INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

APPROACH TO VISUALIZE THE SUPPLY CHAIN COMPLEXITY INDUCED BY PRODUCT VARIETY

Max Brosch, Gregor Beckmann and Dieter Krause
Hamburg University of Technology

ABSTRACT
Due to the high level of individualization and globalization, companies increase their product variety, which leads to an increased internal complexity at the level of the products, business processes and the supply chain.
The Institute of Product Development and Mechanical Engineering Design (PKT) has developed the Integrated PKT approach for developing modular product families, to reduce the internal variety with methods, that are aiming to handle, to reduce and to avoid complexity. To extend this approach to the level of the supply chain, the method Design for Supply Chain Requirements is under development. The important first step is to ascertain and to visualize the supply chain complexity induced by product variety. An approach to realize this first step is presented in this paper.

Keywords: Design for Supply Chain Requirements, complexity, supply chain, product variety

1. INTRODUCTION

Actual trends like globalization of competition, new environmental requirements, increasing individualization of services and shorter product life cycles, introduce new challenges to companies. In the course of these developments the markets are converting from mass markets into micro markets, where products must be adapted to the individual needs of the customers. Companies try to adapt to these trends by developing product variants [1]. Internally this leads to an increase in complexity at the product level e.g. in the amount of parts and components and at the process level e.g. due to increased production efforts and the impact on the supply chain. To handle these interacting types of complexity an adapted variety-management is developed.
Examples could be identified in the industrial practice, in which even small changes to customers' requirements have a great influence on the processes of the company. This was discovered, for example, at a corona stations manufacturer. Corona stations prepare surfaces to optimize the adhesion of printing inks, adhesives, etc. These stations consist of a central system of electrodes as the functional unit and the support drum, generators, side frames made of steel and spreader bars made of aluminium. They are not lacquered typically. If the customer wants these parts to be lacquered, it leads to an increase in complexity within the processes. At first a new sub-process, the lacquering, has to be implemented, which is not part of the general process. In addition the customer's request induces the company to use other materials because the impression of the colour varies on different materials. This exchange of materials has further effects on the process of procurement, as new suppliers have to be found and new contracts have to be negotiated. Moreover, this leads to variations in the production process if the new material requires different treatment.
In this example the complexity is increased not only in the business process (new sub-process) but also in the supply chain (new suppliers, possibly outsource the lacquering) by providing another product variety. Since this increase in complexity raises the indirect costs within the company, it is necessary to reduce the complexity.
Recent studies in literature mainly focus on reducing the complexity of the production process. Since complexity problems not only affect the production processes, but also the management and following sub-processes and the supply chain, a new method has to be developed. This enables a holistic approach to both the product view and the view of the supply chain and identifies the product specific causes of complexity, to avoid unpredictable increase in complexity and therefore the increase in costs in the product development phase. Within this method (called Design for Supply Chain Requirements) an important first step is to ascertain and to visualize the actual situation of the supply chain complexity. This first step is presented in detail in this paper, focusing on the following questions:

- How are product variants generated along the supply chain?
- Where is supplemental value enhancement generated along the supply chain, induced by product variety?
- Where is value enhancement removed along the supply chain, induced by product variety?
- Where do weaknesses occur within the supply chain induced by the product structure?
- Is the supply chain and the product structure adapted to the variety-management strategy?

2. STATE OF THE ART AND DISAMBIGUATION

The compilation and visualization of the actual situation of supply chain complexity are the subject of this research, therefore the terms supply chain and complexity are explained. In addition the existing visualisation methods *Value Stream Mapping* and *Deployment flowcharts* are presented. Below the variety- management and the *Integrated PKT Approach for Developing Modular Product Families* (integrated PKT approach) are explained in more detail. The integrated PKT approach reduces the internal variety with methods that are aiming to handle, reduce and avoid complexity. The approach to visualize the supply chain complexity induced by product variety is used as a variety-management method, which will extend the integrated PKT approach to the level of processes.

2.1 Supply chain

Supply chain means the flow of material, information and funds through the network of the involved companies, which extends from raw material suppliers to end users [2]. According to Houlihan the characteristics of a supply chain are [3]:

- It documents all processes from raw material procurement to the end customer services.
- It covers all processes from supplier to end customer as an integrated system.
- It exceeds organizational boundaries.
- The core objective of the supply chain is the creation of value to the customer, which is in a balanced relationship with costs and profits.

Within the supply chain a distinction is made between design of the supply chain and design for supply chain. The goal of design of the supply chain is the optimal design of logistics networks and processes to reduce transportation costs, inventory and cycle times and increase security of supply or delivery capacity. The design for supply chain examines how products must be designed and manufactured to achieve an optimal supply chain design.
Currently, companies are trying to improve their supply chain performance through planning systems, operations management software and real time inventory management processes. But the focus of these systems is operational and does not influence the design and supply chain decisions that set basic targets for supply chain performance of a product line [4].
Lee uses the term ”Design for Supply Chain Management“ to describe such design concepts, which provide much greater efficiency and flexibility in the logistics and distribution aspects of the order fulfilment cycle, by designing products which fit to the requirements of the order fulfilment process [4]. Design for Postponement and Design for Localization are two of these approaches.

2.2 Complexity

The colloquial meaning of complex is complicated, inscrutable and incomprehensible [5].
In scientific usage complexity is understood as a description of a structure linked with systems
According to Patzak, complex systems are determined by their number and diversity [6].
Ulrich and Probst have extended this static view by the dynamics and they understand the complexity as the capability of a system to take a large number of different states in a given period of time [7].
Therefore complexity basically depends on two variables, number and diversity as well as from variability over time. The number and diversity of a system mean the number of elements and their relationships. The variability over time takes the dynamic changes into account.
How complexity depends on these two variables is represented by a matrix. Figure 1 shows the four basic states of complex systems: simple systems, complicated systems, relatively complex systems and complex systems [7].

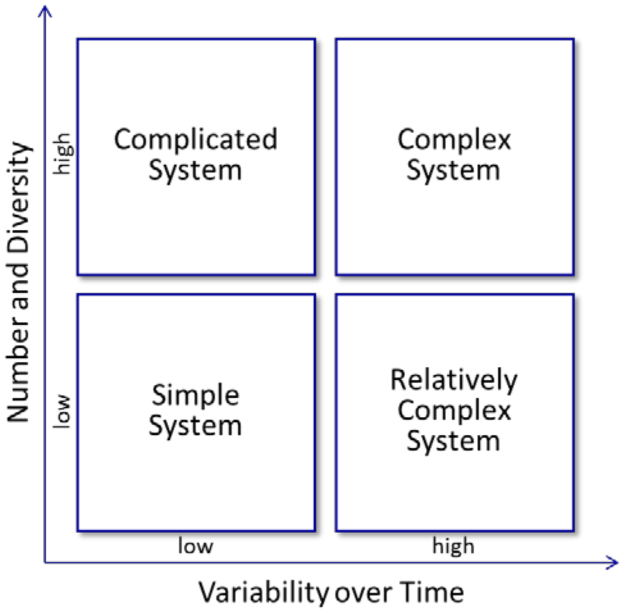

Figure 1. States of Complex Systems [cf 7]

2.3 Variety-management

The better the variety-management, i.e. the ability to handle the variety, the greater the competitive advantage [8]. Therefore successful companies are characterized by the holistic use of a variety-management, which plans, reduces and handles the diversity in all business departments and processes by using appropriate tools, principles and methods [9].

Usually different views exist on the need for a large number of variants within the companies. Thus a high number of variants is preferred in the areas close to the customers, while an extensive standardization of products and thus a small number of variants is required in the areas close to the production [10].

Both product-based strategies such as modularization and platform design as well as process-based strategies such as the postponement strategy and the concept of commonality exist within the variety-management. In this paper the process-based strategies are particularly relevant. The aim of the postponement strategy is to keep as many steps of the processes independent of product variants as possible. Postponement describes the delay of some activities within the value chain to take advantage of better information [11].

Referring to variety-management, the concept of commonality describes a strategy that takes advantage of the equality of resources used across various end products within a product family, to reduce the internal complexity of production and therefore reduce the cost. The shared resources can be equipment, staff, knowledge, components and processes [12].

The process-commonality, i.e. the strategy to utilize the same processes for different products, is one form of commonality, BMW Leipzig, for example, produces all BMW 1 and BMW 3 variants on one single assembly line. The described strategies to reduce and handle the process complexity are shown in Figure 2. Sub-processes can be outsourced completely from the business process and shifted either back to the supplier (outsourcing) or forward closer to the customer (postponement). In addition sub-processes can be unified and thus simplified (commonality).

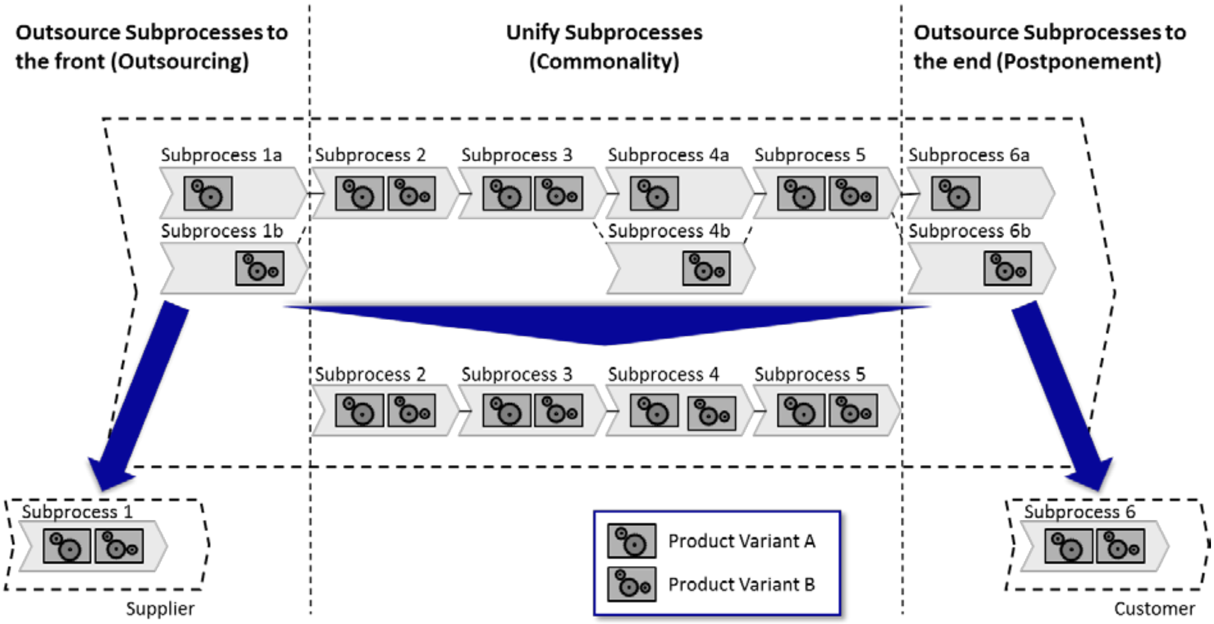

Figure 2. Strategies to Reduce and to Handle the Process Complexity

2.4 Existing visualization methods

According to Becker the following preparatory measures are necessary before recording and modelling the actual state of a process [13]:

- determine the level of detail
- select the visualization
- select the description of views
- identify sources of information

There are several different tools to ascertain and to visualize the supply chain, e.g. ARIS [14] and ICON-SCC [15]. All these tools are developed using the Supply Chain Operations Reference-model (SCOR-model). SCOR is a standard method to describe and analyse all aspects of a supply chain [16]. This method focuses on the business view of the supply chain and does not consider the complexity induced by product variety. Various methods are established in practice, such as *Value Stream Mapping* (*VSM*) and *Deployment Flowchart* (*DF*).
A flow chart is an illustration of program operations and is often used by programmers to illustrate the workings of a computer program or algorithm. A variation of these flowcharts is the DF, which is a business process mapping tool used to articulate the steps and stakeholders of a given process [17].
VSM uses simple graphics or icons to show the sequence and movement of information, materials and actions in a company’s value stream. VSM shows thereby how value is produced and where waste occurs [18].
The level of detail of these two described methods are very different. While VSM is primarily used for very fine level of detail and level of action, DF can be used at a coarser level of detail. The focus of the VSM is to identify waste and the focus of the DF in the representation of flows. This paper presents a visualization method, which has the focus on the complexity and can be used in various levels of detail.

2.5 Integrated PKT approach for developing modular product families

The aim of the variety-management is to produce variants with minimal costs. The Institute PKT has developed the Integrated PKT-approach for developing modular product families, to reduce the internal variety with methods, that are aiming to handle, reduce and avoid complexity. For this purpose the methods *Product Program Planning* [19], *Design for Variety* [20] and *Life Phase Modularization* [21] have been developed or are under development. These methods to handle the variety of products adapt the product architecture to offer a very high external variety on the market without increasing the internal diversity.

Whilst all these methods are product related, this research extends the integrated PKT approach by taking into account the level of the supply chain [22].
Figure 3 shows this extension of the integrated PKT approach.

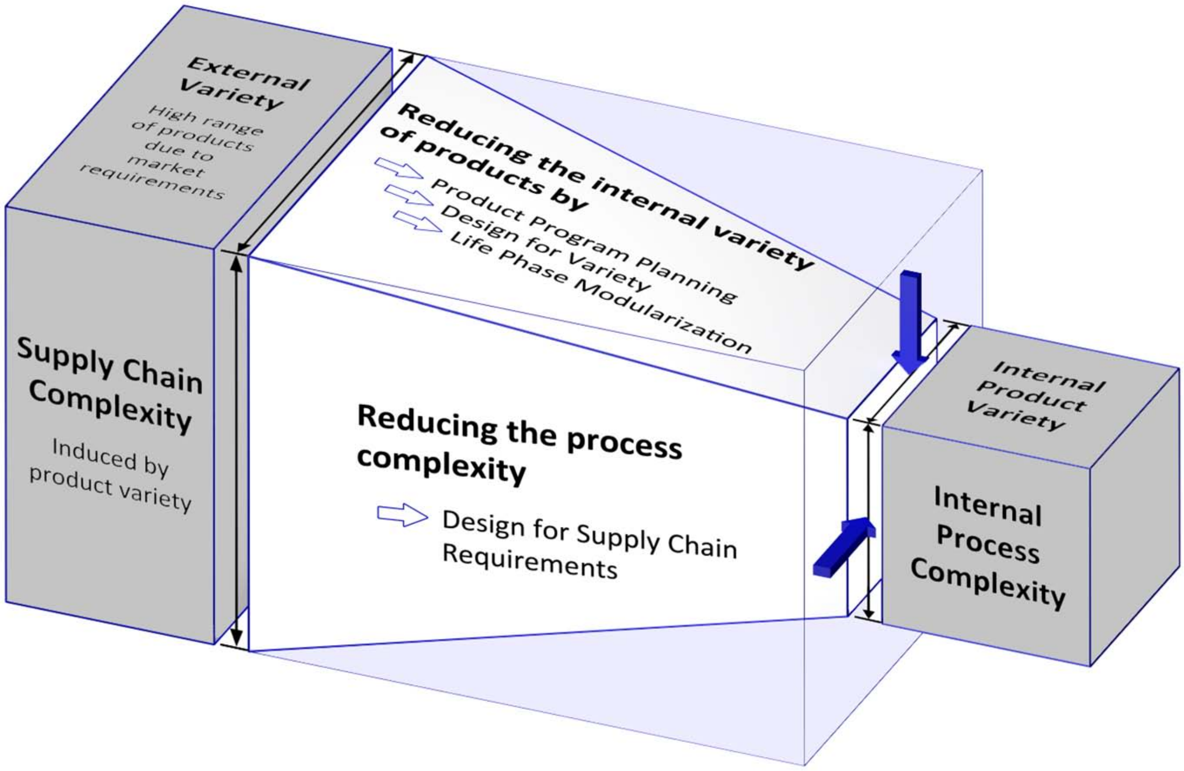

Figure 3. Extension of the Integrated PKT-approach [cf 20]

3. APPROACH TO VISUALIZE THE SUPPLY CHAIN COMPLEXITY

In order to extend the integrated PKT approach with the supply chain complexity, a method is under development, taking into account the local order fulfilment and global distribution of goods within the phase of product development. In future this should create product structures which are optimized also to the supply chain strategy. Figure 4 shows the basic concept of the Design for Supply Chain Requirements method. The need to develop a method to design for supply chain requirements has been identified in various companies in practice.
While recording and analysing the complexity of products and processes, design guidelines are revealed for the product structure, for business processes and for the supply chain. The approach to visualize the supply chain complexity induced by product variety, described below, is aligned within the ascertainment of complexity (see blue mark). The level of the supply chain and its individual stations, such as suppliers, factories, distributors and end users outlines the overall framework of the process view. The level of business processes outlines the processes for order fulfilment within each supply chain station. Therefore the level of detail is higher and the system boundary is defined smaller than in the level of supply chain.
From the design methodology point of view, the product structure is the level which influences the other two levels. In this context the article examines the supply chain and how it is influenced by the product structure. The mutual connectivity with the business processes will be carried out in further research.

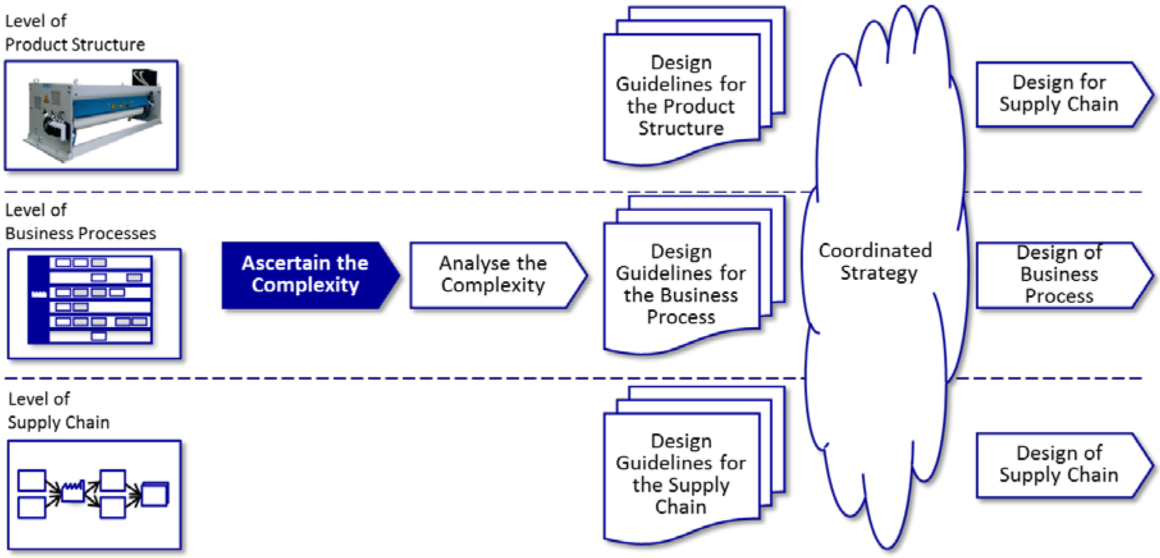

Figure 4. Basic Concept of the Design for Supply Chain Requirements Method

As explained above, the product structure and the different product variants have a big impact on the complexity of the supply chain. Therefore the requirements of the supply chain have to be taken into account in product development to minimize the complexity induced by the product structure.
The procedure to ascertain and to visualize the complexity of the supply chain and their causes is divided into the following steps:

- Ascertainment of the supply chain (section 3.1)
- Identification of the places of product differentiation (section 3.2)
- Ascertainment of the development of product variety along the supply chain (section 3.3)
- Identification of weaknesses and their causes (section 3.4)

For better understanding the steps are illustrated using an example. For confidential reasons the experiences with different companies are merged to a fictional example. This example is modified and contains fictional numbers. Company A is a manufacturer of electrical appliances. These consist of purchased electronic components and enclosure parts. The enclosure parts consist of two standardized side shields made of plastic and various aluminium side bars to adjust the length, because the electrical appliances exist in different size groups. The purchased parts are assembled in the factory. To distribute the appliances within Europe, the products are forwarded to two different hubs. Hub1 is in France and operates the Western European market and Hub2 operates the Eastern European market from Poland. The sale is carried out by different sales companies (SC) in different countries. Figure 5 shows the structural design of the Supply Chain.

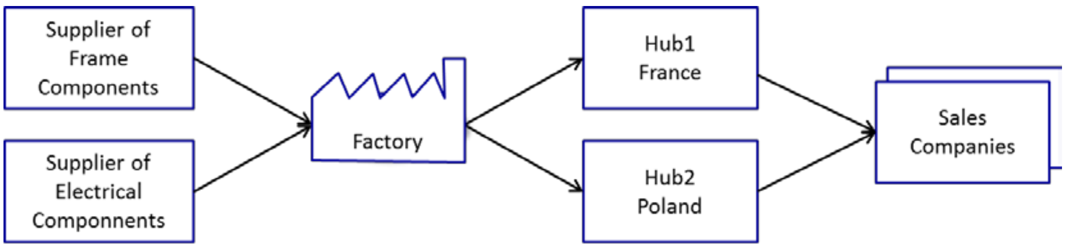

Figure 5 Structural Design of the Supply Chain of Company A

In this paper, four scenarios are examined which increase the supply chain complexity.

- Scenario 1 – The electrical equipment must be tested. In some countries the law, however, requires a new testing every 12 months. Therefore, the testing should be carried out shortly before the sale.
- Scenario 2 – Some sales companies in Eastern Europe sell the electrical equipment with an electric valve instead of the standard pneumatic valve. Hub2 obtains the electric valves from another supplier, and assembles them in the electrical equipment.

- Scenario 3 – Similar to the mentioned corona example, some customers require a variant in which the side panels and the side bars have the same colour. For this, the side panels are also made of aluminium and lacquered together with the side bars.
- Scenario 4 – An instruction manual in local language has to be sold with each product.

3.1 Ascertainment of the supply chain

For the detection and visualization of the supply chain process two different views have to be understood. The first is the structural view of the supply chain, i.e. the structure and the arrangement of the supply chain stations, and the material flows between them. The structural view is shown in Figure 5. The second is the understanding of a supply chain as a process. In each supply chain station, different sub-processes are performed. Even identical sub-processes are carried out, maybe even different, in several stations along the supply chain, because of the increased complexity. To consider both views a swim lane diagram is used for detecting and visualizing the supply chain processes. Here some symbols and items of the explained methods VSM and DF (see section 2.4) are used. The individual swim lanes represent the different supply chain stations. Figure 6 shows that representation. Top left shows the supply chain process for Company A.

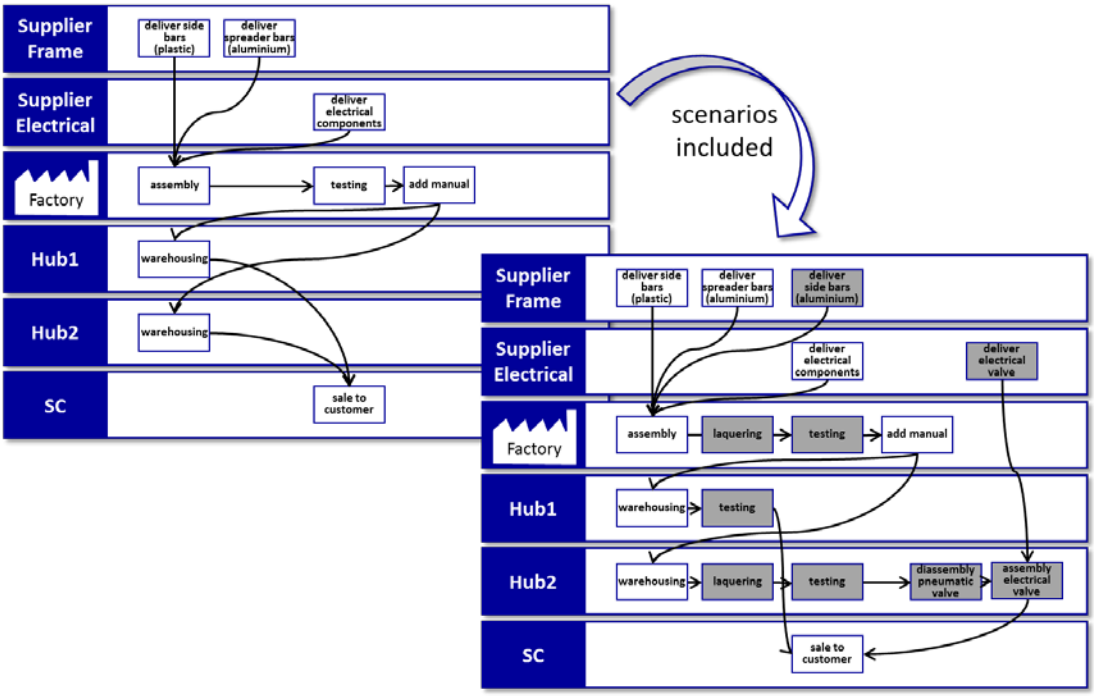

Figure 6 Presentation of supply chain processes using swim lanes

Thereupon (not shown) for each increasing complexity scenario, a further representation is received, in which the additional sub-processes are marked in grey. In scenario 1, for example, the testing is postponed to the hubs. Therefore a new sub-process “testing” is located and marked grey in the swim lanes of the hubs. Figure 6 shows at the bottom right the combination of the four scenarios. The increase in complexity by increasing the number of elements (sub-processes), their compounds and their time-variability can thus be represented.

3.2 Identification of the places of product differentiation

As part of the order fulfilment, the value enhancement does not only take place within the factory or the production unit, but also in the downstream stations of the supply chain such as distribution centres, hubs and sales companies. Therefore supplemental value enhancement is not only generated but also removed. Removed value enhancement means dismantling of already assembled parts, e.g. dismantling of a switching valve to install another valve. Those changes of value enhancement are the places of product differentiation within the supply chain.

The approach to visualize the supply chain complexity uses the following procedure to identify the supply chain stations where value enhancement is removed (marked with a red circle), where

unnecessary value enhancement takes place (marked with orange triangles) and the stations where there is supplemental value enhancement generated (marked with a green quadrangle) (see Figure 7).
In Scenario 2, Hub2 dismantles the previously assembled pneumatic valve to assemble an electric valve. This change in the value enhancement is shown in Figure 7.

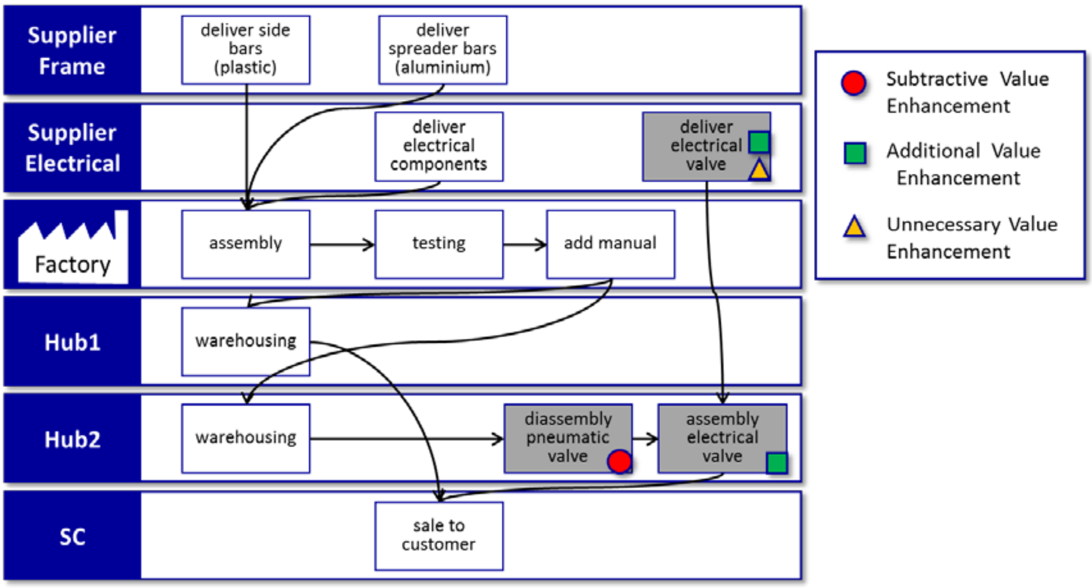

Figure 7 Visualization of the change in value enhancement

The supplemental value along the supply chain is not necessarily negative and unrequested. In the course of a postponement strategy, it could be profitable to postpone the value enhancement within the supply chain. The added value however can only be analysed by the described ascertaining and visualizing method.

3.3 Ascertainment of the development of product variety along the supply chain

So far the focus was on the supply chain. The following steps shift the focus to the product level. To develop an understanding of the origin of product variety along the supply chain, the Module Interface Graph (MIG) and the tree of differentiating attributes are used. MIG is a tool, which was developed within the Life Phase Modularization method to map the product structure [21]. The MIG is an abstract representation of a product in which the components are registered. The approximate space requirements of the components and their locations are marked and the structural connections and the power, information and media flows are added. By developed symbols and items the components can be differentiated whether they are invariant, variant or optional.
The tree of differentiation attributes is used as a model of external product variety. The tree itemizes the product variety by the differentiating factors.
Therefore, a MIG and a tree of differentiating attributes are drawn for the output of each supply chain station. Both in the MIG, and in the tree of differentiating attributes, the components are colour coded, which were handled (assembled, disassembled, etc.) within the supply chain station.
This leads to greater transparency of product variety along the supply chain as well as the current level of postponement.
Two basic findings are obtained with this procedure. First the identification as to what extent modules are manufactured, supplied and installed, which supports the choosing of a modular sourcing strategy for obtaining parts and second, the level of postponement, which supports the identification and decision of the further postponement strategy.

3.4 Identification of weaknesses and their causes

After ascertaining and visualizing the number and diversity as well as variability of complexity, the next step is to identify the weaknesses and their causes within the supply chain. First the information is analysed, which is captured in the steps above. With this analysis such conditions, processes and relationships will be identified which are essential for the optimization of the product development.

Second those product characteristics are identified which induce the complexity within the supply chain. This identification takes place using directed graphs. For this purpose the influencing factors on the individual supply chain stations are ascertained and specified further. Subsequently the key factors are identified. These key factors will be communicated to the product development. Using this cause and effect diagram the product development can design the future products in a way that does not increase complexity.
Also other cause and effect diagrams, such as the Ishikawa diagram could be used instead of the method of directed graphs. Ishikawa diagram, however, is limited to the pure absorption of the causes and effects, regardless of the supply chain stations. To represent them as well, the Ishikawa diagram should be expanded accordingly. Insofar the directed graphs will be used to identify the key factors within this approach.

4. CONCLUSION AND PROSPECT

The complexity and the weaknesses of each station of the supply chain and the appearance of product variety along the supply chain are regularly not ascertained and visualized in companies. In this respect, no reliable information is available for an analysis of causes. Without ascertainment and understanding of this complexity, the requirements for the supply chain stations cannot be considered during the product development process and the optimized level of postponement cannot be identified. Therefore a procedure was developed to ascertain and to visualize the supply chain complexity.
This procedure, to ascertain and to visualize the number and diversity as well as the variability of the complexity, is divided into four steps, which are consecutive.
The resulting transparency is necessary to identify the requirements of the supply chain according to a high product variety. These requirements are used in the future to develop the methodology of Design for Supply Chain Requirements to define corresponding design guidelines of a modular product structure.
The need to develop a method to design for supply chain requirements has been identified in various companies in practice. The approach to visualize the supply chain complexity is already used in one company. It will be further detailed and its practicality verified in other different companies.

REFERENCES

[1] Anderson, C.: *The long tail: why the future of business is selling less of more*. New York: Hyperion, 2006
[2] Beckmann, H.: *Supply Chain Management, Strategien und Entwicklungstendenzen in Spitzenunternehmen*, Springer, Berlin Heidelberg, 2004
[3] Houlian, JB.: *International Supply Chain Management*, in International Journal of Physical Distribution and Materials Management, 14 (3), 1985, pp. 22-38
[4] Lee, H. L.: *Design for Supply Chain Management: Methods and Examples*, paper presented at Conference on Perspectives in Operations Management, UCLA, November, 1991
[5] Malik, F.: *Strategie des Managements komplexer Systeme*, Haupt Berne, 2002
[6] Patzak, G.: *Planung komplexer innovativer Systeme*, Springer, Berlin, 1982
[7] Ulrich, H., Probst, G..: *Anleitung zum ganzheitlichen Denken und Handeln*, Bern Stuttgart, Paul Haupt Verlag, 1995
[8] Conenberg, A.; Prillmann, M.: *Erfolgswirkung der Variantenvielfalt und Variantenmanagement*, Journal Zeitschrift für Betriebswirtschaft 11/1995 pp 1231-1253
[9] Schuh,G.: *Produktkomplexitätt managen*,Vol.2,München/Wien, 2005
[10] Heina, J.: *Variantenmanagement – Kosten-Nutzen-Bewertung zur Optimierung der Variantenvielfalt*, Wiesbaden, 1999
[11] van Hoek, R.: *The rediscovery of postponement, a literature review and directions for research*, Journal of Operations Management, 2001
[12] Dellanoi, R.: *Kommunalitäten bei der Entwicklung variantenreicher Produktfamilien*, Dissertation, Difo-Druck GmbH, Bamberg, 2006
[13] Becker, J.: *Prozessmanagement, Ein Leitfaden zur prozessorientierten Organisationsgestalltung*, Springer Berlin, 2005
[14] Davis, R., Brabänder, E.: *ARIS Design Platform: Advanced Process Modelling and*

Administration, Springer, London, 2008
[15] Busch, A., Dangelmaier, W.: *Integriertes Supply Chain Management*, Gabler, 2nd vol, 2004
[16] Rolf G. Poluha: *Application of the SCOR Model in Supply Chain Management*, Youngstown, New York 2007
[17] Scholtes, P.R.: *The Leader's Handbook: Making Things Happen, Getting Things Done, McGraw-Hill, 1998*
[18] Jones D.T., Womack, J.P.: *Seeing the whole: mapping the extended value stream*, Lean Enterprise Institute, 2002
[19] Jonas, H.; Krause, D.: *Produktfamilienentwicklung im Rahmen des Variantenmanagements*, Design for X, Beiträge zum 21. DfX-Symposium, Buchholz i.d.N., 2010, pp. 169-180.
[20] Kipp, T.; Krause, D.: *Design for variety - efficient support for design engineers*, 10th International Design Conference, - Design 2008, Dubrovnik, 2008, pp. 425-432.
[21] Blees, C.; Kipp, T.; Beckmann, G.; Krause, D.: *Development of Modular Product Families: Integration of Design for Variety and Modularization*, Proceedings of norddesign 2010, Gothenburg, Sweden, 2010, pp. 159 - 168.
[22] Brosch, M.; Krause, D.: *Beherrschung der durch Produktvielfalt induzierten Prozessvielfalt*, Design for X, Beiträge zum 21. DfX-Symposium, Buchholz i.d.N., 2010, pp. 193-204.

Contact: Max Brosch
Hamburg University of Technology
Product Development and Mechanical Engineering Design
Denickestr. 17 (L)
D-21073 Hamburg
Germany
Tel: +49 40 42878 2661
Fax: +49 40 42878 2296
Email: max.brosch@tuhh.de
URL: http://www.tu-harburg.de/pkt

Max Brosch has a Bachelor degree in General Engineering Science and a Master degree in International Production Management, both from the Hamburg University of Technologies (TUHH). He is research assistant at the Institute for Product Development and Mechanical Engineering Design. His research interest is the Design for Supply Chain and Design for Value Enhancement.

Gregor Beckmann studied mechanical engineering at Hamburg University of Technologies (TUHH). He is research assistant at the Institute for Product Development and Mechanical Engineering Design and works on the improvement of the mechanical design education of TUHH. His research interest is the application of knowledge management to support the product development process of modular product families.

Prof. Dieter Krause is head of the Institute Product Development at Hamburg University of Technology. He is member of the Berliner Kreis and the Design Society. Main topics of his research are new design methods with respect to product variety and modularization as well as lightweight design for aircraft interiors.