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Flexibility - Grand Challenge for Product Design and Production: Review and Status

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Abstract

As seen in recent years, the volatile, uncertain, complex, and ambiguous environment has made flexibility in product design and production planning more important than ever. Therefore, companies must be able to quickly respond to the dynamically changing environment. However, research on the flexibility of product design and manufacturing systems has been underway for a long time, only a few studies address their relationship.

In this paper, we give an overview of literature related to flexibility and add transparency to the relationship between engineering changes, product development, and production. Based on that, we propose a conceptual framework for co-development to improve the flexibility of product development and production. As part of the framework, we introduce a visualization that reveals the propagation of changes in the product and into the production to create deeper insights for conjoint redesign. To exploit further synergies of product and production, we suggest modularization with focus on strategic module drivers enhancing flexibility. Further support for the comparison of alternative concepts can be provided through digital twin-based simulations of the production system.

Keywords: flexiblity; modularization; digital twin

1. Introduction

The VUCA (Volatile, Uncertain, Complex, and Ambiguous) environment brings along new challenges for companies accompanying less planning reliability. Since the VUCA environment cannot be avoided, companies need to increase their flexibility for reacting to new or changed requirements or demands and stay competitive. Industrial surveys through different industries reveal that almost one quarter of engineering changes is caused by external changes [1]. The numbers will rise due to volatile markets and the fact that products more and more become part of cyber physical systems whose technologies evolve quickly [2].

Especially in the early phase of product development, many changes occur because of missing information about requirements. Thus, assumptions are made based on misleading forecasts which lead to later changes [3,4]. Those are usually not documented in the Change Management and thus not included in the surveys.

Analysis of the Change Management shows that according to the Rule of Ten, the costs and efforts for changes rise with progressing development maturity. But prevention and front-loading of changes is not a promising solution for companies in a volatile environment. [4] However, implementing flexibility is often associated with pre-implemented buffers and unexploited high investments [5].

This paper presents a conceptual framework "to break the Rule of Ten to enable cost-efficient and quick late changes" [4] through the implementation of flexibility in product development and production. Based on the literature review provided in section 2, the conceptual framework introduces a methodical support of the co-development.

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2. State of the Art

The investigation of Scopus citation database shows the high interest of engineering science in flexibility. First papers about the flexibility date back to the 1920ies and the number of published papers is increasing - from the year 2010 on more than 500 documents per year. One of the most cited papers is the survey of Sethi and Sethi [6] where the authors provide an overview about the different interpretations of the flexibility seen from the manufacturing perspective. Depending on the point of view, different definitions and types of the flexibility are stated in academia, without being clearly distinguished and consistently used [6,7]. Even other expressions are used synonymously to flexibility. Therefore, we also investigated publications considering adaptability, agility, changeability, reconfigurability, versatility and robustness regarding modular products and/or manufacturing.

In this paper we define flexibility according to Mandelbaum [8] as the ability to react or adapt to changes. Even after the start of production it is important to be able to keep the product attractive through ongoing development or derivation of new variants for changing markets [9,10]. Hence product design and production need to be flexible [11].

2.1. Flexibility in Product Design

Challenges in product development are typically addressed through so-called Design for X approaches. One highly cited approach, which addresses the implications of the VUCA environment on a system architecture, is the Design for Changeability by Fricke and Schulz [2]. In the approach, flexibility is mentioned as one of four key aspects besides adaptability, agility and robustness. In contrast to the flexibility - the ability to react easily to changes, the agility is defined as the ability to react quickly, the adaptability as the ability to adjust oneself within a changing environment and the robustness as the ability to continue fulfilling one's performance despite changed circumstances. [2]

In the following different views on how to deal with changing requirements in a VUCA environment and thus increasing the flexibility, as defined in chapter 2, are presented.

In product design in industry, there is a big hype about agile working focusing on organizational aspects of the product development to shorten the time to market, especially in competition with start-ups [12,13,14], which is not sufficient to meet the challenges of the VUCA environment.

In academia, some researchers focus on the evaluation of the likelihood for change. They try to predict future changes in the requirements through trend scenarios and analysis of past data sets from Change Management. Based on that the directly or indirectly affected components are identified [15,16,17,18,19,20,21] and future requirements are considered in advance through either buffer zones and oversized components or parametric design with the postponement of design decisions via parameter variation [18,22,23,24]. Another or complementary way is to examine the Change Management or more specific the Change Propagation in order to improve the capability of dealing with changes in general and estimate the change effort [15,16,18,19,21,25].

Modular product family design can prevent the spreading of changes through decoupling. Furthermore, the product modification can be split into smaller tasks according to modules and can be worked on concurrently which improves the company's responsiveness [26]. In general, modularization allows a good balance between standardization and differentiation, whereby modularity facilitates the derivation of new variants [27,28] for satisfaction of volatile markets. Apart from that, strategic module drivers, which for example consider co-development [26] can support the integration of product changes into the production system. Thus, modularization is often mentioned as a key enabler for flexibility [25,29,30,31,32]. The scientific community is aware of the importance of the topic, but methodical support for the implementation of flexibility is still missing. Especially the methods which are not based on foresight. As recent years told us, the evolvement of technologies and global markets became far less predictable. This concerns in particular the design of products or product families with long development times.

2.2. Flexibility in Production System

Flexibility in manufacturing has been observed in a wide variety of perspectives and defined by various criteria. Sethi and Sethi classified the flexibility in manufacturing into 11 categories [6], whereby this paper only addresses the following five classes, related to the responsiveness respective changing market requirements which afford modifications in the product design and the product structure.

The most fundamental type of the flexibility of a manufacturing system is machine flexibility - the ability of a machine to execute a variety of operations [33]. It serves as a crucial foundation for assessing overall flexibility, since the machine flexibility encompasses the properties of the machine: its equipment including tools, fixtures and its software control. The versatile usage of the machine enables the integration of components or products with new design into the production system and thus avoids the replacement of machines in case of changeovers of the production system [6].

Process flexibility is the ability to produce a diverse mix of part types with minimal efforts respective equipment change in the production system.

Compared to that, material handling flexibility is defined as the ability of a manufacturing system to move a wide variety of components through the shop floor, position and keep them in place for processing [6]. Therefore, tools, fixtures and jigs need to be designed for a versatile utilization over a wide range of components. Hence, changes in the market demand can be met and also the introduction of new products with low setup times and investments. [6]

Already in the 1970s the need for machine, process and material handling flexibility has emerged, when dedicated manufacturing lines (DMLs) became uneconomic, due to the shift from mass production with economies of scale to economies of scope. Flexible manufacturing systems (FMSs) are designed to manufacture a wide variety of products and consist of machines which are able to execute diverse operations. Compared to DMLs, FMSs have lower output rates and afford high investments. [34] Because of that and unexploited capabilities respective machine and process flexibility, FMSs have not gained acceptance [35,36]. To overcome the drawbacks of FMSs and DMLs, reconfigurable manufacturing systems (RMSs) have been introduced. RMSs are designed for the production of a product family with the possibility for reconfiguration in case of future changes. [34]

The capability of a manufacturing system, to produce a part or product with a varying sequence of production steps and/or varying machines, is defined as routing flexibility [6]. Routing flexibility is important in case of a disruption or changeover in the production system. Therefore, the production layout and logistics are decisive. In a line production, disruptions or changeovers lead to a downtime of the whole production line. In comparison, a matrix production can continue to produce at a lower volume if there is at least one machine which covers the concerned operations [37,38].

Operation flexibility is the ability of a component to be manufactured with alternative manufacturing processes and/ or differently sequenced process steps and thus raises the number of possible routes that a component can take through the manufacturing system. [6] Concerning a single item production, the degree of the operation flexibility is dependent of the geometrical design of the component. Regarding assembly processes, the hierarchical shape of the product structure defines whether assembly steps can be performed in parallel with varying sequence or not. The flatter the structure, the higher is the number of assembly groups that can be pre-assembled in parallel.

Current research started with the performance analysis of RMSs in a matrix production via simulations to identify the proper design of manufacturing systems with the right level of flexibility [37,38,39].

Fig. 1 shows the scheme of the new production of the front axle beam from BMW plant Dingolfing, where 8 variants of front axle beams are produced in one production system. The previous production system consisted of one production line for each variant. This high process flexibility was achieved through the replacement of variant specific, mechanical fixtures and jigs by robots with versatile grippers handling, positioning and holding in place the components. [40] For the usage of versatile grippers, the components must be designed with so-called component-integrated fixture features (CFFs) [11]. The necessary machine flexibility is provided for the different welding and weld seam control processes via changeable software programs [41]. The arrangement of these redundantly equipped cells in a matrix layout allows the flexible routing free of a cycle time and with a balanced machine utilization [41]. The cells are connected via a robot axis and Automated Guided Vehicles (AGVs) for supply. The flexible design of the front axle beam production led to a 20% reduction of the investment costs compared to the previous production lines [41]. In case of changeovers due to the integration of new product variants or generations, downtimes are limited to single cells instead of the whole production system [41].

3. Conceptual framework for flexibility

The influence of the VUCA environment on a company cannot be regarded separately in product development and production. Consequently "over-the-wall-engineering", which is common practice, needs to be overcome [42]. Especially in early design phases, product concepts are handed over to production specialists for evaluation and are adapted according to the feedback. But synergies of both departments are not exploited, since the "walls" between the design and the manufacturing standards are not discussed. Therefore, this paper presents a conceptual framework, where product design and production planning co-develop a product family and its corresponding production system to improve the company's flexibility.

Like the puzzle piece shown in Fig. 2, future new or changed components, designed to satisfy customers' requirements or political regulations, need to fit into the product family and the production. The method toolkit for Design for Variety according to Krause et al. [43] already covers some of the aspects enabling flexibility. In general, transparency about the product family can be derived with the so-called Variety Allocation Model (VAM) which maps product properties to functions via operating principles to components and displays their variant characteristics. These relations visualize the path of change propagation in the product. Components with a high number of connections are more likely to affect other components in case of changing requirements or are affected by the change propagation of others. The spreading across product variants of a product family is retraceable via the type of variety of each component. For the visualization of the change propagation into the production system, the VAM needs to be expanded about the product structure including information about the joining relations, as shown in Fig. 3.

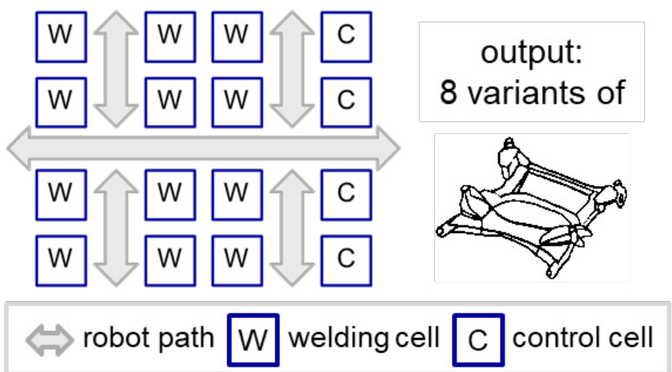

Figure 1: Schematic representation of the front axle beam production

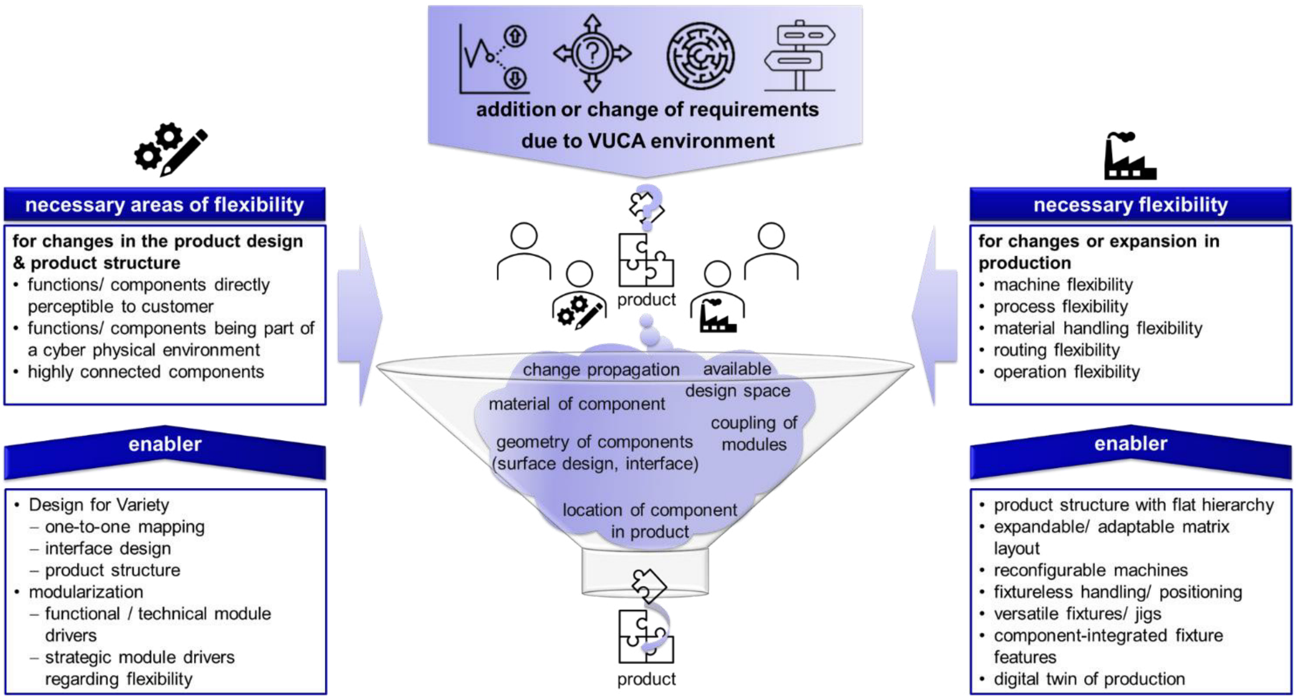

Figure 2: Conceptual framework for flexibility

Besides, the VAM focuses on variant components, but needs to contain all components for this application. The visualized relations also help to identify and separate highly connected components, components/ functions directly perceptible to the customer and those being part of a cyber physical environment, which are more likely affected by change.

The Life Phases Modularization by Krause et al. [43] suits as a basis for co-development, because of the consideration of strategic module drivers which address the requirements from different life phases of the product including the development and the production. As already mentioned in chapter 2.1 modularity can increase the responsiveness of the product development through decoupling of modules and thus preventing change propagation across modules and parallelizing product modification tasks according to the module structure. Furthermore, modularity facilitates the derivation of new variants through the combinability of modules. Since the integration of product modifications into the production is easier in case of a matrix production with a high level of automation and reconfigurable machines, where single cells can be adjusted or added in parallel to the running production as mentioned in the industrial example above, this paper focuses on this type of production in the following. Clustering components according to their joining process helps to share the usage of production cells across modules and thus increase flexibility. Another example of module driver specification can be "parallel process" to cluster components to assemblies to realize a product structure with flat hierarchy and modules with a similar size for material handling. During the modularization, discussions can arise about redesign of the product and the production to avoid investments in case of later changes. As described in the industrial example, component-integrated fixture features and versatile usable production

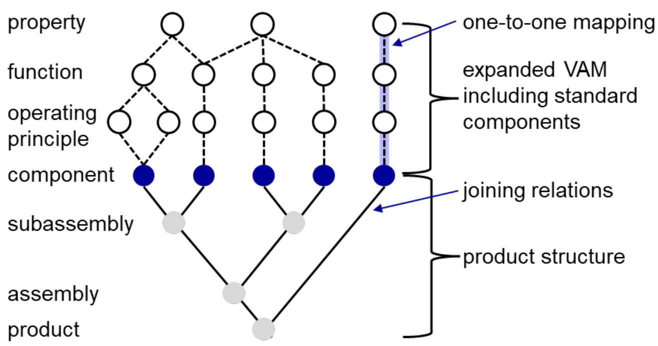

Figure 3: Sketch of the supporting tool for the conceptual framework

equipment were implemented for the sharing of production cells across variants.

Simulations using data from digital representations of the production system – their digital twins (DT) - can give further insights into production strategies and planning. There are two key factors that enable the enhancement of the production system towards more flexibility. First, with the help of sensorization technologies of physical resources, data and information are now more easily available than ever, allowing for flawless real-time simulation and communication between the physical and virtual platforms. Second, advances in simulation technology enable researchers to use different kinds of tools to model the desired production system. Since production system modelling is complicated, a lot of researchers use discrete event system simulation to design production systems and configuration. For example, Zhang et al. [44] proposed simulation-based strategy that combines heuristics and mathematical algorithms to balance the performance of operations and planning costs. And they suggested a framework for a simulation-based approach to designing plant layouts. Siano et al. [45] provided a simulation work to validate the efficacy of two design methodologies. Ducloux [46] introduced an integrated simulation model to forecast the lifespan of components of a product. These DT-based simulations are generally designed to obtain optimal production performance output such as minimizing process time and cost and maximizing resource utilization. However, the biggest advantage of utilizing DT-based simulations in terms of production flexibility is, that it can provide decision-making support and criteria through manufacturing data analysis and comparison of different scenarios. For example, Shanghua et.al [47] presented a cooperative awareness and interconnection framework across organizations for the overall factors affecting predictive maintenance decision-making to address faulty issues on machines, bottleneck prevention and improvement of production systems. Chua et al. [48] proposed a method to build a surrogate model for predicting production performance using input parameters from production plans, by exploiting the capabilities of data pervasiveness on DTs in smart manufacturing.

The benefit of the proposed framework for modularization lies in the co-development of the product. Product design and manufacturing gain deeper knowledge on how product and production influence each other and thus are able to overcome their boundaries to increase the flexibility. Simulations based on DTs of the production system provide support for decision-making and validation. However, the presented conceptual framework shows some limitations. So far, the framework does not cover product changes regarding software and part manufacturing. It does not provide an evaluation criterion to compare different product and production concepts regarding flexibility. Besides, further research is necessary to gain deeper insights into the potentials of a matrix production. Therefore, simulations need to be conducted. The framework and its applicability will be tested and elaborated in an industrial case study.

4. Closing remarks

In this paper, we gave an overview of the different views on flexibility and proposed a conceptual framework which shows how current research approaches can be combined to exploit the synergies for flexibility in product development and production to meet the challenges of the VUCA environment. Transparency about the change propagation, from product properties via functions, operating principles and components to the product structure, helps to redesign a product family and the corresponding production concept to keep the spreading of future changes low. Further coordination of product and manufacturing to reach overall flexibility, is enabled by Life Phases Modularization with focus on module drivers for flexibility. The DT-based simulations of the production system provide information for the evaluation and validation of the developed concepts. However, the applicability of the presented conceptual framework is not proven yet. Testing and elaborating the framework in an industrial case study is subject of further research.

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