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Flexibility-Driven Planning Of Flow-Based Mixed-Model Assembly Structures

Nils Föhlisch[1], Peter Burggräf[1,2], Tobias Adlon[1], Christopher Kapella[1]
[1]Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Campus Boulevard 30, 52074 Aachen, Germany
[2]Chair of International Production Engineering and Management (IPEM), University of Siegen, Paul-Bonatz-Straße 9-11, 57076 Siegen, Germany

Abstract

Trends such as mass customization, changing customer preferences and resulting output fluctuations increasingly challenge the production industry. Mixed-model assembly lines are affected by the rising product variety, which ultimately leads to ascending cycle time spreads and efficiency losses. Matrix assembly addresses these challenges by decoupling workstations and dissolving cycle time constraints while maintaining the flow. Both matrix and line assembly are flow-based assembly structures characterized by assembly objects moving along the stations. In assembly system planning, competing assembly structures are developed and the one best meeting the use case's requirements is selected for realization. During assessing requirements and selecting the superior assembly structure, the systematic consideration of flexibility is often not ensured within the planning approach. Therefore, a preferred assembly structure may not have the flexibility required for a use case. The systematic and data-driven assessment of required and provided flexibility in assembly system planning is necessary.

This paper presents an assessment model that matches a use case's requirements with the flexibility of flow-based assembly structures based on production program and process data. On the one hand, requirements are defined by flexibility criteria that evaluate representative product mixes and process time heterogeneity. On the other hand, provided flexibility of flow-based assembly structures is assessed in a level-based classification. A method for comparing the requirements and the classification's levels to prioritize assembly structures for application in a case is developed. The flexibility requirements and assembly structure of an exemplary use case are determined and discussed under the planning project's insights to evaluate the developed model. This work contributes to the objective and data-driven selection of assembly structures by utilizing use case-specific data available during the phase of structural planning to meet flexibility requirements and ensure their consideration along the assembly planning process.

Keywords

Flexibility Assessment; Assembly System Planning; Matrix Assembly; Line Assembly; Flow-based Assembly; Flexibility Requirements

1. Introduction

Due to the increasing individualization, products are tailored precisely to customer needs. Companies use Mixed-Model Assembly Lines (MMAL) to manage the resulting product variety in production and to reduce investment risk [1]. These are used to manufacture a variety of products within one assembly system without the need for retooling [2]. Within the system, a uniform cycle time must be maintained, which is available for executing the processes in each station. Increasing product variety and the associated growth in station-related process time heterogeneity result in rising cycle compensation times, which lead to efficiency losses

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[3]. Even though significant measures are conducted to reduce cycle time spreads, MMAL are reaching the limits of their economic viability [4, 5]. Matrix assembly systems are an approach to simultaneously increase flexibility and efficiency of variant-rich assembly [4]. These combine the advantages of job-shop assembly regarding flexibility and of flow-line assembly regarding efficiency by dissolving the cycle time constraint and decoupling workstations. A flexible flow arises, wherein assembly objects take an individual path through the system [6], which is only limited by the product-specific priority sequence graph [7]. In this context, flexibility describes a system's ability to reversibly adapt its processes to changing conditions within short time [8, 9]. Matrix and line assembly are summarized under flow-based assembly structures, which are characterized by moving assembly objects that pass through working stations according to the flow principle.

So far, the industrial application of matrix assembly has been limited, although the concept is broadly discussed and tested in prototypes in practice. Companies' lack of experience in the use and planning of matrix assembly systems and high planning complexity are possible reasons for the slow introduction [10]. Since matrix assembly emerged, companies increasingly face the question during assembly planning whether matrix assembly is better suited to their challenges than line assembly. Conventional assembly planning procedures mainly consist of four phases [11]. First, the planning task with its requirements and boundary conditions is defined. On this basis, one or multiple competing assembly structures are developed and examined in the concept phase of structural planning. The evaluation is based on a comparison under consideration of the requirements and objectives. The appropriate structure is selected and then concretized in the detailed planning. The result of the detailed planning is implemented in the system realization [12].

Within the requirement specification in the first phase, flexibility is often considered a subordinate factor and quantification of related objectives is difficult. In the absence of quantitatively specified flexibility requirements, matrix assembly structures cannot be objectively evaluated alongside those of line assembly, as it is flexibility that is a key driver of the adoption of a matrix assembly. Therefore, prior to capacity determination and performance simulation, a data-driven procedure is required to evaluate and select the appropriate assembly structures, considering flexibility of flow-based assembly. This paper presents an assessment model that analyzes process time and product mix data of a use case regarding flexibility requirements in order to prioritize flow-based assembly structure alternatives with respect to the best fulfillment. Hence, the research question of this paper is: *"How can flexibility requirements from process time and product mix data be assessed and matched with flow-based assembly structures for prioritization?"*

2. Literature Review

The presented approaches are part of the findings of a structured literature review conducted according to VOM BROCKE ET AL. [13]. Many approaches in literature address criteria for flexibility in certain domains [14-17] and VAN DE GINSTE ET AL. [18] undertake a review focusing on the definition of flexibility as well as corresponding criteria in assembly. The authors analyze scientific articles, from which the 15 most used criteria are extracted. The various criteria result primarily from each company defining flexibility for itself, making manufacturing flexibility challenging to summarize. The most frequently cited criteria are volume, routing, mix, machine and process flexibility. However, the presented criteria are partly similar, respectively redundant and build on each other. It remains unclear which flexibility criteria form a redundant-free set and comprehensively specify the requirements for an assembly structure during system planning.

Several approaches elaborate structural relationships among the criteria and provide hierarchical organizations [17-19]. KOSTE AND MALHOTRA [19] propose a set of criteria for analyzing manufacturing flexibility and propose a hierarchy consisting of five successive tiers. These include the individual resource, shopfloor, plant, functional and strategic business unit tier. The lower tiers partly serve as enablers of the upper ones. It is required to determine which tier respectively criteria are most appropriate and form a redundant-free, comprehensive set for the specification of the requirements while planning an assembly structure. Furthermore, it needs to be detailed how criteria are quantitatively assessed for structural planning.

Several approaches for the criteria-based assessment of flexibility can be identified in the relevant literature [20-23]. ROGALSKI [22] provides an approach for evaluating quantity, product mix and expansion flexibility at different observation levels. The relevant limits of quantity flexibility are represented by the break-even point and the maximum capacity. Product mix flexibility describes the scope for adapting the production program and is calculated from the profit maximum based on the optimum production program and its average, product-specific deviation. To determine expansion flexibility, the break-even points of the various expansion alternatives and a defined target capacity are used. However, the three criteria considered do not cover all aspects relevant for structural planning, e.g. the introduction of new products. In addition, cost- or capacity-based approaches cannot be used for decision support while selecting the appropriate assembly structure, since cost rates and capacities are not known in the early planning phase of structure planning.

SCHUH ET AL. [23] develop a key figure model for the evaluation of flexibility with regard to changes in output, variant mix and products. The basis of the evaluation is the hierarchical modeling of the production system by means of classes for work centers, lines, etc. provided by the key figure model. These contain the attributes required for the modeling and the functions for the flexibility calculation on the considered level. The requirements for the production system are described by means of user-defined reference scenarios. On this basis, the flexibilities are calculated by the functions per workstation and, building on this, for the higher levels. By means of the resulting quantitative key figures, different systems can be compared. However, for the application of indicator models like the presented, the assembly structure for modeling by means of classes must already be designed in detail. Thus, the procedure starts after the concept-defining phase of structure planning. Furthermore, only interlinked assembly structures in the form of workstations, segments etc. connected in parallel or in series can be modeled, and matrix configurations are excluded.

From the review results, it can be concluded that existing cost and capacity-based approaches for flexibility assessment cannot be used for assembly structure planning since the required data is not available in this early planning stage. Additionally, approaches that require modeling a system's structure are insufficient, since the structure is still unknown during assembly structure planning and modeling all potential structures is inefficient. Therefore, this paper aims to develop an assessment model that compares a use case's requirements with the flexibility of flow-based assembly structures based on data available in the early stages of assembly planning. In this way, it contributes to the efficient and data-based evaluation, selection and planning of flow-based assembly structures from both a research and a practical perspective.

3. Flexibility Assessment Model

The flexibility assessment model is developed based on the literature review findings and under continuous reflection with a panel of assembly planning experts consisting of consortium partners of the research project *AIMFREE*. The user of the model specifies the flexibility requirements based on the defined criteria set using production program and process time data. The requirements are then assessed and compared with provided flexibility of flow-based assembly structures in a classification. The appropriate assembly structure alternatives for the analyzed use case are prioritized and design recommendations are derived.

The experts confirmed that from the hierarchy of KOSTE AND MALHOTRA, the relevant criteria for the specification of requirements for the assembly structure are on the plant tier. Additionally, from the available data during the early planning stages, production program and process time data have been identified as beneficial for quantifying flexibility requirements using these criteria. Table 1 shows the data sets that are required for the specification of the flexibility requirements. Reference scenarios and their relations are included, each describing representative sequences of production programs for short-term and long-term change to model requirements over multiple periods.

Table 1: Flexibility criteria for the specification of requirements

Data sets Criteria	Process time data of models and variants	Process time data of new products	Product mix scenarios	Short- term change of product mix	Long-term change of product mix	Short-term quantity scenarios	Long-term quantity scenarios
Product flexibility	**X**						
New product flexibility	**X**	**X**					
General product mix flexibility	**X**		**X**				
Short-term product mix flexibility	**X**		**X**	**X**			
Long-term product mix flexibility	**X**		**X**		**X**		
Volume flexibility						**X**	
Expansion flexibility							**X**

On the basis of the criteria and related data, the requirements and provided flexibility of assembly structure alternatives are compared. The alternatives that span the solution space of structure planning are provided in the classification for flow-based assembly structures in Table 2. The rows of the classification represent flexibility levels, each reflecting assembly structure alternatives. The levels are arranged according to increasing provided flexibility from the first level (low flexibility) to the highest (maximum flexibility). The columns of the classification contain the design dimensions of flow-based assembly structures, which comprise the essential components for structure planning. The cells contain characteristics that are assigned to the dimension of the column and are used in the level corresponding to the row. Thus, a level respectively an assembly structure alternative is composed of the combination of characteristics in a row.

Table 2: Classification of flow-based assembly structures

		Design dimensions		
		Dimensionality of object routes	Synchronization principle of time	Mobility of the production resources
Levels	1	One-dimensional (Line)	Uniform cycle time	Stationary
	2			Moving
	3		Average cycle time	Stationary
	4			Moving
	5	Two-dimensional (Matrix)		Stationary
	6			Moving
	7		Expected operation time	Stationary
	8			Moving
	9		Reaction to assembly progress	Stationary
	10			Moving
	11		Expected operation time and reaction to assembly progress	Stationary
	12			Moving

The data are evaluated using statistical methods to determine the flexibility requirements. The analysis focuses on assessing the heterogeneity of the underlying data as a measure for the required flexibility. Accordingly, the more heterogeneous the values in the data, the higher the flexibility requirements of the use case. For this purpose, the normalized process time difference is considered for product and new product flexibility. For general, short-term and long-term product mix flexibility, the global mean value is determined for each criterion on a cross-process basis, as well as the local mean value, the standard deviation and the minimum and maximum values on a process-specific basis. For volume and expansion flexibility, regression analyses are used for the development of the requirements over several periods. Discrete scales of the provided flexibility are defined with the experts for each design dimension of the classification as a function of the statistical key figures. Each graduation of the scales describes the provided flexibility of a dimension's characteristics. Thus, narrowly defined graduations are assigned to the characteristics with low provided flexibility and broadly defined are assigned to those with high. On this basis, the characteristics are prioritized separately for each dimension. For this purpose, the necessary flexibility resulting from the specified requirements is compared with the provided flexibility defined by the decision rules in form of the functions. The generated prioritizations for each dimension are then aggregated into recommended assembly structures. In the following the assessment of the requirements and the comparison with flexibility of assembly structure alternatives is shown in detail for each criterion.

Product flexibility examines the flexibility requirements that arises due to the process time heterogeneity between the product models. All models in the assembly system are compared with each other so that for each comparison between two, the relative difference of the individual process steps is calculated according to equation (1).

$$Dif_{i,j,p}^{Mod} = \frac{|Z_{i,p}^{Mod} - Z_{j,p}^{Mod}|}{max(Z_{i,p}^{Mod};Z_{j,p}^{Mod})} \; ; \; i \neq j \tag{1}$$

$Dif_{i,j,p}^{Mod}$	Relative process time difference between model i ϵ M and j ϵ M in process step p ϵ P
$Z_{i,p}^{Mod}$	Process time of model i ϵ M in process step p ϵ P
$Z_{j,p}^{Mod}$	Process time of model j ϵ M in process step p ϵ P
M	Models in the assembly system
P	Process steps of the assembly system

A matrix is generated by applying equation (1) to all model comparisons and process steps. While the columns contain the process steps, the rows contain each comparison between two models. The larger the values in the matrix are, the more significant is the process time heterogeneity and therefore the flexibility requirement. Intervals are defined based on the values to determine the necessary degree of flexibility. On the other side, provided flexibility of the characteristics of each dimension in the classification is defined by thresholds resulting from the functions. This means that the more flexible a characteristic is, the larger are the corresponding thresholds. The characteristics and the linked thresholds are encoded to enable automated processing. Those codes are integer values representing the respective characteristic's degree of flexibility. Therefore, the first level's characteristic is linked to the lowest integer value and top the level's to the highest one. The codes are then used to classify each matrix element reflecting the heterogeneity of the related process times. The elements are converted according to the intervals and assigned to one code. For each comparison between two models, i.e., each row of the matrix, the percentages of assignments to the codes are determined. Thereby each defined code holds a percentage regarding the considered model comparison. The percentages are accumulated, starting with the lowest degree of flexibility to the highest. Once the accumulated percentage exceeds a predefined threshold, the corresponding code respectively degree of flexibility is assigned to the model comparison. That leads to one degree of flexibility per model comparison and row. Based on that, the value of all model comparisons and therefore, the required degree of flexibility within the product flexibility is derived.

The analysis of new product flexibility is conducted in analogy to product flexibility. However, within this criterion, the expected process steps of new products are compared with those of existing products. It is assumed that new products in an assembly system basically share some of the properties of existing products and can be compared regarding identical, deviating, additional and omitted process steps. For this purpose, a similarity analysis is conducted. If there are few changes in process steps necessary to assemble the new product and if the process time heterogeneity is sufficiently low, the resulting flexibility requirement is minimal and vice versa. The latter condition is checked using a defined threshold.

Product mix flexibility analyzes process time heterogeneity of representative general, short- and long-term product mixes. Within general product mix flexibility, process time heterogeneity within each representative product mix is examined. Process time mean values and standard deviations of each process step and within each product mix are calculated. Using those parameters, scatter ranges representing the required flexibility are derived. The upper and lower bounds of the scatter ranges are calculated according to equation (2).

$$s_{psi,p}^{high/low} = MV_{psi,p} \pm \sigma_{psi,p} \tag{2}$$

$s_{psi,p}^{high/low}$	Upper/lower scatter range bound of process step p ϵ P in product mix scenario psi ϵ PS
$MV_{psi,p}$	Mean value of process step p ϵ P in product mix scenario psi ϵ PS
$\sigma_{psi,p}$	Standard deviation of process step p ϵ P in product mix scenario psi ϵ PS
PS	Representative product mix scenarios of the assembly system

The larger the ranges and the more these spread around the cross-mix mean value $MV_{psi,p}$, the greater the process time heterogeneity and therefore, the flexibility requirements. Analog to product flexibility, thresholds are formed within the product mix flexibility to assign the scatter ranges to the assembly structure alternatives' characteristics and their codes respectively. The thresholds are calculated as function of the cross-mix mean value and standard deviation. To evaluate the scatter ranges, they are compared with the thresholds of the intervals according to equations (3) and (4).

$$s_{psi,p}^{high} \leq G_c^{high} \tag{3}$$

$$s_{psi,p}^{low} \geq G_c^{low} \tag{4}$$

$G_c^{high/low}$	Upper/lower threshold of characteristic c ϵ C
C	Characteristics of the assembly structure alternatives

Equations (3) and (4) are checked for all characteristics, starting with lowest flexibility continuing to highest. A characteristic and the corresponding code are assigned once both inequations are fulfilled. Similar to product flexibility, a matrix is derived, which contains the assigned concepts in the form of their encoded values. The rows constitute the process steps while the columns comprise the representative product mixes. Each defined code holds a percentage regarding the considered mix comparison. The percentages are accumulated, starting with the lowest degree of flexibility to the highest analog to product flexibility. Once the accumulated percentage exceeds a predefined threshold, the corresponding code respectively degree of flexibility is assigned to the mix comparison. Based on that, the value of all mix comparisons and therefore, the required degree of flexibility within the general product mix flexibility is derived.

Short- and long-term product mix flexibility examine process time heterogeneity considering the change between mix scenarios. On the one hand side, short-term product mix flexibility focuses on the short-term change from one production program to another, for example within a daily or weekly period. Long-term product mix flexibility considers trend changes in the program over the long time horizon, such as within years, and therefore considers two or more mixes in a row representing a trend. The criteria compare different representative product mixes analyzing the changes in location and size of the scatter ranges of mean value and standard deviation in each process step. Therefore, the differences of the process specific mean values and standard deviations are calculated using equations (5) and (6). To classify the determined values, intervals are defined and linked to the characteristics in the classification. Similar to the abovementioned procedure, the determined values are assigned to the intervals. This results in matrices from which the flexibility requirements and the respective characteristics are derived.

$$\Delta MV_{psi,psj,p}^{short/long} = \frac{|MV_{psi,p} - MV_{psj,p}|}{\max(MV_{psi,p}; MV_{psj,p})} \tag{5}$$

$$\Delta \sigma_{psi,psj,p}^{short/long} = \frac{|\sigma_{psi,p} - \sigma_{psj,p}|}{\max(\sigma_{psi,p}; \sigma_{psj,p})} \tag{6}$$

$\Delta MV_{psi,psj,p}^{short/long}$	Difference between mean values of process step p in product mix scenarios psi and psj ϵ PS
$\Delta \sigma_{psi,psj,p}^{short/long}$	Difference between standard deviation of process step p in product mix scenario psi and psj ϵ PS

Volume and expansion flexibility are analyzed under consideration of output quantities since a system's scalability is decisive. Several short- and long-term quantity scenarios can be taken into account to consider different market developments and corresponding flexibility requirements. While volume flexibility considers the ability to alter the output quantities in the short-term, expansion flexibility takes long-term variations into account. Using the output quantities and relations indicated in the input data, short-term and long-term scaling coefficients are generated using linear regression analysis. These coefficients are assigned to predefined intervals which correspond to characteristics in the classification and were identified analyzing use case data sets including experts' experience. Depending on the use case, several output quantities can reflect different scenarios and therefore, several short- and long-term scaling coefficients. These are equally applied in determining the flexibility requirements of volume respectively expansion flexibility.

As mentioned above, the characteristics of the assembly structures in the classification are associated with codes that reflect their degrees of flexibility. These codes are utilized within each flexibility criterion in order to prioritize the characteristics and thereby derive the criteria specific design recommendation. Thus, a common reference is provided to aggregate the results and derive the overall design recommendation on the basis of the criteria weighting. The characteristics prioritized in this way for the three dimensions form the recommended assembly structures respectively levels in the classification.

4. Critical Reflection

The assessment model has been embedded in a software application for use in industry projects and for evaluation with the expert panel of the research project *AIMFREE*. The software requires entering the input data of the considered use case. Based on that, the application automatically calculates and determines the flexibility requirements. From this, design recommendations for the assembly structure are derived. The assessment model has been applied to several use cases utilizing related data sets for evaluation and improvement purposes.

In order to critically reflect and illustrate the application of the presented model in a practical context, the flexibility assessment and derivation of the design recommendation is exemplified by a use case that was carried out to verify the assessment model. The participating assembly planning experts knew neither the use case under consideration nor its implementation in reality and are therefore not biased. The use case of the aggregate manufacturer is characterized by many variants with partly high cycle compensation times, a highly seasonal order volume and a required annual output of 3,000 pieces. Concerning the mix of the two main models, a short-term change from 80/20 % to 20/80 % was defined as a requirement. In the following, the results of the application and the evaluation with the expert panel are presented focusing on the significant product and general product mix flexibility. The results of the assessment in Figure 1 and 2 show that the system consists of two segments characterized by different required flexibility. The left part of each figure refers to the first segment, whereas the right part refers to the second segment.

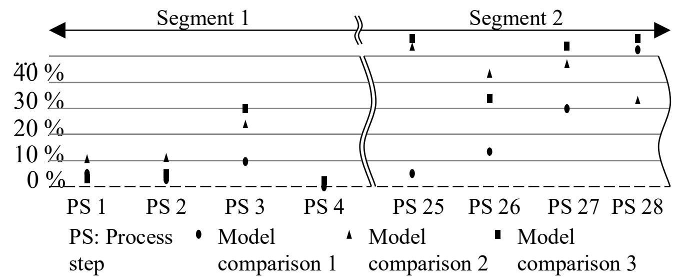

Figure 1: Results for the assessment of product flexibility

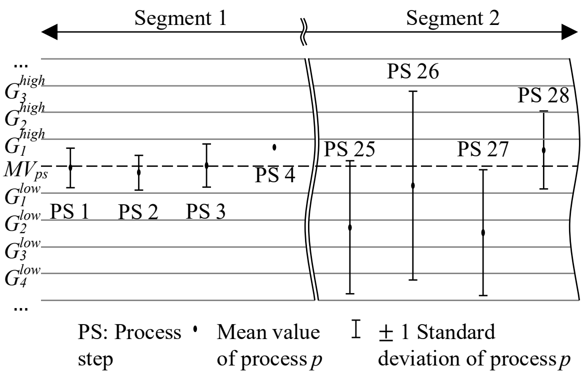

Figure 2: Results for the assessment of general product mix flexibility

Figure 1 highlights that in the second segment, the heterogeneity between the models is much more distinctive than in the first one. Therefore, a one-dimensional assembly system with an average cycle time and mobile production resources results as a criteria-specific design recommendation for the first segment. For the second segment, highly flexible structure alternatives result as criteria-specific design recommendation from the high required flexibility. A similar result is achieved for general product mix flexibility in Figure 2. The figure shows that the scatter ranges in the first segment are significantly smaller than those in the second one. In addition to that, the scatter ranges are close to the cross-scenario mean value in the first segment, while the second ones are less centred and accordingly more heterogeneous. The aforementioned thresholds have been established in Figure 2 in the form of horizontal lines representing the comparison of required and provided flexibility. Due to that, for the first segment, a one-dimensional assembly system with uniform cycle time and mobile production resources results as a criteria-specific design recommendation. For the second segment, a two-dimensional control-based assembly system with mobile production resources follows as a criteria-specific design recommendation.

Before the application of the assessment model, the expert panel manually analyzed the requirements and data of the use case coming to the conclusion that segmenting the assembly system into two sequential sub-systems is promising as those strongly differ in terms of required flexibility. The experts considered a clocked assembly line appropriate for the first segment and a flexible respectively matrix assembly structure for the second one. This consideration was kept secret while applying the assessment model to the use case to later compare the results. In summary, the application of the assessment model delivered a similar design recommendation as the assembly planning experts but additionally provided a rationale using the assessment results. By doing so, the segmentation point between the segments was confirmed.

During the application of the assessment model for evaluation, it became evident to the supervising experts that especially the quantitative assessment of the flexibility requirements proved to be of significant help for structure planning. The objective connection between available production planning data and the derived recommendation strongly supported transparency of the prioritization of alternatives and related decision-making. The comments of the experts proved that utilizing the assessment model focuses the discussion on the most relevant aspects for planning an assembly structure. The model delivers appropriate as well as valuable recommendations efficiently since for generating a similar recommendation result, only a fraction of the time compared to the manual approach of the experts was required.

5. Conclusion and Outlook

Given increasing cycle time spreads and efficiency losses, assembly planners face the challenges of developing alternatives to conventional line assembly that enable flexible and at the same time efficient production. The decoupling of workstations and dissolving the cycle time constraint within matrix assembly systems has the potential to overcome these challenges. Thus, the presented work focuses on developing an assessment model for the requirement-led planning of flow-based assembly structures. The model enables the planner to determine the use case-specific flexibility requirements based on data and efficiently prioritize respectively select the appropriate assembly structures for further consideration in the further planning stages of capacity planning and performance simulation. An interdisciplinary panel of experts accompanied the model development and evaluation underlining the benefits of the practical application in industry use cases. The evaluation confirmed the advantageousness of the assessment model in comparison to existing and manual approaches underlining the gain in efficiency and transparency when it comes to the data-driven specification of flexibility criteria and determination of the appropriate assembly structures. During the reflection, further research questions and potential extensions were identified. Additional research is beneficial in the sensitivity analysis of the parameters and interval values included in the model. Moreover, the integration of the model into a fully comprehensive assembly planning procedure is advantageous.

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Biography

Nils Föhlisch (*1992) is research associate at the Department of Factory Planning at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University since 2019.

Prof. Dr.-Ing. Peter Burggräf (*1980) is scientific head of the Department of Factory Planning at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University and has been head of the Institute of International Production Engineering and Management at the University of Siegen since 2017.

Tobias Adlon (*1989) is chief engineer of the Department of Factory Planning at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University since 2020.

Christopher Kapella (*1995) was a master thesis student and student research assistant at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University.