Assessment scheme for product and production flexibility – An industrial case study

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Abstract

Volatile markets and the integration of products into cyber physical systems state new challenges for companies. Especially products with long development times are more difficult to design since the quality of market forecasts decreases and the rate of change increases. It becomes necessary to continuously develop products and implement smaller changes according to current market trends to keep them attractive and remain able to offer them at a competitive price.

To manage the challenging market development, companies need to increase their flexibility. Therefore, the product family and the production system must be redesigned together to facilitate the implementation of unpredictable product changes in the product family and the corresponding production system.

This paper presents a case study conducted at a German car manufacturer, which is used to derive criteria for the comparison of modular product concepts in terms of flexibility from a product development and production perspective.

Keywords: flexibility, responsiveness, modularization, production, cyber physical system

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1 Introduction

Volatile markets and the integration of products into cyber physical systems state new challenges for companies. Especially products with long development times are more difficult to design since the quality of market forecasts decreases and the rate of change increases (Fricke, Schulz: 2005, Beauville dit Eynaud et al.: 2022). In cyber physical systems, components with diverging lifecycles are combined. In particular, the shorter value lifetime of software components causes changes or enhancement of hardware components. It becomes necessary to continuously develop products and implement smaller changes according to current market trends to keep them attractive and remain able to offer them at a competitive price (Peterson, Summers: 2021, Fricke, Schulz: 2005).

To manage the challenging market developments, companies need to increase their responsiveness. For instance, in the automotive industry products are developed with the knowledge that a new version will be launched about three years later with predefined changes. The production system is (re)designed specifically for this product family, but due to the long amortization period, it will also be used for the next one. Any product change must be compatible with the production system with regard to production technology, assembly sequence and cycle time, to avoid costs and inefficiencies. To facilitate the implementation of unpredictable changes, it is necessary to redesign the product family and the corresponding production system together with a focus on flexibility. Modularization is a suitable tool to incorporate flexibility in the product design and consider strategical aspects from other life phases such as the production. It supports the development of products with decoupled modules, enabling parallelization of processes in development and production.

2 Research Background

There is a great amount of literature regarding flexibility and related expressions, but none of them includes specific guidelines or measures to support the engineer in the design for flexibility (Beibl et al.: 2021). Nor do they contain suitable characteristics for the early phase to compare concept alternatives regarding flexibility.

2.1 Product Development

In product development the expression flexibility does not play such an important role as in the production science. The main focus lies on the implementation of changes (Beibl et al.: 2021). Nevertheless, there are approaches to incorporate flexibility in the development process and the product design. Fricke & Schulz (2005) introduce nine principles (including their interrelations) which support the implementation of future product changes. Further guidelines are presented by Palani Rajan et al. (2005) and Tilstra et al. (2015). However, there is a lack of methodological support for the implementation of these principles and the evaluation of the concepts developed.

Others in turn derive possible product changes from forecasts. Hence define change-critical components and analyze the impact of these changes on the product (family) (Palani Rajan et al.: 2005, Greve et al.: 2021) as well as the production system (Suh, Weck, Chang: 2007).

Moreover, modularity is often mentioned as an enabler for flexibility (Tilstra et al.: 2015, Palani Rajan et al.: 2005, Sanchez: 2005, Schwede et al.: 2022, Saleh, Mark, Jordan: 2009). Although modularization methods do not provide specific measures to increase and assess the flexibility of alternative design concepts (including their processes) (Saleh, Mark, Jordan: 2009). From modularization with consideration of strategic module drivers (Krause, Gebhardt: 2023, Erixon, Yxkull, Arnström: 1996, Halfmann, Elstner, Krause: 2011) it is known that certain module drivers such as parallelization increase the flexibility in the assembly (Küchenhof, Krause: 2020).

2.2 Production

The survey by Sethi & Sethi (1990) provides a detailed overview of the different perspectives on flexibility seen from the perspective of production and is still of relevance. They distinguish between eleven types of flexibility. Some of them can be assessed by key figures such as ratios of possible alternatives to actual alternatives. More recent literature introduces new organizational forms of production systems which offer promising flexibility. New possibilities for flexibility arise with the application of the Internet of Things, data analytics and other technologies to derive a cyber physical production system (Enrique et al.: 2022). But guidelines on how to design a flexible production system have not been found.

3 Research Question

The presented motivation and research background highlight the need for methodical support for engineers in developing product and production concepts with higher flexibility. This leads to the question which characteristics of the product and the production system are to be considered in the comparison of concept alternatives in terms of flexibility.

4 Research Method

To derive an assessment scheme regarding flexibility, an industrial case study was set up at a German car manufacturer. Modularization workshops were conducted with the aim of developing a product family including production concepts for higher flexibility. The characteristics for flexible product design and production systems were derived through observation of the discussions during the workshop, participant feedback, and the analysis of the developed product and production concepts. Based on that, criteria to assess and compare concept alternatives were defined.

4.1 Description of the Industrial Case Study

The industrial case study consists of two workshops which were held onsite at the German car manufacturer. The workshop participants were selected from product development and production. The product development participants were from the department for complete vehicle pre-development, with varying expertise in geometric and functional design. The production participants were experienced planners from various production units as well as colleagues from pre-development. Two of the participants had previous experience of flexible production systems. Three of ten participants could only join via video conference. The workshops were performed using a former product family of cars which shared some components and production facilities. The different car models were offered with a high external variety and produced in high volumes in a line production. The task was to apply the life phases modularization (see Krause, Gebhardt: 2023) in a slightly modified way with focus on flexibility regarding the implementation of future unknown changes. Therefore, the redesign of the product family and the production system was considered a greenfield approach. Topics concerning logistics and efficiency planning were left aside.

To modularize a complex and large product like a car, suitable scopes with corresponding levels of detail were defined. The complete vehicle was modularized using a lower level of detail in the first workshop. The developed draft of modules served as a starting point for further workshops with a smaller scope but higher level of detail. For example, the second workshop covered two of the twelve pre-defined modules from the first workshop focusing on the front part of the car.

Each workshop started with a brief introduction to the concept of flexibility and why the current product design and production system may no longer be suitable for the market environment. This was followed by an explanation of modularization, including the specific method which was to apply. The life phases modularization starts with the acquisition of module drivers and specifications for each life phase, which are then used as categories to cluster components in network diagrams. To prepare the participants for their task, barriers and enablers related to the integration of changes were discussed. Based on that, the goals for the modularization with focus on flexibility were defined together. In the third step, modules are derived from the component clusters and discussed among the life phases.

The preparatory work revealed that the production units have diverging goals, challenges, and boundary conditions. These cannot be captured in a single network diagram during the life phases modularization. For this reason, the life phase production was split up into car body construction, paint shop, assembly, and final assembly. Nevertheless, the participants of the different production units worked as one team on the life phases of the production. As a supplement to the network diagram the team was asked to draw the product structure and start with the final life phase, namely the final assembly. Through this, the input of the final assembly defined the output of the pre-assembly and so forth. This procedure prevents the team from defining inconsistent in- and output for the different life phases, as the assembly structure was to be built with a single set of component cards. The workshops concluded with a presentation of both teams' results and a final discussion of the findings. The main findings, feedback on the workshop implementation and method application were summarized on a whiteboard. During the first workshop, the participants created a preliminary modular structure for the entire car, albeit at a low level of detail. In the second workshop, which focused on the front part of the car, one concept was developed from the product development perspective and two from the production perspective.

4.2 Analysis of the Industrial Case Study

The analysis of the industrial case study focusses on the results of the second workshop, due to the higher level of detail and easier comparability of alternative concepts of the front part of the car.

The participants from the product development aimed to develop modules separately and encapsulate change propagation within them. Changes shall be integrable into series products for module-wise further development of the products and technical validation. Therefore, they started with the clustering of components according to technical functional aspects and discussed the functional and geometrical coupling of components. With increasing familiarity with the method step, the participants refined the network diagrams and applied strategical aspects such as the module driver styling by Erixon (1998). To keep the design of the product attractive, components such as decorative trims and covers which are visible to the customer shall be decoupled for easy redesign. Components of the car body which carry characteristics for the differentiation of car models are clustered separately. Overall, the team was satisfied with its developed component cluster. They derived only one concept for the modular product structure of the front part of the car, since almost no discrepancies appeared. The participants solely refined the cluster through the definition of the modules. Interfaces raised questions about the structural decoupling of modules for greater flexibility. However, the design of interfaces is not considered within the life phases modularization. Further research is required regarding the role of interfaces in the redesign.

The pre-defined goal for the production was to maintain stable production processes despite the steady integration of changes. As a starting point, the participants drew the current assembly structure. From the viewpoint of the final assembly, pre-assembly groups were defined to reduce restrictions resulting from the chain of sequential assembly steps. These assembly groups state the output of the previous life phases of the production. To further decouple production processes and areas for easier change integration, the participants used “parallelization/ decoupling” of assembly and pre-assembly groups as a clustering category. The component firewall (see bottom line in Figure 1) was identified to be a suitable carrier for pre-assembly of the pedalry and the brake cylinder, due to its stronger structural coupling. Instead of gluing the firewall to the car body in the car body construction, the pre-assembled components can be mounted on the car body via a single step in the assembly, as opposed to multiple sequential steps. The main challenge concerning the integration of changes into joining processes is the complex and expensive clamping device. Clamping devices are particularly used in the car body construction to build the car body within the desired tolerances and are designed for each variant. Especially the shell design, which constitutes the common car body structure, requires clamping devices to force and keep the metal sheets in position for joining. Therefore, a concept alternative using profile-shaped components was discussed (see Figure 1).

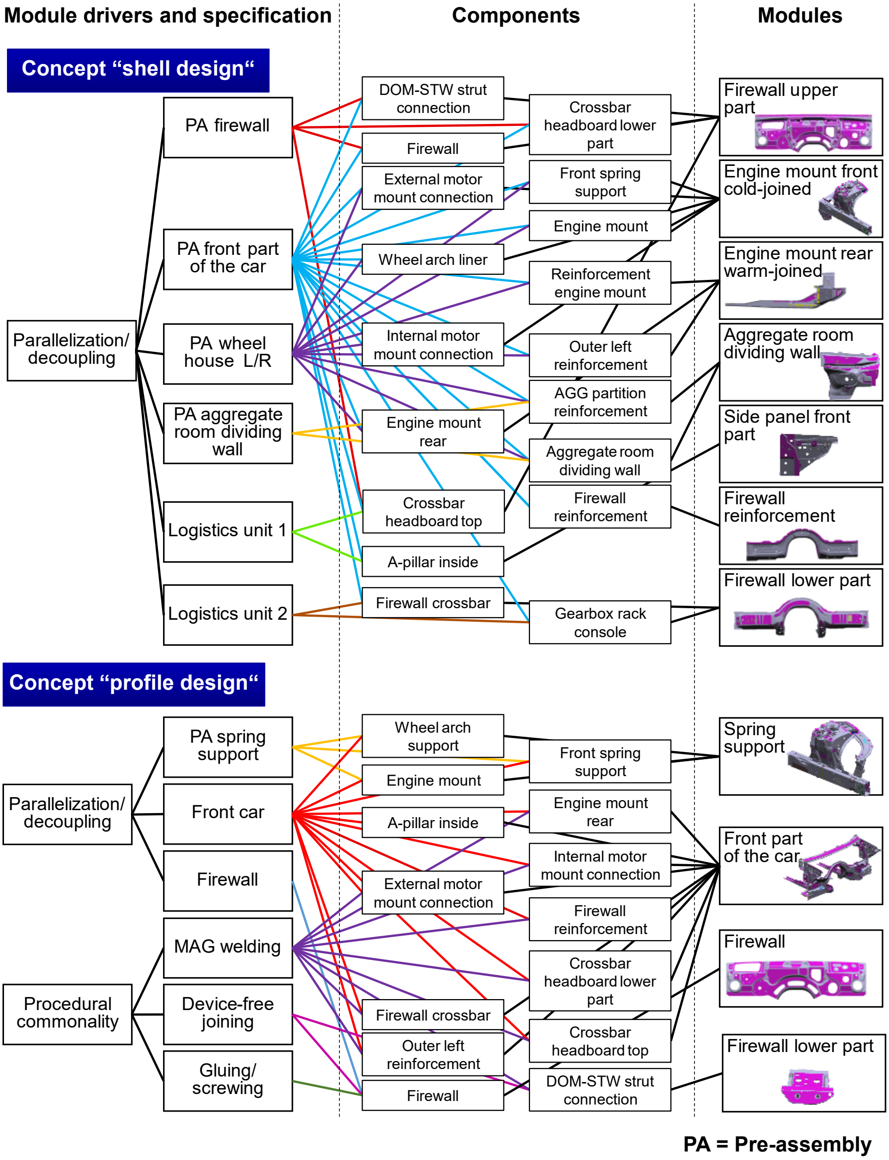

Figure 1: Edited network diagrams of the life phase car body construction

This would allow to join at least components which are not part of a critical tolerance chain, without any clamping device. Changes can be easily integrated through reprogramming of the robots, using the same joining technology. However, the design is restricted to one material, ensuring the weldability of the assembly group. Comparing the two concepts concerning flexibility, the participants concluded that the interface design and chosen material restrict the choice of joining technologies. Depending on the perspective, different concept alternatives are prioritized due to the diverging flexibilities in design and joining technologies regarding reconfiguration of the production process and equipment. For example, MIG/ MAG welding restrains the freedom in design but provides greater freedom concerning the interface. If robots position the components without special devices, commonal usage of the production units is possible across assembly groups and their versions. Separate testing in terms of operability or dimensional accuracy was seen as a strategic aspect to generate prompt quality feedback and do rework, especially in case of testing new or changed production processes for prototypes. The team's focus was on the decoupling of production processes. The participants explained that they lack ideas for processes and production equipment for commonal usage. Transferring solutions from other production systems was seen as not applicable, due to divergent boundary conditions.

5 Evaluation Criteria for Flexibility

The analysis of the case study showed that various aspects must be taken into account when evaluating and comparing product concepts regarding flexibility. This is supported by the literature which presents different criteria for evaluating flexibility in the field of product development and production. The following criteria are derived from the analysis of the life phase product development.

- The encapsulation of functions in modules is important to avoid or at least limit the propagation of changes across module boundaries. This aspect can be evaluated by counting the connections, often represented as flows, between modules: the lower the number of connections, the better the modular concept.
- The encapsulation of components related to styling or characteristics for model differentiation (like the side frame) into modules is important to facilitate the redesign of the product's appearance. Therefore, appropriate modules including interfaces must be defined. This specific type of decoupling can be evaluated by counting non-appearance-related modules that are affected by an appearance redesign.
- The design of the interface and the corresponding joining technology are essential for the freedom in the redesign of modules. However, no specific characteristic has been identified so far for the evaluation of this aspect. Depending on the interface, different solutions are suitable, such as standardization in the case of plugs and clips. Screw connections can be easily adapted to the new design and mounted in the car body construction as well as

in the assembly. Special welding technologies can be used similarly to additive manufacturing to join components whose interfaces no longer fit after redesign and thus preventing the propagation of changes across modules.

The following criteria are derived from the analysis of the life phases of the production.

- The definition of modules according to pre-assembly groups is important for decoupling and parallelizing production processes. Changes are easier to implement in small production units than in long sequential process chains. Long sequential process chains are an indicator for mounting single components on the product. This decoupling or parallelization can be evaluated by counting the sequential process steps in the assembly structure: the lower the number of sequential steps in a row, the better the modular concept.
- Depending on the product structure and the joining technology, different requirements arise for component positioning and clamping, which can result in significant investments in production equipment. To address this aspect, the number of clamping devices can be counted, with a lower number indicating a better modular concept.
- The design of the interface and the corresponding joining technology are essential for the integrability of redesigned modules into the production. However, no specific characteristic has been identified so far for its evaluation. Some interfaces only require reprogramming or retraining of robots and staff, while others require a redesign of production steps and equipment.

6 Discussion and Outlook

This paper provides a brief overview of research approaches concerning flexibility in product design and production. An industrial case study was conducted at a German car manufacturer to identify characteristics of the product, and the production system for the comparison of concept alternatives regarding flexibility.

The analysis of the case study revealed that decoupling was seen as a crucial factor for flexibility. The team of the product development focused on creating modules based on functional and appearance module drivers to encapsulate changes into modules. The team of the production defined clusters of pre-assembly groups which shape small production units where changes can be implemented more easily. Another important aspect is the product’s interfaces which are decisive for the change propagation in the product and into the production system. The interface design determines the joining technology and required production equipment. Further analysis of the interfaces is necessary to derive a set of criteria for the comparison of concept alternatives.

Nevertheless, not all of the developed criteria are visualized in the network diagrams of the life phases modularization. However, other tools from the toolbox of the Integrated PKT-Approach (according to Krause, Gebhardt: 2023) provide suitable visualizations of the information and may be utilized for this purpose. Further research is necessary to develop an evaluation scheme for flexibility and to test it.

Future research should consider the productivity of the production system by using digital models to compare the performance of alternative product and production concepts, as well as their associated monetary aspects.

References

Beauville dit Eynaud, A., Klement, N., Roucoules, L., Gibaru, O., & Durville, L. (2022): Framework for the design and evaluation of a reconfigurable production system based on movable robot integration. The International Journal of Advanced Manufacturing Technology, 118(7-8), 2373–2389. https://doi.org/10.1007/s00170-021-08030-1

Beibl, J., Lee, J., Krause, D., & Moon, S. K. (2023): Flexibility - Grand Challenge for Product Design and Production: Review and Status. In: *Procedia CIRP,* 119, 91–96.

Enrique, D. V., Marcon, É., Charrua-Santos, F., & Frank, A. G. (2022): Industry 4.0 enabling manufacturing flexibility: technology contributions to individual resource and shop floor flexibility. In: *Journal of Manufacturing Technology Management,* 33(5), 853–875.

Erixon, G. (1998): Modular Function Deployment: A Method for Product Modularisation. Dissertation, The Royal Institute of Technology, Stockholm.

Erixon, G., Yxkull, A. von, & Arnström, A. (1996): Modularity – the Basis for Product and Factory Reengineering. In: Annals of the CIRP, Vol. 45, 1-6.

Fricke, E., & Schulz, A. P (2005): Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. In: Systems Engineering, Vol. 8, No. 4, 342-359. https://doi.org/10.1002/sys.20039

Greve, E., Fuchs, C., Hamraz, B., Windheim, M., & Krause, D. (2021): Design for future variety to enable long-term benefits of modular product families. In: *Proceedings of the Design Society,* 1, 993–1002. https://doi.org/10.1017/pds.2021.99

Halfmann, N., Elstner, S., & Krause, D. (2011): Product and process evaluation in the context of modularization for assembly. In Proceedings of 18th International Conference on Engineering Design (ICED 11) (pp. 271–281).

Krause, D., & Gebhardt, N. (2023): *Methodical development of modular product families: Developing high product diversity in a manageable way.* Berlin, Heidelberg: Springer.

Küchenhof, J., & Krause, D. (2020): INITIAL INTEGRAL PRODUCT AND ASSEMBLY STRUCTURING: A CASE STUDY. Proceedings of the Design Society: DESIGN Conference, 1, 2305–2314. https://doi.org/10.1017/dsd.2020.88

Palani Rajan, P. K., van Wie, M., Campbell, M. I., Wood, K. L., & Otto, K. N. (2005): An empirical foundation for product flexibility. In: *Design Studies,* 26(4), 405–438. https://doi.org/10.1016/j.destud.2004.09.007

Peterson, M., & Summers, J. D. (2021). Recommended Methods Supporting Adoption of the Agile Philosophy for Hardware Development. In Volume 6: 33rd International Conference on Design Theory and Methodology (DTM). American Society of Mechanical Engineers. https://doi.org/10.1115/DETC2021-70621

Saleh, J. H., Mark, G., & Jordan, N. C. (2009): Flexibility: a multi-disciplinary literature review and a research agenda for designing flexible engineering systems. In: *Journal of Engineering Design,* 20(3), 307–323. https://doi.org/10.1080/09544820701870813

Sanchez, R. (2004): Creating Modular Platforms for Strategic Flexibility. Design Management Review, 15(1), 58–67. https://doi.org/10.1111/j.1948-7169.2004.tb00151.x

Schwede, L.-N., Greve, E., Krause, D., Otto, K., Moon, S. K., Albers, A., et al. (2022): How to Use the Levers of Modularity Properly - Linking Modularization to Economic Targets. In: *Journal of Mechanical Design,* 144(7). https://doi.org/10.1115/1.4054023

Sethi, A., & Sethi, S. (1990): Flexibility in manufacturing: A survey. In: *International Journal of Flexible Manufacturing Systems,* Vol. 2, 289-328. https://doi.org/10.1007/BF00186471

Suh, E. S., Weck, O. L. de, & Chang, D. (2007): Flexible product platforms: framework and case study. In: *Research in Engineering Design,* 18(2), 67–89. https://doi.org/10.1007/s00163-007-0032-z

Tilstra, A. H., Backlund, P. B., Seepersad, C. C., & Wood, K. L. (2015): Principles for designing products with flexibility for future evolution. In: *International Journal of Mass Customisation,* 5(1), 22. https://doi.org/10.1504/IJMASSC.2015.069597

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