explain relations between decisions and consequences and to verify ideas and concepts. Adequate time and resources needed for establishing the visual representations is of major importance. The development task can be convergent (reducing complexity) or divergent (adding complexity) [Lengler and Eppler 2007].
- **Knowledge transfer** can be efficiently supported by visual representations, making them important for training, changing ways of thinking and guidance. Because of the expansive and long-term character of the purpose, the visual representations used can be laborious. Visualisations can be used to elicit tacit knowledge and to evolve and store knowledge [Dick 2006].
- [Engwall et al. 2005] note the use of visual representations for **management of development (**administrating, organising, sense-giving, and team-building).

4. Visual design of the representation

The specific choice of how to visually represent content depends on the characteristics of the contents, the users involved and the functions and aims that the visual representation will be used for (Figure 5) [Spence 2007]. The design of visual representations can be described by main properties, visual principles, visual coding and visual parameters [Bertin 2010], as illustrated in Figure 6.

- **Properties** are, for example, the level of detail and level of completeness, or the representation of detail, overview or both [Lengler and Eppler 2007].
- **Visual principles** describe the basic set-up of a visual representation design (e.g. matrices, charts, node-link diagrams) [Duarte 2008]. Several visual principles can be combined in one visual representation. Since they define the basic structure of the visual representation they are coupled with the types of structural relations of the data and information elements.
- **Visual techniques** are ways of precise visual representation of each data and information element, or their relations, e.g. color, line types, labels, text or shapes.

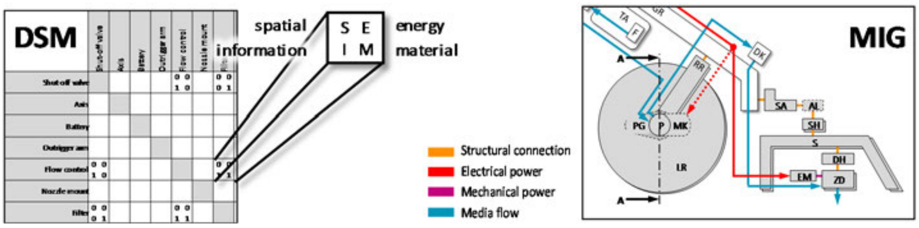

Figure 6. Different visual principles (matrix vs. linked chart) and techniques (text + position vs. color + position + shape) of the same data [Pimmler and Eppinger 1994], [Blees 2011]

4.3 Research needs for visual representations for the development of modular product families in literature

Directly related to visual representations used as methodical tools during development of mPFs, the following aspects are mentioned as needs for the conceptual design of visual representations:

- Appropriateness of visual representations to ([Schumann and Müller 2000], [Dick 2006], [Lengler and Eppler 2007], [Maier et al. 2013]):
    - designer understanding and conventions

  - regional and cultural differences
  - the task to support and resulting application parameters (e.g. time & resources)
  - company specific communication and IT standards
- Incorporation of state of a product design compared to its ideal to show target achievement and room for improvement [Spence 2007]
- Combined representation of information and real product geometries [Mortensen et al. 2011], pictures [Pedersen 2010] or sketches [Tjalve et al. 1979] for better understanding and memorization
- Improved visualisation of variety, complicated products [Mortensen et al. 2008], [Eilmus et al. 2012], relations of information elements [Dick 2006] and domains of origin (e.g. market, product and production) [Harlou 2006]
- Visual hints for beneficial actions in a current situation [Dick 2006]
- Representation at different levels of abstraction [Sahin et al. 2007]
- Better shared understanding in the light of increased communication efforts of interdisciplinary development [Dick 2006]

5. Study in Industry

In order to achieve a general overview of the use of visual representation in the development of mPF a study of nine companies in German industry was conducted. Further study aims are to derive conclusions about measures of improvement for concepts of the visual representations.
The study covered the topic of method transfer into practice as well. Results of this second part are presented in [Beckmann et al. 2014].

5.1 Research objects and methods

The institute PKT has hosted a series of two-day advanced training workshops to teach designers about practice methods for the development of mPF [Krause et al. 2013b]. Workshops included presentations and interactive exercises on the Modular Function Deployment (MFD) [Erixon 1998], technical functional modularisation using the rhombus-shaped network diagram of the METUS approach [Göpfert 1998], the design structure matrix (DSM) [Pimmler and Eppinger 1994], the Design for Variety method (DfV) [Kipp 2012] and the Life Phases Modularization of the integrated PKT-approach [Blees 2011]. Participants of the 2013 workshops were contacted afterwards for a survey (18 persons); twelve engineers from seven companies and two consultancies participated, mostly design engineers and managers of design departments, who face increasing complexity of products and processes. Industrial sectors varied from materials handling to ship machinery, bearings, test plants and production systems. Three interviewees were consultants reporting experience from four client companies.
Because of the pre-existing familiarity of interviewees and researchers and sound background knowledge of the companies the study method of interviewing promises efficient data acquisition without being imprecise. An interview outline was given to the interviewees beforehand for preparation. The interviews were conducted by telephone. A scheme of semi-structured interviews was used to cover the necessary data demands while covering the case-specific answers in unstructured questioning in detail. Due to the low number of available participants, a pilot was constrained to internal peer testing only [Blessing and Chakrabarti 2009]. Note-taking was shared by the interviewer and two other observers, with rotating tasks during the interview to keep better focus. Notes were compared directly after each interview with deviating results discussed and reconstructed. Findings were categorized and sorted by number of appearance. The results were sent to the interviewees to verify their statements.

5.2 Results

If not stated otherwise the following paragraphs list statements given by three or more interviewees.

Corporate strategies for the development of modular product families

Even though all companies are producing highly variant products only two enlist strategies for handling product structures or variety at a top management level. Strategies are mostly at the level of development management.

Visual representation concepts applied in product development

The majority of the companies apply simply structured lists, structures within bill of materials or variant trees to define and administer product modules and variety – partly connected with Product-Data Management Systems. Two respondents stated that configuration software solutions are the main tools used in their companies for the same purpose.

Experiences with the applied visual representation concepts

The following aspects have been stated as being beneficial to the successful application of visual representations as tools for developing mPF:

- Common language and compliance with work customs
  - Appropriateness to involved users vocabulary and understanding
  - Suitability for management presentations
  - The number of different tools and templates used in development should not escalate in operation and principles
  - The visual appearance of product and parts should be at the centre of visual representation.
- Easy understanding and 'uncluttered' image
- Automation of visualisation and further use of results
- Provide guidance for the designers and minimise possible errors
- Facilitate broad overview of product structures as well as details (only two answers apply)

Further important influencing factors in designing mPF

Asked what aspects are important to consider when developing mPF, the following answers were given:

- evaluation of impacts by modularization - monetarily if possible
- integration and improvement of product planning
- alignment across segments of the product program (only two answers apply)

Applicability, advantages and disadvantages of visual representation concepts

Concerning visual representation concepts from several methods, interviewees were asked to evaluate applicability within their company (Section 5.1).

- **Matrix-based visualisation** concepts were mostly assessed as poorly applicable due to difficulty in communication of contents and results to stakeholders and senior managers.
- Visualisation concepts embedding **shapes and contours of the real parts and products** were judged as being easier to understand, fostering creativity and being more convenient for communication across teams (e.g. the Module Interface Graph (MIG)). However, efforts required to create these representations were considered to be too high.
- Visual concepts displaying **information from more than one company department** or data domain were often considered helpful in developing mPF, e.g. the Tree of external Variety (TeV) or the Modular Process Chart (MPC).
- Applying new concepts and coding within visual representation is avoided, especially when the visual representations are passed on in the company.

6. Conclusions and further research

Findings indicate and confirm the rare **use of visual representations** in practice. Data of product modularity and variety is mostly added to existing representations already in use in industry. Visual representations developed for mPF are scarcely used. Just as well, ways of visual representations judged helpful were not observed as being applied in the companies. Many characteristics of a specific development task determine the **efficiency of using a visual representation** as a tool for the task (Figure 5). From literature, these fields are the data and information needed, the specific task itself, and the users/‘receivers’ of the visual representation, with their education and convention. Results from the industry study presented give further details and additions to these characteristics. The acceptance and understanding of even abstract visual concepts is significantly enhanced by the incorporation of systematics familiar to users and thus specific to companies or even users.

Further research activities will include a comparison of existing visual representations for developing mPF. Comparison will include the **influencing factors** from literature and the study presented here. Practical studies and experiments aim to reveal critical relations between the visual design of representations and their support in development.

Sufficient guidance on how to integrate all these factors into the design of a visual representation is missing – as well as accurate knowledge about impact mechanisms on design success.

A survey of the practices of researchers developing the design of visual representations will help to describe theses mechanisms and the prevalent practice. Research activities will lead to the development of a guideline for designing concepts of supportive visual representations for the development of modular product families.

Acknowledgement

The authors wish to thank the German federal Ministry of Education and Research for founding this work, all participants of the Workshop on Modularization and the interviewees.

References

Andreasen, M. M., Mortensen, N. H., Harlou, U., "Multi Product Development: New Models and Concepts", Design for X: Beiträge zum 15. Symposium 2004, Meerkamm, H. (Ed.), Lehrstuhl für Konstruktionstechnik, Erlangen, 2004.

Beckmann, G., Gebhardt, N., Krause, D., "Transfer of methods for developing modular product families into practice – an interview study", 13th International Design Conference - Design 2014, Dubrovnik, 2014.

Beckmann, G., Krause, D., "Process Visualisation of Product Family Development Methods", International Conference on Engineering Design ICED13, Seoul, Lightning Source, Inc. La Vergne, USA, 2013.

Bertin, J., "Semiology of graphics", Esri Press, Redlands, Calif, 2010.

Blees, C., "Eine Methode zur Entwicklung modularer Produktfamilien", TuTech Verlag, Hamburg, 2011.

Blessing, L. T. M., Chakrabarti, A., "DRM, a design research methodology", Springer, New York, 2009.

Buur, J., "A theoretical approach to mechatronics design", Institute for Engineering Design, IK publication, Lyngby, Coppenhagen, 1990.

de Lange, N., "Geoinformatik in Theorie und Praxis", Spriner, Berlin, 2006.

Dick, B., "Untersuchung und Modell zur Beschreibung des Einsatzes bildlicher Produktmodelle durch Entwicklerteams in der Lösungssuche", Verl. Dr. Hut, München, 2006.

Duarte, N., "slide:ology", O'Reilly Media, Sebastopol, 2008.

Eilmus, S., Gebhardt, N., Rettberg, R., Krause, D., "Evaluating a methodical approach for developing modular product families in industrial case studies", 12th International Design Conference - Design 2012, Dubrovnik, 2012, pp. 837–846.

Engwall, M., Kling, R., Werr, A., "Models in Action: How Management Models are Interpreted in New Product Development", R&D Management, Howells, J.H. and Enkel, E. (Eds.), 2005, pp. 427–439.

Erixon, G., "Modular function deployment", The Royal Inst. of Technology, Dept. of Manufacturing Systems, Assembly Systems Division, Stockholm, 1998.

Franke, H.-J., "Variantenmanagement in der Einzel- und Kleinserienfertigung", Hanser, München, 2002.

Gebhardt, N., Beckmann, G., Krause, D., "ProductFamilyModels and Knowledge Transfer Support for the Development of Modular Product Families", The Ninth Norddesign Conference 2012, Center for Industrial Production, Aalborg University, Aalborg, 2012.

Göpfert, J., "Modulare Produktentwicklung", Dt. Univ.-Verl, Wiesbaden, 1998.

Harlou, U., "Developing product families based on architectures", Department of Mechanical Engineering, Technical University of Denmark, Lyngby, 2006.

Henderson, K., "On line and on paper", MIT Press, Cambridge, Mass., 1999.

Jiao, J., Simpson, T. W., Siddique, Z., "Product family design and platform-based product development: a state-of-the-art review", Journal of Intelligent Manufacturing, Vol. 18, 2007, pp. 5–29.

Kipp, T., "Methodische Unterstützung der variantengerechten Produktgestaltung", TuTech-Verlag, Hamburg, 2012.

Krause, D., Beckmann, G., Eilmus, S., Gebhardt, N., Jonas, H., Rettberg, R., "Integrated Development of modular Product Families. A Methods Toolkit", Advances in product family and product platform design: Methods & Applications, Simpson, T.W. (Ed.), 2013a, pp. 245–269.

Krause, D., Ripperda, S., "An assessment of methodical approaches to support the development of modular product families", International Conference on Engineering Design ICED13, Seoul, 2013.

Krause, D., Ripperda, S., Gebhardt, N., Eilmus, S., Hackl, J., Beckmann, G., "Workshop on Modularization Methods, Research training for engineers", Hamburg University of Technology, 2013b.

Lengler, R., Eppler, M.J., "Towards a periodic table of visualisation methods of management", Proceedings of the IASTED International Conference on Graphics and Visualisation in Engineering, 2007, pp. 83–88.

Lindemann, U., "Methodische Entwicklung technischer Produkte", Springer, Berlin, Heidelberg, 2009.

Maier, A., Wynn, D., Howard, T., Andreasen, M., "Perceiving design as modelling: a cybernetic system perspective", An anthology of theories and models of design, Chakrabarti, A., Blessing, L.T.M. (Eds.), Springer, Berlin, 2014.

Mortensen, N. H., Hansen, C. L., Hvam, L., Andreasen, M. M., "Proactive modeling of market, product and production architectures", International Conference on Engineering Design ICED11, Copenhagen, 2011.

Mortensen, N. H., Harlou, U., "Multi-Produkt-Entwicklung - praxisorientierte Werkzeuge und praktische Erfahrungen", Handbuch Konstruktion, Steinhilper, R. and Rieg, F. (Eds.), Hanser, München, 2012.

Mortensen, N. H., Pedersen, R., Kvist, M., Hvam, L., "Modelling and visualising modular product architectures for mass customisation", International Journal of Mass Customisation, Vol. 2, 2008, p. 216.

Otto, K. N., Hölttä-Otto, K., Simpson, T. W., "Linking 10 years of modular design research: alternative methods and tool chain sequences to support product platform design", Proceedings of the ASME IDETC/CIE 2013, ASME, New York, NY, 2013.

Pedersen, R., "Product Platform Modelling", DTU Management Engineering, Kgs. Lyngby, 2010.

Pimmler, T. U., Eppinger, S. D., "Integration analysis of product decompositions", Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Mass., 1994.

Sahin, A., Terpenny, J. P., Goff, R. M., "A Graphical Modeling Environment for Configuring Modular Product Families and Platforms", ASME IDETC/CIE 2013 (Ed.), New York, ASME, 2007, pp. 1263–1275.

Salvador, F., "Toward a Product System Modularity Construct: Literature Review and Reconceptualization", IEEE Transactions on engineering management, 2007, pp. 219–240.

Schumann, H., Müller, W., "Visualisierung - Grundlagen und allgemeine Methoden", Springer, Berlin, 2000.

Shneiderman, B., "The Eyes Have It: A Task by Data Type Taxonomy for Information Visualisations", Proceedings Visual Languages, Boulder, Colorado, 1996.

Simpson, T. W. (Ed.) 2013, "Advances in product family and product platform design: Methods & applications", Springer, Berlin, 2013.

Spence, R., "Information visualisation", 2nd ed., Addison Wesley, Harlow, England, New York, 2007.

Star, S. L., Griesemer, J. R., "Institutional Ecology, `Translations' and Boundary Objects", Social Studies of Science, Vol. 19, 1989, pp. 387–420.

Tjalve, E., Andreasen, M. M., Frackmann Schmidt, F., "Engineering graphic modelling", Newnes-Butterworths, London, Boston, 1979.

Ware, C., "Visual thinking for design", Morgan Kaufmann, Burlington, MA, 2008.

Waßmann, H., "Systematik zur Entwicklung von Visualisierungstechniken für die visuelle Analyse fortgeschrittener mechatronischer Systeme in VR-Anwendungen", Paderborn, Heinz Nixdorf Inst., 2013.

Dipl.-Ing. Nicolas Gebhardt, Scientific Assistant
Hamburg University of Technology, Institute for Product Development and Mechanical Engineering Design
Denickestraße 17, Hamburg, Germany
Telephone: +49 40 42878 4257
Email: nicolas.gebhardt@tuhh.de
URL: http://www.tuhh.de/pkt