Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 128 (2024) 204–209

www.elsevier.com/locate/procedia

34th CIRP Design Conference

Product and production design - Rethinking views on flexibility

Julia Beibl[a]*, Jan-Philipp Disselkamp[b], Roman Dumitrescu[c], Dieter Krause[a]

[a]Institute of Product Development and Mechanical Engineering Design, Hamburg University of Technology, Denickestrasse 17, 20173 Hamburg, Germany
[b]Fraunhofer IEM, Zukunftsmeile 1, 33102 Paderborn, Germany
[c]University Paderborn - HNI, Fürstenallee 1, 33102 Paderborn, Germany

* Corresponding author. Tel.: +49-151-601-23275 ; fax: +49-40-42878-2296. *E-mail address:* julia.beibl@tuhh.de

Abstract

The recent years have shown that long global supply chains are vulnerable considering volatile markets. As a result, efforts to achieve supply chain resilience are increasing. Achieving resilience requires flexibility, incorporated in product development, which can be implemented by the production system. Flexibility also offers the advantage in the context of sustainability that production facilities remain in use longer than rigid production lines because they can be better retrofitted. Furthermore, volatile markets challenge companies with a higher frequency of changes of requirements and decreasing forecast quality. Accompanied by a decreasing time-to-market and higher complexity of products companies need to increase their overall flexibility. A particular challenge is that routing flexibility is not used in production, for example, because the control effort is too time-consuming and complex. The use of AI and cyber-physical systems provides support to manage the control effort and thus enable flexibility in production. This paper discusses the role of flexibility in product development and production planning. The characteristics of products and production systems are analysed to identify important design aspects for flexibility. Comparing different systems shows for instance that non-linear structures with flexible links offer strategic advantages.

Keywords: flexibility; product & production design; Design for X;

1. Introduction

Nowadays companies are facing short technological lifecycles as well as innovation pushes and the customers' expectation to be provided with them. This quickly changing market environment is also referred to as a volatile, uncertain, complex, and ambiguous (VUCA) world in the literature [1,2]. However, products and production systems are designed for a long sales period or lifetime [3,4] and are therefore planned long in advance, which is in contradiction to the rapidly changing market requirements. To proactively handle the VUCA world, strategic flexibility can be employed [5–7], enabling the continuous development of a product even after the start of production. New technologies, such as AI and the Industry 4.0 theorem, offer new possibilities for increasing flexibility. However, based on current research, it remains unclear how to co-design a product and production system which provides sufficient flexibility to allow the integration of unknown future changes [8,9]. Fig. 1 illustrates the propagation of change from the market to product and production design, represented as a wave of change, which spills over into the production system. The ideal production system, with a flexible structure and reconfigurable machines, then allows new products or products with new features to be easily integrated and produced.

This paper examines the required flexibility from the perspective of product development. Therefore, the impact of product changes on the production system are deduced through analysis and reasoning. Furthermore, it analyses the correlation between the production system's flexibility and its characteristics to outline important design aspects.

10.1016/j.procir.2024.03.010

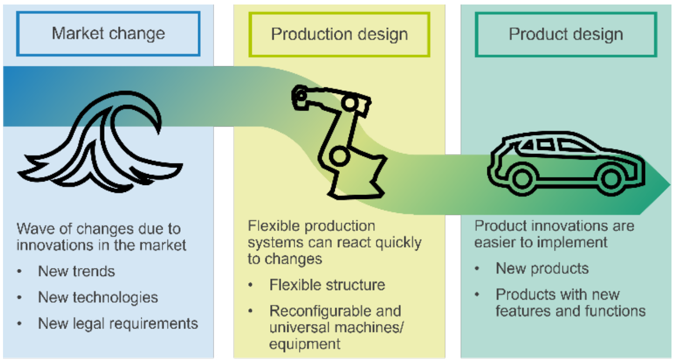

Fig. 1. Changes requiring flexibility in product and production design.

2. State of the Art

Current research points out the high interest in flexibility of research [8] and industry [10]. Although, flexibility in product development and production has a long and well-established history of research, recent surveys show that companies worldwide indicate the need for further research concerning flexibility, resilience and so forth [10].

In the technical context of product development, flexibility refers to the ability to cope with environmental turbulence and to react rapidly to new technological and market information which may arise during lengthy development phases [11]. From the perspective of production, Sethi and Sethi [12] provide an extensive overview of flexibility, which was expanded by Shewchuk and Moodie [13] and contains more than 50 terms, considering different aspects of flexibility.

Golden and Powell investigated flexibility at the organisational level and the contribution of IT systems [14], while other researchers focus on other aspects of flexibility at lower levels of an organisation, such as operational flexibility [15]. MacCormack and Verganti [11,16] and Biazzo [17] analysed the influence of uncertainty in the product development process and deduce key characteristics for a flexible process design. Modularisation is widely discussed as a means of contributing to the flexible design of products [18,19]. Seidenberg et al. [20] in turn examined the impact of modularisation on the production.

In the context of production, flexibility is defined as the ability of a company to adapt its production systems to short-, medium- and long-term changes to a sufficient degree [21]. Thereby, internal and external flexibility are distinguished [21]:

- **Internal flexibility:** Internal flexibility refers to a company's ability to adapt its production systems to short-, medium- and long-term changes by reconfiguring and relocating individual elements of the production system within a production site.
- **External flexibility:** External flexibility refers to the relocation of individual elements of production systems or entire production systems between production sites and is therefore also referred to as location flexibility.

This paper investigates the influence of product changes on the production system and the resulting need for internal flexibility. Blecker and Kaluza [22] state that the organisational form of production is a crucial aspect concerning flexibility. The production system's organisational form consists of two dimensions: the basic structure and the distribution of capacity and capability over machines [7]. The basic structure is characterised by the interlinkage and layout of the machines. Products produced on machines arranged in a row must follow the installed process sequence and defined cycle time. The rigid interlinkage of machines allows no deviations in sequence and time. Buffers in production lines offer flexibility in the event of short disruptions to production, without causing a breakdown of the entire production line. Lines of machines containing buffers are described as line structures with elastically or loosely interlinked machines. Line structures containing parallel connected machines are called a network structure [23]. Flexibly interlinked area structures consist of machines that are all interlinked with each other, allowing a varying process sequence [24]. Machines arranged in parallel can either offer the same operations (capability) to increase the output (capacity) or different operations for product variants. They are called line-less production systems. In general, production lines are designed as a line structure for the maximum expected sales volume [7] to avoid the cost of additional redundant tools for each operation [25]. In case of the transgression of the maximum planned sales volume, the existing production line must be duplicated (line by line) to produce a multiple of the quantity [26]. Another possibility is to duplicate only those parts of the production system (machine by machine) which state a bottleneck [26]. In contrast, line-less production systems are designed for low volume with the flexibility to increase the volume in fine steps (machine by machine) [27].

The following describes the most common organisational forms of production, which are analysed in terms of flexibility in chapter 3.

- **Workbench manufacturing:** The workbench principle is a rather rare organisational form in industry. It is mainly used for manual activities without the use of large machines which are to find in tool and jig making [23].
- **Workshop production:** Workshop production is a type of production that combines production systems with similar activities and organises the workstations according to the processing methods. Orders are processed in batches and after all order parts have been processed, they are transported to the next processing station [23,28].
- **Flow production:** In flow production, machines are arranged according to the sequence of operations in a line or network structure [29]]. Workpieces move directly, without waiting for other parts, to the next machine according to the defined cycle time. However, waiting time can occur due to buffers in the production line. [23] Flow production is widely used for the manufacturing of components and the assembly of components or products [28].
- **Island production:** In this organisational form, machines are arranged according to spatial and organisational aspects considering the equipment to produce a group of similar components or entire products. The peculiarity of the island production is that a semi-autonomous group of

workers performs the same sub-processes. Furthermore, the flow-oriented machine arrangements with a one-piece-flow eliminate idle time between operations [23].

- **Cellular manufacturing:** In cellular manufacturing systems, similar components are produced in several independent work cells, which consist of different machines, designed for product families with similar processing requirements [27,30,31].
- **Flexible manufacturing systems:** A flexible manufacturing system consists of automated machines with an automatic tool change to produce a group of similar components. Its material flow is free of a cycle time and allows varying routes. Different types of layouts exist [23], but changes to the machine layout are not possible [30–32].
- **Reconfigurable manufacturing system:** Reconfigurable manufacturing systems aim to flexibly adapt production capacity and functionality within a family of parts. To respond to unexpected fluctuations in demand, reconfigurable manufacturing systems have an open system architecture that allows existing systems to be expanded. By using reconfigurable manufacturing systems, it is possible to create a 'living' factory that can adapt to market and customer requirements [25,31,33].
- **Modular matrix production:** A modular production is based on decoupled machines. The workpieces are navigated through the production system as needed, according to necessary processes and the current system status free of a cycle time. The aim is to process orders in a specified time instead of pushing a product through the production according to a defined cycle time [34].

Recent approaches focus on the control of autonomous robots in terms of navigation [35,36], which is essential for flexible routing in line-less production systems. Therefore, different types of vision systems and a factory's digital twin are used in combination [35,36]. Furthermore, process perception is studied to increase the autonomy of robots and reduce the teaching effort in case of changes. Technological progress in computer vision enabled the improvement of object detection for autonomously working robots [35,36]. Garbie [37] introduced a method for the reconfiguration process, taking the different organisational forms and basic structure of production system into account in the evaluation concerning flexibility. Deka et al. [38] present a mathematical design method for additively manufactured products to increase the use of additive manufacturing beyond rapid prototyping, due to its short lead time. The method integrates the design of customized filaments and the corresponding process to meet the desired product properties.

3. Analysis of production systems in terms of flexibility

Although, there is a great amount of literature about flexibility and its different types, there is no description which characteristics of the product and the production system contribute to the defined types of flexibility. Especially not how the design of the product and the production system influence each other [8]. Guidelines to increase flexibility do not provide clear guidance for engineers to derive measures for action. This chapter gives an overview of possible product changes and their impact on the production system. Based on this, requirements for flexibility are derived, which are then mapped to the relevant characteristics of the production system. Fig. 2 depicts the triangular relation between flexibility and the production system's basic structure and organisational forms, which is examined in more detail below.

3.1. Influence of market changes on the product

The implementation of new or changed market requirements in the product may take the form of additional features, changes in component's performance or appearance. These changes influence the design (geometry & material) of the components, their location in the product and the assembly structure. In general, extending the product with additional components affects the assembly structure and is limited by the available design space, which may result in the rearrangement of components.

Design changes may involve geometry and/or material, which lead to redesign of interfaces, affect the design space and further affect the assembly structure. A change in material can require a component's relocation in the product and/ or changes to the assembly sequence due to incompatibility of material properties with production process steps or its surrounding environment. Changes in the location of a component always have an impact on the assembly structure.

Volatile markets cause shifts in demand in terms of the number of orders and their distribution over product variants.

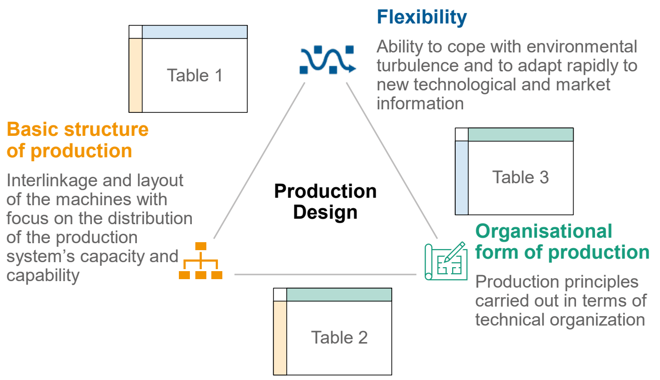

Fig. 2. Different aspects of flexibility concerning production design.

3.2. Influence of product changes on production

The product changes described affect the production system in terms of its overall structure, the allocation of process steps to machines and the design of the machines including their equipment.

Changes in design (in terms of geometry & material) may result in the modification or redesign of moulding tools, fixtures, handling devices or other type specific tools. It may also require the modification or integration of new manufacturing and joining techniques. In addition, the processing effort and process time may be affected. These changes to the manufacturing and joining process can result in a deviation from the production sequence.

The sequence of process steps, the layout of the machines and thus the material flow are sensitive to changes in the assembly structure. The impact of product changes on the production system is highly dependent on the specific product, its modifications, and the corresponding production system.

3.3. Requirements concerning flexibility

The requirements for flexibility are based on potential product changes described above and their impact on the production system. These align with the various types of flexibility summarised by Sethi and Sethi [12] in the context of manufacturing.

At the machine level, reconfigurability of the machines, their equipment, and machining programs is decisive [12]. Tools such as moulding tools and fixtures, which are designed for the specific geometry of a component, are often very expensive [23,25,39] and can only be modified to a minor extent. Depending on the manufacturing and joining technique, the use of robots and component-integrated fixture features can replace fixtures [39,40]. The reconfigurability of machines with respect to their manufacturing and joining techniques allows for their reuse in various ways, extending their utilisation [12].

Certain product changes are related to structural aspects of the production system. Modifying the sequence of process steps can cause either a re-routing of the material flow or a re-arrangement of the machines. Additional process steps or longer processing times may be required for certain product variants, resulting in a varying material flow in terms of route and/or pace.

To reduce the change effort, the sequential assembly restrictions [12,41] and the linkage of machines in terms of the production layout and cycle time need to be decoupled. The parallelisation of process steps for pre-assembly or alternative assembly sequences decouples production areas [12,41]. In turn, the implementation of changes can be narrowed down to the concerned assembly group without influencing other production areas [41]. This is partially implemented industry. For instance, the cockpit and the drivetrain of a car are pre-assembled separately. However, the assembly of the vehicle itself consists of a long chain of sequential assembly steps which limits changes to the product and the production design due to the line structure with a fixed cycle time. It is important to note that autonomous robots are being used in industry to transport products instead of conveyor belts. However, a flexible flow in terms of process sequence and cycle time has not yet been implemented.

The production system's capacity and capability to produce a varying product mix must be flexible due to volatile markets affecting the number of orders and their distribution over product variants [12]. Additionally, the development of new product variants or versions may require the expansion of the production system with new production techniques.

Implementing changes quickly without causing downtime is critical to maintaining competitiveness. Conversely, delaying implementation until a planned shutdown results in loss of orders, production volume and competitiveness.

3.4. Allocation of flexibility requirements to production characteristics

The production system is characterized by the interlinking and layout of the workstations and the distribution of its capacity and capability over its machines. Table 1 shows how these characteristics contribute to the flexibility requirements described in section 3.3.

Machines in a line or network structure are usually rigidly interlinked or elastically/ loosely, including buffers to compensate short process downtimes [23]. Because of the sequential order of machines and the material flow with a fixed cycle time, these production systems provide limited flexibility [42,43], as depicted in the first row of Table 1. Any rearrangement regarding the order of machines or process steps affects the whole production line [34,44]. Deviations from the cycle time lead to a loss of productivity [38]. Minor cycle time deviations of certain variants can be compensated by producing according to a specific product mix [34].

Table 1. Contribution of the basic structure of a production system to its flexibility.

Basic structure of the production system	Flexibility 1	2	3	4	5	6	7	8
Interlinkage and layout of the machines								
Rigidly/ elastically interlinked line structure	◑	◑	◑	◑	○	○	◑	◑
Rigidly/ elastically interlinked network structure	◑	◑	◑	◑	◑	◑	◑	◑
Flexibly interlinked area structure	◑	●	●	●	●	●	●	●
Distribution of a production system's capacity and capability								
None	○	●	◑	◑	○	○	◑	◑
Line by line	◑	●	◑	◑	◑	◑	◑	◑
Machine by machine	●	●	●	●	●	●	●	●

○ not applicable ◑ partially applicable ● applicable

1: Seamless integration/ adaption without downtime
2: Planned integration/ adaption during downtime
3: Adaption of the process sequence causing structural change
4: Expansion of the production system's capacity/ capability
5: Change of the material flow due to a varying process sequence
6: Parallelisation of process/ production steps (pre-assembly, separate assembly)
7: Variable product mix (variants, product generations)
8: Variable process times

Network structures contain parallel machines or production lines [23]. The parallel paths allow the implementation of changes without influencing the rest of the production line. Thus, they offer more possibilities for deviations from the cycle time, material flow, and assembly sequence (refer to the second row) [26,29].

Production systems in the form of an area structure are not restricted by sequential order, allowing for easy structural changes in the arrangement of machines and the addition of new machines to increase capacity and capability (refer to the third row). Due to the flexibly interlinked machines, it is possible to vary process routes [12] and processing times.

The effort required for the expansion and adaption of a production system is defined by the distribution of capacity and capability among its machines [12], as well as whether or not a planned downtime is required for implementation. Production systems with a line structure consisting of machines, which are dedicated to different process steps and designed for the maximum expected sales volume, typically increase their capacity (line by line) through adding additional lines (refer to the fourth row) [26]. Interventions in these systems cause downtime and a loss in quantity as the machines cannot be used redundantly. In a network structure single machines can be added (refer to the sixth row) to increase the capacity of the line's bottle neck [26]. Area structures can distribute their capacity over several machines with the same functionality, allowing scalability on a machine-by-machine basis. The use of redundant machines or production lines allows for changes to be implemented seamlessly without causing any downtime [12]. A finely graduated capacity distribution allows interventions with less losses.

4. Performance of organisational forms of production systems regarding flexibility

To assess the flexibility of various production system's organisational forms, they must first be characterised objectively. Table 2 shows their characterisation based on the interlinking and layout of workstations, as well as the distribution of capacity and capability across machines. Table 1 and 2 present the relations used to compare the flexibility of the organisational forms, depicted in Table 3.

Based on Table 3, the following conclusion can be drawn regarding the comparison of the different organisational forms in terms of flexibility: Flow production, island production, cellular manufacturing and flexible manufacturing systems are the least flexible system forms. All other organisational forms of production systems, which allow deviations from the production sequence and cycle time to a greater extent and with less effort, are more capable of coping with volatile markets.

Table 2. Characterisation of organisational forms of production systems by their basic structure.

Basic structure of the production system	Organisational form of the production system							
	1	2	3	4	5	6	7	8
Interlinkage and layout of the machines								
Rigidly/ elastically interlinked line structure	○	○	●	●	●	◐	○	○
Rigidly/ elastically interlinked network structure	○	○	●	◐	○	◐	○	○
Flexibly interlinked area structure	○	●	○	○	●	◐	●	●
Distribution of a production system's capacity and capability								
None	○	○	●	●	○	○	○	○
Line by line	○	●	●	●	○	●	○	○
Machine by machine	●	●	◐	◐	○	●	●	●

○ not applicable ◐ partially applicable ● applicable

1: Workbench manufacturing
2: Workshop production
3: Flow production
4: Island production
5: Cellular manufacturing
6: Flexible manufacturing systems
7: Reconfigurable manufacturing system
8: Modular matrix production

However, the seamless integration of product changes depends on the distribution of a production system's capacity across several machines with the same capability (see Table 1). This is typical of flexible manufacturing systems, reconfigurable manufacturing systems and modular matrix production. Workbench manufacturing and workshop production also show high flexibility. In industry, flow production is still the dominant form of organisation for high-volume production. However, Artificial Intelligence opens up new opportunities for controlling complex processes with autonomous robots and calculating the optimal material flow for flexibly interlinked machines in real time. This enables the implementation of new organisational forms with flexible material flow.

Table 3. Comparison of organisational forms of production systems regarding flexibility.

Flexibility	Organisational form of the production system							
	1	2	3	4	5	6	7	8
Seamless integration/ adaption without downtime	●	●	◐	◐	○	◐	●	●
Planned integration/ adaption during downtime	●	●	◐	◐	●	◐	●	●
Adaption of the process sequence causing structural change	●	●	◐	◐	○	◐	●	●
Expansion of the production system's capacity/ capability	●	●	◐	◐	○	◐	●	●
Change of the material flow due to varying process sequence	●	●	◐	◐	◐	◐	●	●
Parallelisation of process/ production steps (pre-assembly, separate assembly)	●	●	◐	◐	◐	◐	●	●
Variable product mix (variants, product generations)	●	●	◐	◐	◐	◐	●	●
Variable process times	●	●	◐	◐	◐	◐	●	●

○ not applicable ◐ partially fulfilled ● fulfilled

1: Workbench manufacturing
2: Workshop production
3: Flow production
4: Island production
5: Cellular manufacturing
6: Flexible manufacturing systems
7: Reconfigurable manufacturing system
8: Modular matrix production

5. Discussion and conclusion

This paper provides a brief overview of the challenges that companies face in the volatile, uncertain, complex, and ambiguous (VUCA) world. It explains the importance of flexibility in product development and production and demonstrates how changes propagate from the VUCA world through product development and into the production system. The analysis of production systems concerning product changes outlines important characteristics to evaluate them in terms of flexibility. In this regard, common production systems with varying organisational forms are compared based in their layout, machine interlinkage and distribution of capacity and capability across machines. The comparison indicates that production systems, which do not have a line structure with rigid interlinkage, provide strategic flexibility to better cope with volatile markets.

The comparison did not consider the productivity of the production system. It needs to be analysed for production design, where digitalisation provides virtual models for simulation of production systems in terms of productivity. Methodical support for flexibility in the product development process are subject of further research. Further research is needed on providing methodical support for flexibility in the product development process. Additionally, it is important to consider the limitations on purchasing in terms of supply flexibility.

Acknowledgements

The article's publication fees and a share of the conference participation were funded by Bayerische Motoren Werke AG. We express our gratitude for their support.

References

[1] Stein S. Reimagining global citizenship education for a volatile, uncertain, complex, and ambiguous (VUCA) world. Globalisation, Societies and Education 2021;19:482–95.

[2] Mack O, Anshuman K, Andreas K, Burgartz T, editors. Managing in a VUCA World, 1st ed. s.l.: Springer-Verlag 2015.

[3] Bauernhansl T, editor. Fabrikbetriebslehre 1. Berlin, Heidelberg: Springer Berlin Heidelberg 2020.

[4] Pawellek G. Ganzheitliche Fabrikplanung: Grundlagen, Vorgehensweise, EDV-Unterstützung, 1st ed. Berlin, Heidelberg: Springer; 2008.

[5] Cingöz A, Akdoğan AA. Strategic Flexibility, Environmental Dynamism, and Innovation Performance: An Empirical Study. Procedia - Social and Behavioral Sciences 2013;99:582–9.

[6] Tolio T, editor. Design of Flexible Production Systems: Methodologies and Tools. Berlin, Heidelberg: Springer Berlin Heidelberg 2009.

[7] Lotter B, Wiendahl H-P, editors. Montage in der industriellen Produktion, 2nd ed. Berlin, Heidelberg: Springer Vieweg 2012.

[8] Beibl J, Lee J, Krause D, Moon SK. Flexibility - Grand Challenge for Product Design and Production: Review and Status. Procedia CIRP 2023;119:91–6.

[9] Disselkamp J-P, Cieply J, Dyck F, Grothe R, Anacker H, Dumitrescu R. Integrated product and production development - a systematic literature review. Procedia CIRP 2023;119:716–21.

[10] Geissbauer, Reinhard; Bruns, Michael; Wunderlin, Jens. PwC Digital Factory Transformation Survey 2022; 2022. https://www.pwc.de/de/strategie-organisation-prozesse-systeme/operations/smart-manufacturing/digital-factory-transformation-survey-2022.html [accessed October 18, 2023].

[11] MacCormack A, Verganti R. Managing the Sources of Uncertainty: Matching Process and Context in Software Development. J of Product Innov Manag 2003;20:217–32.

[12] Sethi AK, Sethi SP. Flexibility in manufacturing: A survey. Int J Flex Manuf Syst 1990;2.

[13] Shewchuk JP, Moodie CL. Definition and Classification of Manufacturing Flexibility Types and Measures. Int J Flex Manuf Syst 1998;10:325–49.

[14] Golden W, Powell P. Towards a definition of flexibility: in search of the Holy Grail? Omega 2000;28:373–84.

[15] Yu K, Cadeaux J, Luo BN. Operational flexibility: Review and meta-analysis. International Journal of Production Economics 2015;169:190–202.

[16] MacCormack A, Verganti R, Iansiti M. Developing Products on "Internet Time": The Anatomy of a Flexible Development Process. Management Science 2001;47:133–50.

[17] Biazzo S. Flexibility, Structuration, and Simultaneity in New Product Development. J of Product Innov Manag 2009;26:336–53.

[18] Sanchez R, Mahoney JT. Modularity, flexibility, and knowledge management in product and organization design. Strategic Management Journal 1996;17:63–76.

[19] Schwede L-N, Greve E, Krause D, et al. How to Use the Levers of Modularity Properly—Linking Modularization to Economic Targets. Journal of Mechanical Design 2022;144.

[20] Seidenberg T, Disselkamp J-P, Schräder E, Anacker H. Towards an Optimised Value Creation Network for Modular Investment Goods. Proc. Des. Soc. 2022;2:2513–22.

[21] Aurich JC, Barbian P, Wagenknecht C. Prozessmodule zur Gestaltung flexibilitätsgerechter Produktionssysteme. Zeitschrift für wirtschaftlichen Fabrikbetrieb 2003;98:214–8.

[22] Blecker T, Kaluza B. Heterarchische Hierarchie: Ein Organisationsprinzip flexibler Produktionssysteme. Klagenfurt: Inst. für Wirtschaftswiss; 2004.

[23] Wiendahl H-P, Wiendahl H-H. Betriebsorganisation für Ingenieure, 9th ed. München: Hanser; 2019.

[24] Göppert A, Schukat E, Burggräf P, Schmitt RH. Agile Hybrid Assembly Systems: Bridging the Gap Between Line and Matrix Configurations. In: Weißgraeber P, Heieck F, Ackermann C, editors. Advances in automotive production technology – theory and application: Stuttgart Conference on Automotive Production (SCAP2020) ; Philipp Weißgraeber, Frieder Heieck, Clemens Ackermann editors. Berlin, Heidelberg: Springer Vieweg; 2021:3–11.

[25] Koren Y, Gu X, Guo W. Reconfigurable manufacturing systems: Principles, design, and future trends. Front. Mech. Eng. 2018;13:121–36.

[26] Hesse S. Automatische Montagemaschinen. In: Lotter B, Wiendahl H-P, editors. Montage in der industriellen Produktion. 2nd ed. Berlin, Heidelberg: Springer Vieweg; 2012:195–272.

[27] Wemmerlöv U, Hyer NL. Research issues in cellular manufacturing. International Journal of Production Research 1987;25:413–31.

[28] Holtewert P, Wiendahl H-H. Fertigungs- und Montagesysteme. In: Bauernhansl T, editor. Fabrikbetriebslehre 1. Berlin, Heidelberg: Springer Berlin Heidelberg; 2020:129–64.

[29] Wiendahl H-P, Hegenscheidt M. Verfügbarkeit von Montagesystemen. In: Lotter B, Wiendahl H-P, editors. Montage in der industriellen Produktion. 2nd ed. Berlin, Heidelberg: Springer Vieweg; 2012:331–63.

[30] Benjaafar S, Heragu SS, Irani SA. Next Generation Factory Layouts: Research Challenges and Recent Progress. Interfaces 2002;32:58–76.

[31] Bortolini M, Galizia FG, Mora C. Reconfigurable manufacturing systems: Literature review and research trend. Journal of Manufacturing Systems 2018;49:93–106.

[32] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. Journal of Manufacturing Systems 2010;29:130–41.

[33] Koren Y, Heisel U, Jovane F, et al. Reconfigurable Manufacturing Systems. CIRP Annals 1999;48:527–40.

[34] Kern W. Modulare Produktion; 2021.

[35] Bavelos AC, Kousi N, Gkournelos C, et al. Enabling Flexibility in Manufacturing by Integrating Shopfloor and Process Perception for Mobile Robot Workers. Applied Sciences 2021;11:3985.

[36] Gkournelos C, Kousi N, Christos Bavelos A, et al. Model based reconfiguration of flexible production systems. Procedia CIRP 2019;86:80–5.

[37] Garbie IH. A methodology for the reconfiguration process in manufacturing systems. Journal of Manufacturing Technology Management 2014;25:891–915.

[38] Deka A, Nellippallil AB, Hall J. Integrated design exploration of products, materials, and processes in additive manufacturing using inverse design method. Int J Interact Des Manuf 2022;16:717–31.

[39] Schlather F. Methodische Auslegung bauteilintegrierter Spanntechnik fuer das Fuegen von Metallblechstrukturen. München; 2020.

[40] Schuh, Günther; Bergweiler, Georg; Fiedler, Falko. Flexible Body Shop Through Fixtureless Production with Component-integrated Fixture Features (CFF); 2021. http://dx.doi.org/10.13140/RG.2.2.34382.59200/1 [accessed March 13, 2024].

[41] Halfmann N. Montagegerechtes Produktstrukturieren im Kontext einer Lebensphasenmodularisierung, 1st ed. Hamburg: TuTech Verl.; 2015.

[42] Huettemann G, Gaffry C, Schmitt RH. Adaptation of Reconfigurable Manufacturing Systems for Industrial Assembly – Review of Flexibility Paradigms, Concepts, and Outlook. Procedia CIRP 2016;52:112–7.

[43] Hofmann C, Brakemeier N, Krahe C, Stricker N, Lanza G. The Impact of Routing and Operation Flexibility on the Performance of Matrix Production Compared to a Production Line. In: Schmitt R, Schuh G, editors. Advances in Production Research. Cham: Springer International Publishing AG; 2019:155–65.

[44] Lödding H. Verfahren der Fertigungssteuerung. Berlin, Heidelberg: Springer Berlin Heidelberg; 2016.