5th Conference on Production Systems and Logistics

Classification Of Flow-Based Assembly Structures For The Planning Of Flexible Mixed-Model Assembly

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Abstract

The increasing product variance due to the growing individualization of customer requirements leads to smaller batch sizes and higher process time spreads in mixed-model assembly. The resulting decline in efficiency pushes conventional, less flexible assembly lines to the limits of their economic viability. Matrix assembly is an approach to increase flexibility and efficiency by decoupling workstations and dissolving cycle time constraints while maintaining flow. Both matrix and line assembly are flow-based assembly structures characterized by assembly objects moving according to the flow principle. Due to the numerous design options of flow-based assembly structures and the need to consider flexibility as a central decision criterion, the complexity of structural planning increases. The variety of the design options as well as their compatibility make it challenging for assembly planners to decide which configuration provides sufficient flexibility for their use case.

This paper presents a novel level-based classification for flow-based assembly structures that identifies the relevant configurations, ranks them according to provided flexibility, and breaks down the characteristics as well as their compatibility. The classification enables planners to efficiently compile, evaluate and select the flow-based structure configurations suitable for the individual use case during assembly structure planning. Planning efficiency and results are improved by transparently providing all configurations and their characteristics' compatibility to the planner without any research effort. The configuration selection focusing on flexibility by means of the classification can be the starting point of a subsequent simulation of the system behavior concerning efficiency.

Keywords

Mixed-Model Assembly, Matrix Assembly, Line Assembly, Flexibility, Efficiency, Assembly Planning

1. Introduction

In times of increasing individualization and diversification of customer requirements, the number of units per variant decreases and manufacturers use mixed-model assembly lines (MMAL) to minimize investments and associated risks [1, 2]. Different product variants with related characteristics are assembled in the same assembly line without retooling [3]. The different scopes in assembly stations make it increasingly difficult to maintain a uniform cycle time within the system [4]. Despite significant efforts for measures to reduce the cycle time spread and to optimize the variety of variants [4], conventional, clocked MMAL reach the limits of economic viability [5]. Therefore, companies are looking for assembly structures that are able to cope with the changing conditions in a short time and a paradigm shift towards more flexibility is emerging [2, 6, 7].

DOI: https://doi.org/10.15488/15252
ISSN: 2701-6277
publish-Ing.

Both line and matrix assembly form the flow-based assembly structures. Assembly objects move according to the flow principle through a series of assembly stations to be completed [8]. Matrix assembly makes use of the advantages of job-shop assembly regarding flexibility and of flow-line assembly regarding efficiency by decoupling workstations and dissolving the cycle time constraint [5]. Assembly objects each take an individual path through the assembly stations, which can be approached independently of each other [9]. In comparison to MMAL, matrix assembly is highly flexible and provides better efficiency for specific use cases [6]. In case of unforeseen events such as a disrupted or unavailable assembly station, it can easily be skipped by adjusting the path of an affected assembly object and the system can be changed proactively [10]. The significant advantages of matrix assembly go along with a higher control effort of the entire assembly and increased space requirements [11]. Currently, matrix assembly systems are not known to be fully deployed in series production, although the concept is broadly discussed in research and tested in prototype applications in practice [12]. Reasons for the slow introduction include companies' lack of experience in the use and planning of matrix assembly systems and the high planning complexity.

The majority of conventional approaches to assembly planning are based on the sequential phases *Formulation of the planning task, Rough planning, Detail planning* and *System implementation* [13]. After the formulation of the planning task and requirements regarding system adaptability, the rough planning is performed. In this, alternative characteristics are combined and thereby competing system configurations developed. After an evaluation, the superior configuration is selected, and the detailed planning is conducted.

When developing concepts during rough planning, planners are guided by classifications that differentiate assembly structures based on their constituting characteristics. Due to the increased planning scope in the structural planning of matrix assemblies, the known dimensions of those classifications do not describe the relevant characteristics with distinction. As a result, the system configurations of flow-based assembly structures are not transparent and structural planning becomes inefficient because planners must undertake research efforts to identify configurations. Hence a classification applicable for the structural planning of all flow-based assembly structures is required. In this paper, a novel classification for flow-based assembly structures to organize relevant configurations according to the provided flexibility is proposed. Therefore, the following research question is to be answered: *How can the cause-effect relationships of flow-based assembly structures be consolidated in a classification for efficient structural planning?*

2. Literature Review

The presented systematic literature review follows the approach described by VOM BROCKE ET AL. [14] and aims at identifying the key publications representing configurations of flow-based assembly structures and approaches to classify assemblies. The review scope and strategy were defined according to the taxonomy of literature reviews described by COOPER [15], extended by the Starlite mnemonic [16]. The concepts in the research field pursue the common goal of overcoming the challenges of multi-variant assembly, such as limited efficiency in particular, by increasing flexibility. This topic was conceptualized by iteratively identifying the main search terms for flexibilization and the domain. Accordingly, the search string (flexib* OR agil* OR matrix) AND ("assembly line" OR "assembly system" OR "mixed-model assembly") was applied for titles, keywords and abstracts resulting in 2,822 publications. These were analyzed using the PRISMA methodology [17] and 44 relevant publications remained after the screening process. A forward and backward citation search provided additional four publications. In the following, selected insights regarding concepts of flow-based assembly structures and classifications are presented.

2.1 Concepts of Flow-Based Assembly Structures

Flow-based assembly structures comprise both line and matrix assembly. The review results show that concepts to improve flexibility of conventional line assembly such as dynamic line balancing, sequencing, cycle time modifications, optimized system segmentation, flexible worker utilization and team work are already used in industrial practice and are therefore not presented in detail. However, these concepts reveal levers to improve flexibility like structuring in less dependent sub-systems, mitigating cycle time constraints and extending the utilization of workers' capabilities. In the following, the insights regarding matrix assembly structures are presented referring to these flexibility levers.

FOITH -FÖRSTER ET AL. investigate the productivity per area of assembly structures and show that it drops for line assemblies with a higher proportion of variants due to the cycle time spread, whereas modular structures such as matrix assembly roughly maintain their level [18]. GÖPPERT ET AL. develop a matrix assembly structure by dissolving the coupling of assembly stations established in assembly lines with the aim to increase the flexibility while maintaining efficiency [12]. This involves arranging self-adaptive and reconfigurable stations in the form of a grid within a segment of high flexibility requirements. MINGUILLON also uses a grid arrangement of stations that can perform multiple operations and have redundancy [19]. The assembly is cycle time-independent with individual processing times and unrestricted material flow. HOTTENROTT AND GRUNOW investigate the initial configuration of matrix assembly structures regarding mixed-model assembly of heterogeneous vehicles [6]. The authors show an average efficiency gain of 24.5 % using a matrix assembly compared to an assembly line if workers are not allowed to drift out of stations. The concepts share the same fundamental characteristics that the station coupling and cycle time constraint are dissolved but the authors provide negative definitions, i.e. it is shown which characteristics of a line assembly are omitted without naming the substituting mechanisms. The variety of similar, respectively synonymous terms, creates intransparency with respect to the central configuration characteristics.

By mitigating the cycle time constraint, its synchronization function needs to be substituted by means of planning and control. Although the analyzed publications do not explicitly refer to the applied extend of both, central concepts can be identified. GÖPPERT ET AL. describe an approach where individual order routes are controlled depending on the system status, such as resource availability, and a digital twin reacts to assembly progress at short notice [12]. BURGGRÄF ET AL. make use of a similar control approach that allows the assignment of assembly operations to stations without restrictions on fixed assembly sequences [9]. In contrast, the approach described by GRESCHKE ET AL. uses the same sequence of operations as in a line structure, so that the planning and control effort is reduced at the expense of flexibility [5]. HOTTENROTT AND GRUNOW allow a flexible operation sequence in the assembly precedence graph with focus on planning [6]. Orders are assigned to individual time periods in production and short-term planning includes the allocation of orders to AGVs. MINGUILLON develops a method for the control of a matrix assembly to increase the robustness against disturbances by means of predictive-reactive scheduling [19]. Scheduling comprises the temporal allocation of orders to stations and is carried out predictively on the basis of delivery dates. In addition, reactive rescheduling is used to respond in near-real time to disruptions that exceed anticipated levels. The approach combines planning and control scopes but is limited to cases with sufficient predictability of processes. In summary, concepts with a focus on planning, primarily controlling concepts and such with a combination of planning and control can be distinguished.

Different degrees of achieved flexibility can be distinguished regarding the utilization of workers' capabilities. FOITH-FÖRSTER ET AL. compare different structure types for assigning capabilities to assembly stations: universal structure, technology structure and single-process structure [18]. An assembly station of the universal type combines all assembly functions required to assemble the product in one single station. In contrast, the stations of a technology-based structure can just perform parts of the process (e.g. screw fastening). The highest specialization is realized within single-process stations designed for single operation only. In a matrix assembly, stations require multiple capabilities and redundancy is essential for flexibility according to several authors. In the concept according to GRESCHKE ET AL., the stations are equipped with multiple tools to perform various assembly operations [5]. KERN ET AL. make use of a flexible allocation of workers to stations so that capability profiles can be adapted [7]. The analysis of HOTTENROTT AND GRUNOW underlines that the mobility of workers has strong influence on efficiency [6]. SCHMITT ET AL. describe a matrix assembly concept, which is characterized by the fact that all assembly-relevant assets are mobilized and thus a maximum of flexibility is achieved [20]. In conclusion, the assignment and adaptability of the capabilities in a matrix assembly has strong influence on flexibility and efficiency. The concepts reach from fixed to fully adaptable capability profiles by using mobile production resources including workers and equipment. In case of mobile resources, the capability profile of a station results from the combination of the capabilities of the present workers and equipment. The mobility of resources enables the utilization of all available capabilities in a matrix assembly and is thereby key to maximum flexibility.

2.2 Approaches to Assembly Structure Classification

Classifications structure complex systems by differentiating the objects in the research field. In this chapter, useful approaches for the classification of assembly structures are introduced. LATOS ET AL. summarize eight conventional assembly structures by distinguishing the kinematic variables of stationary and moving assembly objects and workstations, as well as the direction and type of movement [21]. For example, stationary workstations characterize job shop assembly, where assembly objects are routed in an undirected and aperiodic manner. Moreover, a clocked line assembly considers stationary workstations and moving assembly objects, while its kinematics can be described as periodical due to the cycle time. Although this classification is a well-established concept in assembly planning, the level of detail regarding the kinematics parameters is insufficient to differentiate matrix assembly structures appropriately. The characteristic *undirected movement* is unspecific in the context of matrix assembly and *aperiodic movement* is also not further specified to match the variances of cycle time independence. Furthermore, the mobility characteristics are not intended to describe complex movement of production resources in a matrix assembly.

To the best of the authors' knowledge, there is no classification that can adequately describe line and matrix assembly structures simultaneously with specific dimensions applicable to assembly planning. The following classifications do not refer to assembly, but feature model structures that are beneficial for the classification of assembly structures. FROHM ET AL. present a classification for automation in manufacturing by breaking down activities into physical and cognitive tasks while acknowledging the cooperation between workers and technology [22]. The model contains seven levels of automation, from fully manual to fully automatic control, by which each manufacturing task can be classified. The level structure ensures easy usability for planners in automation planning and can be transferred to a classification for flow-based assembly structures to make different levels of flexibility transparent. Another level-based classification is SAE J3016 [23], which describes the degree of driving automation for on-road motor vehicle systems from no to full driving automation. This concept creates an easy-to-use methodology to allocate automation systems within six levels. The driving task is divided into its three main dimensions and characteristics are selected per dimension. Each level in the classification represents a relevant combination of characteristics. The model structure can be transferred to differentiate characteristics and classify configurations in the context of flow-based assembly structures by representing configurations as levels based on their constituent characteristics. Additionally, levels can be ranked according to their degree of provided flexibility.

In summary, the following conclusions regarding flow-based assembly structures and corresponding classifications can be derived. The characteristics applied in matrix assembly structures are only made transparent to a limited extent and it is uncertain which configurations exist for flow-based assembly structures. Furthermore, overall flexibility of structures remains unclear. Configurations cannot be distinguished by applying existing assembly classifications in the phase of structural planning and the entity of potential solutions cannot be identified efficiently during assembly planning with limited resources. From this, the following objectives are derived to answer the research question. The classification needs to represent the relevant configurations of flow-based assembly structures in a technology- and industry-independent way. Additionally, the level of detail of the classification is required to be adequate for the rough planning phase to enable the efficient identification of the suitable assembly structure for an application.

3. Morphology of Flow-Based Assembly Structures

The basis to identify the relevant assembly structure configurations for the classification are the concepts of flow-based assembly structures that emerge from the structured literature review. The methodological approach for the analysis is based on an empirically justified type determination according to KLUGE [24]. The morphology and classification were developed with regular involvement and systematic collection of feedback of an assembly expert panel. In addition to research institutes, the panel's consortium consists of automotive original equipment manufacturers and system enablers. In the first development phase (chapter 3), the relevant comparative dimensions are extracted that adequately capture both the similarities and differences between the concepts under investigation and finally characterize the types. For this purpose, the concepts are systematically abstracted and the relevant dimensions and their characteristics are distinguished with support of a morphological analysis according to ZWICKY [25]. Empirical regularity is analysed by means of iterative grouping. The second phase (chapter 4) focuses on the identification of the relevant types, respectively assembly structure configurations.

The resulting morphology of flow-based assembly structures contains the dimensions *Dimensionality of object routes, Synchronization principle of time* and *Mobility of production resources* in the columns (Tab. 1). Starting from the top, the characteristics in a column are ordered from high to low restrictions to adaption in an assembly structure and, by doing so, represent a ranking from low to high provided flexibility of the characteristics.

Table 1: Morphology of flow-based assembly structures

	Dimensions		
	Dimensionality of object routes	Synchronization principle of time	Mobility of production resources
Characteristics (Flexibility ↓)	One-dimensional (Line)	Uniform cycle time	Stationary
	Two-dimensional (Matrix)	Average cycle time	Moving
		Expected operation time	
		Reaction to assembly progress	
		Expected operation time and reaction to assembly progress	

3.1 Dimensionality of Object Routes

The *Dimensionality of object routes* describes the degree of freedom of the routing of assembly objects between stations. *One-dimensional* and *two-dimensional* object routes are differentiated. One-dimensional routes correspond to the sequence and strict coupling of stations in a technological process direction which is the same for all assembly objects in the sense of a line assembly. All assembly objects take the same path through the assembly system. The flow is directional and objects cannot return to previous stations.

If stations are arranged in the form of a grid and assembly objects move freely without route restrictions, the object routes are considered *two-dimensional*. Accordingly, any other station in the system can be approached from each other and assembly objects can follow order-specific routes.

3.2 Synchronization Principle of Time

The dimension *Synchronization principle of time* describes the extent to which planning respectively control is used to coordinate work scopes between stations in the time dimension. A distinction is made between the five characteristics *Uniform cycle time, Average cycle time, Expected operation time, Reaction to assembly progress and Expected operation time and reaction to assembly progress*. These differ in particular concerning the degree of cycle time dependency, which in turn has a major influence on the amount of planning, respectively control, required during operation.

In an assembly structure with a *Uniform cycle time*, synchronization takes place using a cycle time, which is equal for all stations and after which the assembly object moves to the next station. The work scopes of an assembly station must be completed within the cycle time.

In an assembly structure with an *Average cycle time*, synchronization is achieved using a cycle time to be maintained on average over a defined number of cycles for all stations. The work scope of a product variant at a station may exceed the cycle time, provided that this time overrun is compensated in the subsequent cycles by variants with a smaller scope. This requires an appropriately coordinated sequencing of variants.

The third synchronization principle describes an assembly structure in which synchronization is achieved without cycle time constraint using planning based on *Expected operation times*. The expected operation time is an individual time slot per work scope for an assembly object, which is estimated based on available data such as MTM analyses and empirical values. Buffer times can be included in the planning to account for potential interruptions in the assembly process. The route through the assembly is pre-planned for each assembly object based on the distribution of operation times across stations for the planning period. The production resources in a station are bound to the predefined operation time when carrying out the work scope assigned to them.

In an assembly structure, which is synchronized by means of control in *Reaction to assembly progress*, the assembly progress is permanently monitored at all stations. When an assembly process is completed, the system reacts by assigning the next station to be approached by the assembly object in a situationally aware manner. No planning of the object route exists in advance. By doing so, there are fewer restrictions compared to a system based on an assembly schedule, such as synchronization using expected operation times.

An assembly structure can also be synchronized using a combination of planning in advance based on expected operation time and control in reaction to the assembly progress. In this case, the synchronization principle of *Expected operation time and reaction to assembly progress* is applied. As in the third characteristic, planning is carried out in advance according to the planning horizon. During operation, this plan is processed and, in parallel, the assembly progress is permanently monitored, as in the fourth characteristic. If deviations from the original plan occur, the system reacts by adapting control and, if the interruption is severe, the plan.

3.3 Mobility of Production Resources

The dimension *Mobility of production resources* describes the assignment of the resources assembly personnel and operating equipment to an assembly station differentiating between *stationary* and *moving*. If personnel and resources are *stationary*, they are permanently assigned to a specific station. Therefore, only the capability profile required at the respective station is used as a subset of the qualification matrix of the individual worker and the operating equipment.

The characteristic *moving* describes that the assembly personnel and/ or the operating equipment can move between assembly stations and thus change the place of use in the assembly system as required. In this way, the entire qualification matrix of the worker and/ or operating equipment can be utilized and capacities at stations can be varied. The capability of a station is thus determined by the capability profiles of the present worker and operating equipment.

4. Classification of Flow-Based Assembly Structures

In the second phase of the methodological approach, the classification is developed based on the morphology by means of an analysis of the cause-effect relationships. Initially, the model structure is developed based on the findings regarding the classifications leading to a chart with a stepwise increase of provided flexibility described by levels (Tab. 2). The classification uses dimensions as columns with characteristics represented in the cells. A configuration of a flow-based assembly structure, respectively a flexibility level, is determined by the combination of characteristics as a row in the chart. The analysis comprises the formation of all combinations of characteristics in the morphology and subsequent prioritization with regard to practical relevance by the expert panel. The priorities are assigned based on empirically found concepts and the experiences of the experts. Relevant combinations, respectively assembly structure configurations, are classified as flexibility levels from low to high provided flexibility in the classification. The levels are ranked according to provided flexibility by pairwise comparisons of the levels' characteristics combinations. A level has superior flexibility if the combination of characteristics provides fewer restrictions for adaption during operation (chapter 3).

Table 2: Classification of flow-based assembly structures

<table>
<tr><th></th><th colspan="3">Dimensions</th></tr>
<tr><th>Levels (Flexibility)</th><th>Dimensionality of object routes</th><th>Synchronization principle of time</th><th>Mobility of production resources</th></tr>
<tr><td>1</td><td rowspan="4">One-dimensional (Line)</td><td rowspan="2">Uniform cycle time</td><td>Stationary</td></tr>
<tr><td>2</td><td>Moving</td></tr>
<tr><td>3</td><td rowspan="4">Average cycle time</td><td>Stationary</td></tr>
<tr><td>4</td><td>Moving</td></tr>
<tr><td>5</td><td rowspan="8">Two-dimensional (Matrix)</td><td>Stationary</td></tr>
<tr><td>6</td><td>Moving</td></tr>
<tr><td>7</td><td rowspan="2">Expected operation time</td><td>Stationary</td></tr>
<tr><td>8</td><td>Moving</td></tr>
<tr><td>9</td><td rowspan="2">Reaction to assembly progress</td><td>Stationary</td></tr>
<tr><td>10</td><td>Moving</td></tr>
<tr><td>11</td><td rowspan="2">Expected operation time and reaction to assembly progress</td><td>Stationary</td></tr>
<tr><td>12</td><td>Moving</td></tr>
</table>

The usability and advantageousness of the developed classification in a practical context were reflected and evaluated by the 19-member panel of experts. By leveraging the expertise of the broad-based panel, an interdisciplinary evaluation including all disciplines involved in assembly planning was performed. The semi-structured reflection according to DÖRING AND BORTZ [26] was based on three assembly use cases and their products (chainsaw, automotive drive train and mobile crane assembly). The experts were asked to select the appropriate flexibility level for the individual application. The particular products were chosen due to their different requirements and each use case was described by crucial figures and properties relevant for planning. The chainsaw assembly was characterized by many variants in a single system (45 variants), a very high output quantity (30,000 pcs/year) and a long-term conversion of the shares from combustion engine variants to electric drive. The automotive use case contained five drive variants to be assembled in high output quantity (200,000 pcs/year) and with high volatility of variant shares. The use case with mobile cranes had a low output number (50 pcs/year) with only three main variants but with a wide variety of individualization options. Weighing the advantages and disadvantages of each level, the experts evaluated the extent to which a level was suitable for the particular use case. On this basis, the favored level was selected. For the chainsaw use case, the experts suggested splitting the system into a line segment (level 1 or 3), assembling the mostly variant independent base of the saw and a two-dimensional segment for the variant dependent assembly (level 9). A similar segmentation approach was considered for the mobile crane use case, but due to high operation duration and good predictability level 8 was favored for the overall structure. For the automotive assembly, the experts dismissed all levels with two-dimensional object routing due to too high expected effort for sequencing to re-establish the pearl chain for the following line segment and favored level 4. Finally, the experts evaluated the classification's advantages in such a planning situation.

All participating experts confirmed the classification's advantageousness for structural planning and its good usability in a practical context. The classification focuses on the aspects of an assembly structure that are essential in structural planning and reduces complexity by structuring the potential solutions. The experts noted that by using the classification, more attention is paid to the holistic view. This is particularly important when planning assembly structures with two-dimensional object routes. It was emphasized that an assembly could be segmented and the appropriate flexibility level is selected segment by segment. The classification structure supports the planning of such segment combinations and significantly reduces the required time to find an appropriate configuration as basis for more detailed analysis. Before planning an assembly structure, planners no longer have to laboriously search for dimensions, respectively characteristics, and analyze their compatibility. The classification also offers added value by being applicable for benchmarks by comparing the flexibility level of multiple assemblies. Additionally, it can be used to develop strategic target images and roadmaps by classifying the status quo of an assembly in the level structure and contrasting it to a target flexibility level or an evolution of levels in a schedule.

During the evaluation, interesting insights were obtained concerning the expected behavior of the levels. The experts confirmed that the flexibility grows with the levels while complexity also increases. Overall, it was seen as a prerequisite for the efficiency of two-dimensional levels that process times are sufficiently high or, in the case of low times, a correspondingly high work in process is kept in the system. To enable workers to move between stations, the number of stations or operating areas in the case of multiple workers per station needs to be higher than the number of workers. This applies analogously to moving operating equipment and the ratio is highly use case-dependent. In contrast, if workers and operating equipment are stationary, a significantly higher work in process at all stations is required to achieve maximum resource utilization. Overall, the achievable utilization of the system is determined by the interaction of the ratio of workers to stations, respectively operation areas, the mobility of resources and the amount of work in process.

Additionally, as the level increases, the order sequence, which is fixed in line systems, must become more flexible, or at least its dependence must be reduced. In the context of the use cases, the behavior of the systems in case of interruptions was discussed on the basis of the levels. It was underlined that for assemblies with a synchronization principle based on expected process times, higher planning reliability or lower susceptibility to interruptions is required than for primarily controlling systems. Especially for levels 5 to 8, good predictability of process times and limited fluctuation in the production program are essential. For these levels in particular, process times should not be too short and worker mobility is seen as an important enabler for high efficiency. Levels 11 and 12 were not favored because the expected effort measured against the benefit is still considered too high for the complexity described by the discussed use cases.

5. Conclusion and Outlook

This paper presents a classification that organizes all flow-based assembly structure configurations as foundation for structural planning in the rough planning phase. The classification contributes to improving planning efficiency and results by making configurations as well as their elements' compatibility transparent and thereby supports the planners. In summary, the formulated research question is answered by the flexibility levels including their characteristics combinations structured in the classification.

Extensions and possible classification improvements were identified for future research activities. For ease of use in practice, operationalization of the classification is desirable. A methodology that guides planners step-by-step through the process of structural planning using the classification needs to be developed. Ideally, this methodology is accessible to planners by utilizing a tool so that planner sonly need to enter input information of an use case and the appropriate flexibility levels are automatically prioritized. Furthermore, the knowledge of the implications of using a flow-based assembly structure for adjacent planning tasks needs to be extended for each level of the classification. This can further improve planning efficiency and counteract uncertainties during decision-making in interdisciplinary planning teams.

Acknowledgements

This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within *The Future of Value Creation – Research on Production, Services and Work* program in the *Industry 4.0 – Transformability of Companies in the Value Creation of Tomorrow (InWandel)* funding measure [02J21C130] and managed by the Project Management Agency Karlsruhe (PTKA). The authors are responsible for the content of this publication.

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Biography

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