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# Agent-based Order Release In Matrix-Structured Assembly Systems

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## Abstract

The introduction of new variants and the difficulty of forecasting future market demand and developments aggravate the synchronisation of assembly lines. This ultimately leads to cycle time spreads and thus to efficiency losses, e.g. due to lower employee utilisation. In response, matrix-structured assembly systems have been developed as a concept of cycle time independent flow production. Essential characteristics of this type of assembly systems are the dissolution of both one-dimensionally arranged assembly stations as well as cycle times across assembly stations. In recent years, the focus has been on assembly control for the routing of orders through a matrix-structured assembly system. However, order release strategies have largely been neglected, which means that the actually promised performance of this new organisational form of assembly cannot be fulfilled. An agent-based release decision enables the optimal scheduling of new orders taking into account current information from the assembly system such as station states or the processing progress of orders that have already been released. This work extends and builds on existing agent-based approaches to control matrix-structured assembly systems in regard to order release. This results in a theoretical improvement in key performance indicators such as throughput time and station utilisation. For this purpose, the release process, as well as the associated calculation logics and constraints, are described and the implementation in an environmental model is outlined. An essential part of calculation logics is the prediction of all possible paths and capacity requirements resulting from routing and sequence flexibility. This work contributes to the practical realisation and economic operation of matrix-structured assembly systems.

## Keywords

Matrix-structured assembly; agile assembly; assembly control; multi-agent system; order release

## 1. Introduction

Matrix-structured assembly systems are gaining progressively more attention in research. They are considered a potential solution for addressing the ongoing challenges caused by shorter innovation cycles and volatile market conditions through the use of a flexible organizational assembly form [1–4]. Key features of this new organizational form are the breakup of one-dimensionally arranged assembly stations and the elimination of uniform cycle times for all assembly stations [4]. This enables the processing of orders on a situational basis and depending on current circumstances in the assembly system. Resources at assembly stations can not only be used for station-specific assembly steps, but rather for all assembly steps which require this resource. Since the possible routes of an order are known a priori by the assembly system, whereas the actual routing is determined as a response to the situation and depending on the actual availability of the assembly stations, assembly control gains significantly in importance [4–8]. In matrix-

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structured assembly systems, assembly control deals with the assignment of orders and assembly steps to assembly stations, taking into account current resource availability or disruptions. This shifts the complexity from line balancing to assembly control [9,10]. Assembly control deals with the customer- and order-related design of material and information flows. This includes the systematic interaction of material-processing and material-moving areas in a time-related context [11]. Important functions of assembly control are order release and order monitoring, job scheduling, worker assignment, material supply and disruption management [12].

In principle, assembly control can be realized by both centralized and decentralized control architecture. In the application context, centralized architectures are based on extensions of the flexible job shop problem [13–15]. In comparison to decentralized architectures, centralized architectures show better results in simulations with respect to tardiness and lead time [5]. However, for complex problem formulations as well as extensive scenarios, optimal solutions cannot be determined in polynomial time. Centralized control architectures cannot guarantee the requirements of real-time capability [5,8,13–15] which limits their applicability to control matrix-structured assembly systems [5,9]. Accordingly, research in this area has largely focused on decentralized control architectures, which can be well modelled by Multi-Agent systems (MAS) [16–18]. Several studies already have highlighted the efficiency and close to real-time performance of MAS-based assembly control systems [2,5,10,19–21].

Especially in the variant-rich and disruptive operational practice, it is indispensable that orders are only released when the assembly system has foreseeable sufficient capacities for order processing [10]. However, order release as a subtask of assembly control is largely neglected. So far, no functional approaches exist that go beyond random, alternating, or time-based order release. This contradicts the basic principles of matrix-structured assembly systems, according to which orders are only released into the assembly system in case of sufficient resource availability. To realize the performance potentials of matrix-structured assembly systems and to ensure the practicability of agent-based assembly control, a combined view of existing assembly controls and order release is required. Therefore, this paper presents a modular concept for agent-based order release in matrix-structured assembly systems. The concept is derived and described in a system-independent way. It includes the definition of necessary interfaces to the assembly control as well as processes for information management and decision-making in the order release mechanisms. Finally, an outlook on the software implementation is given and the added value and limitations of the concept are discussed.

## 2. Assembly control in matrix structured assembly systems

### 2.1 Agent-based control strategies

A MAS consists of several agents that jointly perform one or more tasks through interaction. An agent is a delimitable software unit with defined goals. This unit is embedded in a closed environment and is capable of performing autonomous actions while interacting with other agents in the environment to achieve the defined goals [22]. MAS are particularly characterized by high stability and reliability. They are significantly less likely to fail in dynamic environments than monolithic architectures. Overall, the greater the dynamics and turbulence of the environment, the higher the superiority of MAS becomes [23].

The existing MAS in the area of research at hand differ in terms of their modelling depth and scope, but they can all be considered as possible control systems. Therefore, the approach according to MAYER et al. is exemplarily presented in the following [10]. This approach is based on four agent types: Order release agent, routing agent, workstation agent and vehicle agent. Figure 1 shows these with respect to their interaction and main information flows.

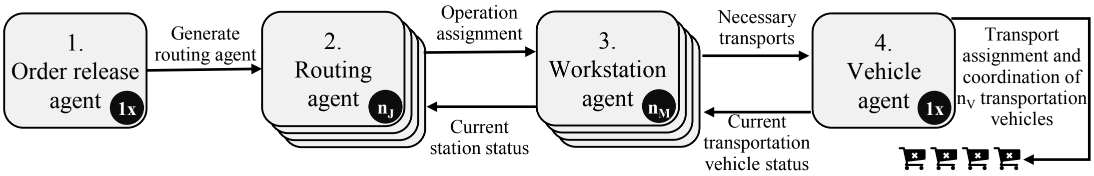

Figure 1: Exemplary decentralized agent-based control approach [10]

The order release agent decides on the timing and product type for the release of orders into the assembly system. The release itself is triggered when the work-in-progress (WIP) falls below a defined threshold. After releasing an order, the routing agent is generated and regularly calculates optimal routing minimizing the individual makespan for the assigned order. The optimization via Monte-Carlo Tree Search (MCTS) is triggered when a routing agent's operation has been finished or by order release. The next type of agent is the workstation agent, which is generated for each workstation in the system and serves to optimize the workstations' schedules and minimizes their idle time between the operations using the same MCTS. The fourth type of agent described by MAYER et al. is the vehicle agent. Like the order release agent, there is only one central vehicle agent to assign and coordinate the transportation vehicles. Its aim is to minimize the total transport costs in terms of time. As an alternative approach, BURGGRÄF et al. distribute the tasks of assembly control among the three agent types: assembly station agent, order agent, and manager agent, the latter also being responsible for order release [5]. However, these alternative approaches differ only in their modelling, while the core functions of assembly control are handled in a similar way.

In the following, the presented and other selected approaches are discussed in the context of the application in order to show concrete deficits in the release mechanisms. However, the basic idea for formulating a release agent according to MAYER et al. seems promising and will be adopted in the following explanations.

### 2.2 Limitations regarding order release

SCHENK et al. define the verification of resource availability as an essential task of order release [24]. According to GRESCHKE, order release is also an important sub-task of assembly control in matrix-structured assembly systems [8]. It has been shown that MAS are suitable for the control and simulation of matrix-structured assembly systems due to the comparatively faster solution-finding, especially if unexpected disturbances and path deviations are to be expected [2,4,5,8]. Existing approaches for agent-based assembly control neglect feedback from the production operation of the assembly system.

While BURGGRÄF et al. do not specify the order release, SCHÖNEMANN et al. apply a randomized distribution of orders to represent a *worst case* scenario [4,5]. GÖPPERT et. al. also utilize a random distribution approach with a fixed interarrival time to model the order release, similar to that of SCHÖNEMANN et al. [7]. The exemplary presented approach of MAYER et al. also only uses randomized and alternating release and refers to the necessity of advanced order release mechanisms. In the present research field, only one advanced approach could be identified. MÜLLER and SCHMITT provide an approach for sequencing order pools, which is based on the quantification of similarities as well as the minimization of similarities between two successive orders. Accordingly, a static order pool and a fixed order processing sequence are assumed. [25] However, this contradicts the core of the responsiveness of a matrix-structured assembly system just as much as a randomized release of assembly orders without matching capacity supply and demand.

In summary, it can be stated that the complete exploitation of the potentials of matrix-structured assembly requires the development of appropriate approaches for order release. Since the basic idea of MAS is extensibility, a corresponding extension of existing MAS in the context of application is a logical consequence. Therefore, order release tasks must be embedded into existing assembly control systems including the definition of interfaces and release mechanisms. In the following, concrete properties for an agent-based order release are derived and used to propose a general solution.

## 3. Design of an agent-based order release

### 3.1 Essential properties

To formulate individual properties of an order release in matrix-structured assembly systems, the deficits of existing control approaches as well as the general performance promises of matrix-structured assembly systems were evaluated using available literature. The findings were then reviewed within the consortium of the AIMFREE research project, which ultimately led to the formulation of six specific properties of a suitable approach. These are presented in the following:

The **first property** is motivated by the assumption of multi-functionality of assembly stations in matrix-structured assembly systems. Multi-functionality describes the ability of assembly stations to perform several different operations along the assembly precedence graph. The resulting increased routing flexibility improves the overall system efficiency [7,26,27]. Thus, capacity calculation must be detailed on an assembly operations level as a single consideration of capacities at the system or station level can lead to bottlenecks in the execution of specific operations. If considered solely at the operation level, assembly stations with comprehensive and multi-functional capability profiles would be scheduled multiple times. Therefore, the capacity situation must be analyzed at both the operation level and the system level. Information at this level of detail must be provided to the order release agent in order to evaluate both levels. The **second property** is the need to consider all possible paths and related capacity demands of an order through the assembly system. First of all, this includes the flexibility of the assembly precedence graph (process sequence flexibility), i.e. the possibilities of processing the operations of an order in different sequences. Furthermore, it includes the possibility resulting from the redundancy of capabilities that the same order selects different paths or stations in a system [15]. In accordance with this flexibility, both unreleased orders and orders that have already been released must be evaluated. In the latter case, all orders in the system must be analyzed in regard to the remaining paths and the capacity utilization to be derived from them. The **third property** is the event-driven release orientation. Periodic release mechanisms are not effective since it has been proven that lead times vary in the application context [28]. The release process needs to be triggered by current events such as the completion of an order. This ensures that current circumstances and information of the assembly system are taken into account for the release decision. The **fourth property** deals with the consideration of individual assembly system operation goals by parameterizing the decision behaviour as proposed by BURGGRÄF et al. [5]. Thereby, due to the agent-based approach of assembly control, the behaviour is encapsulated, but the performance indicators of the assembly system are influenced by order details and released orders. By parameterizing the decision behaviour, individual production strategies can be taken into account, e.g. to minimize lead times, delays or fluctuations in capacity utilization. The **fifth property** is the consideration of order-specific characteristics such as due-dates as well as individual orders [13]. Orders are therefore not grouped in production lots. Instead, in addition to the specification of the product type to be assembled, an order contains further information such as the completion date or margin. This information can also be included in the release decision. The last and **sixth property** is the practicability of the approach regarding solution time [5,9]. An upper boundary can be set by limiting the calculation time of a decision to be significantly shorter than the shortest operation time. Generally, the usage of outdated information needs to be minimized. After formulating comprehensive properties for an agent-based order release, a concrete approach will be presented in the following.

### 3.2 Embedding of the order release agent

Similar to MAYER et al., the task of order release is embedded in a single order release agent (ORA) and is part of the agent-based assembly control. Together with the matrix-structured assembly system and an order pool the environmental model is formed. The ORA can retrieve or provide information to its surrounding. To initiate the order release process, the ORA can proactively listen to events or be trigged by events in the environmental model. Once triggered, the ORA performs several subtasks related to the decision-making. These subtasks include the request of information such as waiting orders in the order pool. Since the order pool is usually managed by higher planning levels, it cannot be generally interpreted as a direct component of the assembly system or assembly control. Thus, it is located in the environment. However, the order pools provide information to their surrounding. The ORA saves the result of the order release and makes it available to the environment model. The interaction and the functionalities of the ORA are illustrated in Figure 2.

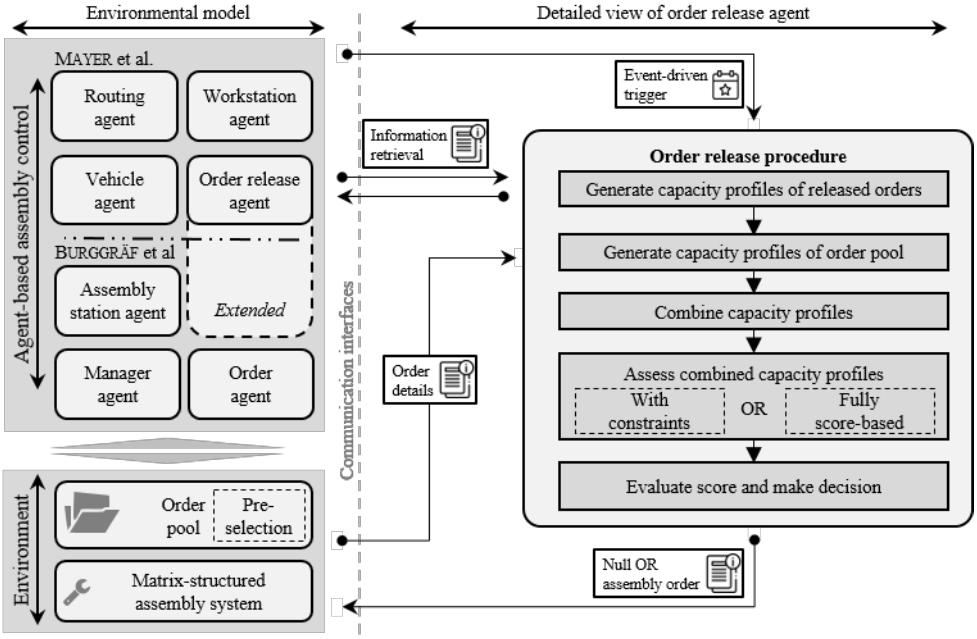

Figure 2: Concept, interactions and functionalities of the order release agent

As soon as the ORA is triggered by a defined event such as order or operation completion, the ORA first wants to replicate the current capacity situation in the assembly system. To do this, it retrieves information about the assembly system from the agent-based assembly control. The information includes available assembly stations as well as their capability profiles. Furthermore, the current order progress of released orders in the assembly system is retrieved. Based on the characteristics of the assembly system, the available capacity can be determined at the operation and system level. Using all path combinations, all the possible capacity profiles of the released orders are generated. In combination with the capacity profiles of the orders in the order pool the order-specific capacity fit can be derived. For this purpose, either an entire order pool or pre-selected groups (e.g. by determining volume cycles [13]) can be used.

The evaluation of the orders with regard to their suitability for release can be done either with restrictions for the capacity limits or through a fully score-based approach. In case of using constraints, overcapacity is not allowed in the system. Consequently, all orders which would exceed the capacity at any given time are rejected. To efficiently verify this, the product specifications of the orders in the order pool are considered first. Then the capacity constraints for all products in the order pool are evaluated and the product with the best capacity fit that does not violate the constraints is selected. In the next step, all orders containing the identified products are filtered. Those filtered orders are score-rated on order-specific information as the due-date and margin. Once all orders are viewed, the best order with the best score is chosen and released. If there is no order which satisfies the constraints or if there is a product which would fit, but no orders with this product exist, no order is released, and the agent goes into standby. Alternatively, a fully score-based approach to capacity evaluation can be used, which neglects hard capacity constraints. The fully score-based evaluation also determines a capacity fit for each product. However, if a product would overfill the available capacity, it’s not set invalid. Instead, a lower capacity fit is assigned to the product. Afterwards, the order pool is filtered for orders containing the product with the best capacity fit. Then, a score based on the weighing of capacity fit and order characteristics is formed. After all orders are rated, the best order is chosen. To avoid that the ORA continuously releases orders, a threshold can be set in the final result-evaluation and decision-making. Through this matching, there is a possibility that no order is released at all. Thus, the fully score-based approach enables the strategic release of orders which could possibly overload the assembly system for a short time by up-scoring certain order details such as due dates. The behaviour of the ORA could be further influenced by adding weighting factors which weight individual operations higher than others, resulting in a better utilization of this operation. Margin, due dates or other order characteristics can be weighted similarly to influence the overall behaviour of the order release agent.

Finally, the results of the capacity evaluation are processed to derive a concrete release decision. If no order was passed down from the capacity evaluation, no release is triggered. Otherwise, a specific assembly order will be released. The release of an order can also be set as a triggering event, so that the described process is initiated again.

### 3.3 Evaluation of the capacity fit

The main challenge in implementing the ORA and the release mechanisms is the formulation and evaluation of the capacity profiles. In preparation for the presentation of a concrete approach to address this challenge, a fictive case including a nomenclature is illustrated in figure 3.

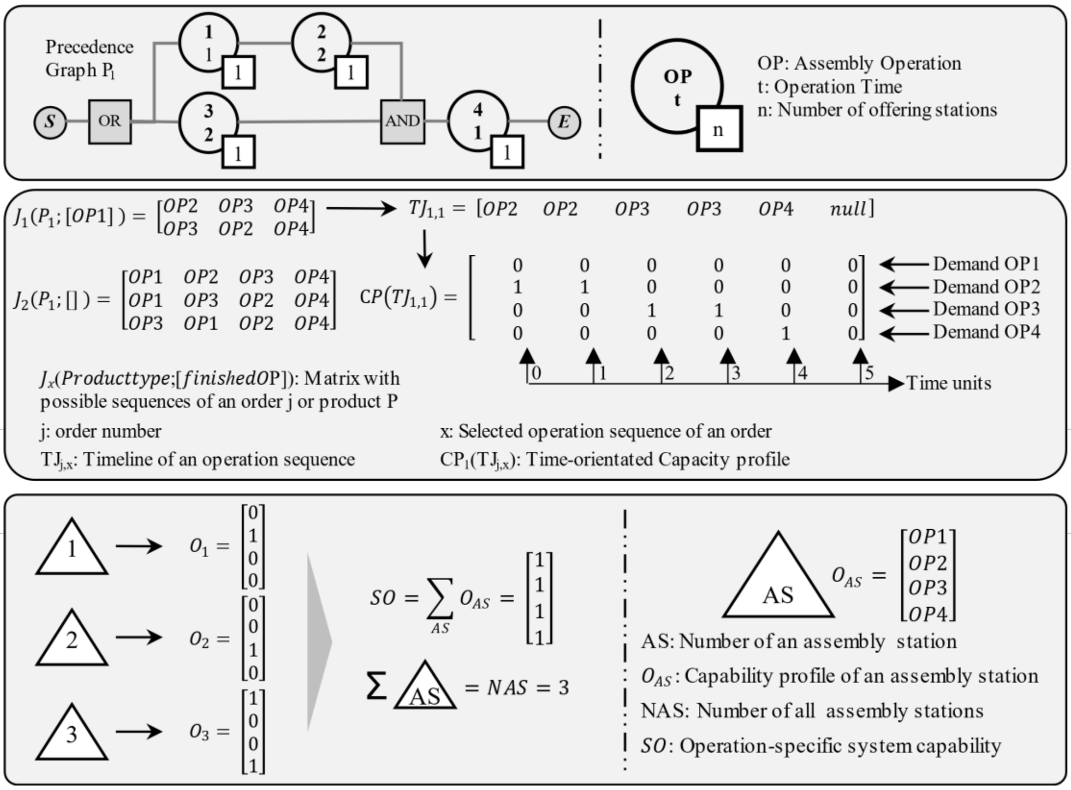

Figure 3: Case scenario and preparation of a capacity profile

Given is a product P1 with four different operations and precedence constraints. For example, the processing time of operation OP4 is one time unit and all other operations must be finished before OP4 can be started. All possible paths can be derived from the assembly precedence graph. These are formulated as a matrix, taking into account operations that have already been carried out, with each line describing a possible processing sequence. The order $J_1(P_1;[OP1])$ has already been processed with respect to OP1, so that two possible processing sequences remain. Now, for example, the first line is used as a possible sequence and gets extended using the given operation durations (see $TJ_{1,1}$). Furthermore, this possible sequence of operations can be transferred into a time-oriented capacity profile by documenting the operation demand line-by-lime (see $CP_1(TJ_{1,1})$). This results in a sequence- and product-specific capacity profile. Furthermore, each assembly station's capability is described with a vector $O_{AS}$ which indicates whether a specific operation can be conducted using a binary variable. For example, the capability profile $O_3$ permits the processing of OP1 and OP4. The operation-specific system capability is described by the vector sum. Figure 4 illustrates how this formulation of capability profiles is applied to match released orders with new release options.

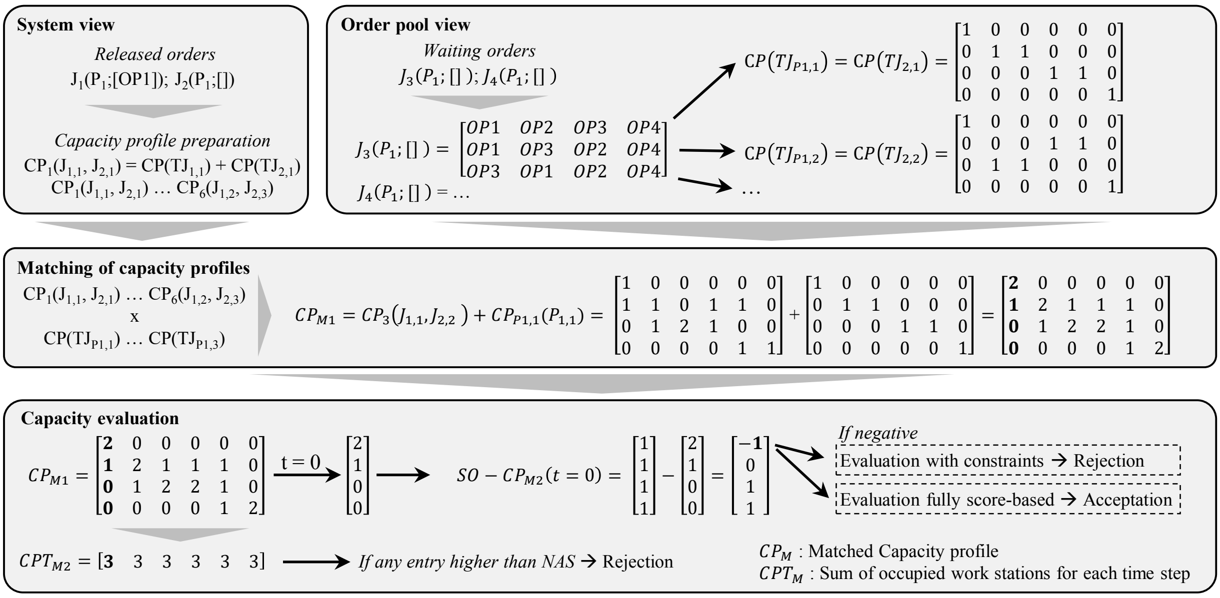

Figure 4: Capacity matching and evaluation

From his surroundings, the ORA finds out that two orders have already been released for processing: $J_1(P_1;[OP1])$ und $J_2(P_1;[])$. As shown in Figure 3, these two orders result in two respectively three possible sequences. Therefore, in a next step, all combinations of the sequences have to be transformed by adding the individual, time-oriented capacity profiles, in this case six profiles. Similarly, from the order pool view, two possible orders are made available for release, in this case each with the product P1. Since no order-specific details (e.g. due dates) are evaluated in the first step, it is sufficient to consider one of the orders on the product level. Just as for the already released orders, the time-oriented capacity profiles are determined. This results in three more profiles, since three possible sequences can be extracted from the precedence graph. The next step is to match the capacity profiles by storing all 18 (six times three) combinations as a capacity profile match. In this way, all possible sequence combinations of the already released orders are matched with those available for release. Then, for a specific time step (here t=0), the demand for the assembly operations is determined and compared with available capacity in the system. In case of a demand overload, depending on the evaluation method (see Figure 2), the matched capacity profile is either rejected or saved as release option with reduced favorability. In order to prevent an overload of the entire system, it is also analyzed whether more stations are occupied by the match than are available. In a similar way, a match is rejected depending on the evaluation method. The process shown must be carried out for all products available in the order pool. Valid matches are prioritized in the following step with regard to further, order-specific characteristics.

## 4. Discussion

The conception of the ORA bases on an environment model consisting of an agent-based assembly control and order pool. While previous approaches use order lists for random, alternating or lot-based release, the ORA decouples the two aforementioned entities of the environment model. The consideration of current information is essential especially in the context of highly dynamic environments like in matrix-structured assembly systems. Static mechanisms, which release random, alternating, or lot-based orders, are not effective in the intended context. If specific capabilities in the assembly system are overloaded, a lack of consideration of capacities leads to queues, longer throughput times and, in the worst case, deadlocks. At the same time, the use of static release mechanisms can lead to assembly stations in the system remaining completely unused. The extent to which the ORA can access an entire order pool must be decided upon the use case. For this purpose, inventory levels and necessary pre-manufacturing processes must be considered optionally. The danger that individual orders are not drawn from the order pool and remain unprocessed is eliminated by taking individual order characteristics into account and considering them in the decision-making process. The presented approach further requires that all possible order paths are considered for all capacity considerations. However, full path planning creates an NP-hard (NP: non-deterministic polynomial-time) problem, which can have a negative impact on performance in complex scenarios. Thus, approaches for the emerging NP-hardness in path prediction have to be elaborated in order to further enable real-time capable control of matrix-structured assembly systems.

## 5. Summary and Outlook

This paper has highlighted the relevance of order release to fulfil the performance promise of matrix-structured assembly systems. The presented approach provides a conceptual framework for embedding an order release agent into the agent-based control of a matrix-structured assembly system. However, this paper does not present concrete algorithms. Nevertheless, it can be concluded that in the dynamic environment of a matrix-structured assembly system, random, alternating, or lot-based order release can lead to efficiency losses. Further research should deal with the actual implementation of concrete algorithms as well as the validation of these within practical examples. However, this possibly requires an approach to address the NP-hardness of path planning. A possible solution would be to filter the order-specific paths with regard to improbable path constellations before analyzing them with regard to their capacity profiles. In this way, the capacity analysis could be excluded for rarely occurring paths or, for example, initially very long paths. The path determination is integrated into the ORA in the presented approach. Alternatively, this could also be outsourced to a separate agent in order to generate further performance advantages using asynchronous programming. In addition, a discounting of future capacity loads based on the net present value method should be discussed in order to give more weight to the near and more predictable future when making decisions. The implementation further includes the determination of weighting factors to enable target-oriented and robust decision making. On the basis of the software implementation, the theoretical potential of an agent-based order release can finally be assessed.

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## References

[1] Göppert, A., Schukat, E., Burggräf, P., Schmitt, R.H., 2021. Agile Hybrid Assembly Systems: Bridging the Gap Between Line and Matrix Configurations, in: Weißgraeber, P., Heieck, F., Ackermann, C. (Eds.), Advances in Automotive Production Technology, pp. 3–11.

[2] Greschke, P., Schönemann, M., Thiede, S., Herrmann, C., 2014. Matrix Structures for High Volumes and Flexibility in Production Systems. Procedia CIRP 17, 160–165.

[3] Schmitt, R.H., Göppert, M.R.A., Hüttemann, G., Lettmann, P., Rook-Weiler, K., Schönstein, D., Schreiber, A., Serbest, E., Steffens, M., Tomys-Brummerloh, A., 2017. Frei verkettete wandlungsfähige Montage, in: Brecher, C., Klocke, F., Schmitt, R., Schuh, G. (Eds.), Internet of Production für agile Unternehmen. AWK, 1. Auflage ed. Apprimus Verlag, Aachen.

[4] Schönemann, M., Herrmann, C., Greschke, P., Thiede, S., 2015. Simulation of matrix-structured manufacturing systems. Journal of Manufacturing Systems 37, 104–112.

[5] Burggräf, P., Dannapfel, M., Adlon, T., Kahmann, H., Schukat, E., Holtwiesche, L., 2020. Real-time scheduling of flexible operation sequences on multifunctional assembly stations. wt Werkstattstechnik online 110 (04), 170–176.

[6] Foith-Förster, P., Bauernhansl, T., 2015. Changeable and reconfigurable assembly systems – A structure planning approach in automotive manufacturing, in: Bargende, M., Reuss, H.-C., Wiedemann, J. (Eds.), 15. Internationales Stuttgarter Symposium, Wiesbaden, pp. 1173–1192.

[7] Göppert, A., Rachner, J., Schmitt, R.H., 2020. Automated scenario analysis of reinforcement learning controlled line-less assembly systems. Procedia CIRP 93, 1091–1096.

[8] Greschke, P., 2015. Matrix-Produktion als Konzept einer taktunabhängigen Fließfertigung. Dissertation. Technische Universität Braunschweig.

[9] Burggräf, P., Dannapfel, M., Adlon, T., Riegauf, A., Schukat, E., Schuster, F., 2020. Optimization approach for the combined planning and control of an agile assembly system for electric vehicles, in: Nyhuis, P., Herberger, D., Hübner, M. (Eds.), Proceedings of the Conference on Production Systems and Logistics, Hannover, pp. 137–146.

[10] Mayer, S., Gankin, D., Arnet, C., Endisch, C., 2019 - 2019. Adaptive Production Control with Negotiating Agents in Modular Assembly Systems, in: 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), Bari, Italy. 06.10.2019 - 09.10.2019, pp. 120–127.

[11] Warnecke, H.J.,, 1986. Ablauf der Montage, in: Spur, G., Stöferle, T. (Eds.), Handbuch Fügen, Handhaben, Montieren, 1. Aufl. ed. Hanser, München, pp. 607–619.

[12] Wiendahl, H.-P., 2014. Betriebsorganisation für Ingenieure, 8th ed. Hanser, München.

[13] Bochmann, L.S., 2018. Entwicklung und Bewertung eines flexiblen und dezentral gesteuerten Fertigungssystems für variantenreiche Produkte. Doctoral Thesis. ETH Zurich.

[14] Buckhorst, A.F., Huettemann, G., Grahn, L., Schmitt, R.H., 2019. Assignment, Sequencing and Location Planning in Line-less Mobile Assembly Systems, in: Schüppstuhl, T., Tracht, K., Roßmann, J. (Eds.), Tagungsband des 4. Kongresses Montage Handhabung Industrieroboter, pp. 227–238.

[15] Burggräf, P., Dannapfel, M., Adlon, T., Schukat, E., Kahmann, H., Holtwiesche, L., 2020. Modeling and evaluating agile assembly systems using mixed-integer linear programming. Procedia CIRP 93, 1073–1078.

[16] Libert, S., Chisu, R., Luft, A., 2010. Softwarearchitektur für eine agentenbasierte Materialflusssteuerung, in: Günthner, W., Hompel, M. ten (Eds.), Internet der Dinge in der Intralogistik, pp. 95–106.

[17] Unland, R., 2015. Industrial Agents, in: , Industrial agents. Emerging applications of software agents in industry, First edition ed. Elsevier, Amsterdam, Netherlands.

[18] Valckenaers, P., van Brussel, H., 2015. Design for the unexpected. From holonic manufacturing systems towards a humane mechatronics society., in: , Industrial agents. Emerging applications of software agents in industry, First edition ed. Elsevier, Amsterdam, Netherlands.

[19] Leusin, M.E., Kück, M., Frazzon, E.M., Maldonado, M.U., Freitag, M., 2018. Potential of a Multi-Agent System Approach for Production Control in Smart Factories. IFAC-PapersOnLine 51 (11), 1459–1464.

[20] May, M.C., Kiefer, L., Kuhnle, A., Stricker, N., Lanza, G., 2021. Decentralized Multi-Agent Production Control through Economic Model Bidding for Matrix Production Systems. Procedia CIRP 96, 3–8.

[21] Tan, Q., Tong, Y., Wu, S., Li, D., 2020. Towards a next-generation production system for industrial robots: A CPS-based hybrid architecture for smart assembly shop floors with closed-loop dynamic cyber physical interactions. Front. Mech. Eng. 15 (1), 1–11.

[22] Wooldridge, M.J., 2009. An introduction to multiagent systems, 2. ed. ed. Wiley, Chichester, West Essex, United Kingdom, 461 pp.

[23] Jeschke, S., 2015. Kybernetik und die Intelligenz verteilter Systeme: Nordrhein-Westfalen auf dem Weg zum digitalen Industrieland, in: Jeschke, S. (Ed.), Exploring Cybernetics. Kybernetik Im Interdisziplinären Diskurs. Springer Fachmedien Wiesbaden GmbH, Wiesbaden.

[24] Schenk, M., 2014. Fabrikplanung und Fabrikbetrieb: Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik, 832 pp.

[25] Mueller, D., Schmitt, T.V., 2020. Production planning in autonomous and matrix-structured assembly systems: Effects of similarity of precedence graphs on order release sequencing. Procedia CIRP 93, 1358–1363.

[26] Burggräf, P., Dannapfel, M., Adlon, T., Kahmann, H., Schukat, E., Keens, J., 2020. Capability-based assembly design: An approach for planning an agile assembly system in automotive industry. Procedia CIRP 93, 1206–1211.

[27] Hofmann, C., Brakemeier, N., Krahe, C., Stricker, N., Lanza, G., 2019. The Impact of Routing and Operation Flexibility on the Performance of Matrix Production Compared to a Production Line, in: Schmitt, R., Schuh, G. (Eds.), Advances in Production Research, pp. 155–165.

[28] Küpper, D., Sieben, C., Kuhlmann, K., Ahmad, J., The 2018. Will Flexible-Cell Manufacturing Revolutionize Carmaking? https://www.bcg.com/de-de/publications/2018/flexible-cell-manufacturing-revolutionize-carmaking. Accessed 31 January 2022.

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