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Path Prediction For Efficient Order Release In Matrix-Structured Assembly Systems

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Abstract

Numerous research papers have already demonstrated the theoretical benefits of matrix-structured assembly systems. Nevertheless, such assembly systems have hardly been used in practice so far. The main reason for this, apart from the technical integration, is the complexity of controlling matrix-structured assembly systems. In theory, decentralized, agent-based control architectures have proven to be particularly suitable. However, order release has been largely neglected so far. Accordingly, the authors' previous work includes a conceptual approach for capacity-oriented order release in matrix-structured assembly systems. This previous approach calculates possible sequences of an order and their capacity requirements on operation and system level considering both routing and sequence flexibility. Furthermore, by combining the possible sequences of released orders with orders to be released and comparing them with the available capacity, the previously suggested approach can systematically carry out capacity-oriented release decisions. However, the NP-hard problem arising from the consideration of all possible sequences in the capacity analysis limits the scalability and real-time capability of the former approach. The present paper aims to extend the previously developed approach. For this, before analysing any capacity implications in order release, a most likely sequence is selected. This is done by deriving possible paths of an order through the assembly system using the given sequences of operations from the assembly precedence graph. Selecting the path and that leads the shortest transportation time, the number of sequences for capacity analysis can be drastically reduced. Doing so, the NP-hardness of the previously developed approach can be circumvented. The paper describes the logic of path prediction in detail and evaluates its impact on order release. This work contributes to the practical realization and economic operation of matrix-structured assembly systems.

Keywords

Matrix-structured assembly systems; assembly control; multi-agent system; order release; simulation

1. Introduction

Matrix-structured assembly systems promise to reduce line balancing efforts in assembly planning and to facilitate the rapid integration of new products into existing production environments. For this purpose, the rigid linkage of assembly stations, as it is common in assembly line production, is eliminated in favour of assembly stations arranged in matrix form. This allows orders to take individual paths through the assembly system depending on their configuration features or the availability of assembly stations. Irrelevant or occupied assembly stations can be skipped. [1] The coordination and assignment of orders to assembly stations is handled by an assembly control system. [2] In general, assembly control refers to all actions and activities that directly affect the assembly system during its operation. The objectives of assembly control are the management of a proper flow of resources and materials, the optimization of capacity utilization, and the monitoring of assembly processes. [3,4]

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In matrix-structured assembly systems, assembly control presents a particular challenge. This is caused by the consideration of flexibility of the assembly precedence graph as well as the redundancy and multifunctionality of assembly stations. The assembly control has to react to events such as malfunctions at short notice and is consequently dependent on real-time data from the assembly system. Literature suggests two architectures for the design of assembly control in matrix-structured assembly systems: centralized and decentralized. [4] The latter, which can be modelled with the help of multi-agent systems (MAS) [5–7], has been found to be more suitable in the present context [8] For example, BURGGRÄF et al., MAY et al. and MAYER et al. present agent-based assembly control systems for matrix-structured assembly systems. [2,9,10]

One task of the assembly control is order release. Order release changes the status of an order from proposed to released and thus triggers the production process. [11] According to SCHÖNSLEBEN, this includes an evaluation of necessary and available capacities to process an order [11]. This capacity evaluation is a complex task in matrix-structured assembly systems. [12,13] Orders are reactively assigned to assembly stations while orders can take various different paths through the assembly system. Consequently, a deterministic prediction of a specific path and thus a general valid capacity evaluation is not possible. Instead, the capacity evaluation must anticipate and combine all possible sequences of orders already released with the possible sequences of orders yet to be released. [13] Based on this motivation, the authors presented a method for capacity-based order release in matrix-structured assembly systems in a previous paper. This former approach describes a capacity evaluation considering all possible operation sequences of released as well as to be released orders. However, this approach shows to NP-hardness (NP: non-deterministic polynomial-time) and thus limitations in terms of scalability for larger problem instances. Accordingly, a suitable approach has to be found to address this deficit. [13] To this end, the present paper extends previous work on capacity-oriented order release in matrix-structured assembly systems. It suggests an approach to limit the sequences used in the capacity evaluation by processing possible paths and related transportation times. For this purpose, the preliminary work in the area of order release in matrix-structured assembly systems is first described and the shortcomings are shown. This is followed by a derivation, description and simulative evaluation of the solution approach. Hence, a concrete test case will be introduced. The paper concludes with a discussion as well as a summary of the results.

2. Order release in matrix-structured assembly systems

2.1 Shortcomings of agent-based assembly controls in multi-agent systems

The known research work on assembly control has so far focused in particular on the core function of assembly control, i.e. assigning orders to the available assembly stations and triggering specific assembly operations at assembly stations. However, other essential functions of assembly control also include material supply, coordination of assembly personnel and order release. [13] Material supply in matrix-structured assembly systems has already been the subject of a wide range of research activities. [14–19]

The coordination of the assembly personnel should be based on the assembly object and thus on the value creation process. Before taking a deeper look at the coordination of assembly personnel, it is therefore first necessary to examine assembly control with regard to order release. For the previous simulation studies, simplified approaches were used. For example, SCHÖNEMANN et al. provided a ConWIP-control, where orders are released in random order from an order pool to limit the number of orders in an assembly system.[20] BOCHMANN implemented an order release with Linear Programming, where orders are sorted by completion date. [21] MAYER et al. also present a ConWIP-control. [10,22] MAYER & ENDISCH use periodic order release [23], as do GÖPPERT et al. and HÜTTEMANN which both model order release as a stochastic process [24,25]. None of the known studies offers a detailed elaboration of order release to take into account short-term changes in capacity availability within the assembly system or the changes in the order pool. Nevertheless, different authors point out the relevance of order release. For example, MAYER et al. expect that by improving order release, more stable lead times can be achieved while reducing deadlocks of orders in the assembly system. [22] GRESCHKE also points out the necessity to consider order release as a part of assembly control and to design it in a combined way. [4] Only SCHUKAT et al. propose a conceptual approach for order release in matrix-structured assembly systems, hence it is detailed below. [13]

2.2 Capacity-based order release in matrix-structured assembly systems

In their previous work, the authors presented a methodology for order release for matrix-structured assembly systems. It is implemented as part of an agent-based assembly control by BURGGRÄF et al. [8] as separate order release agent (ORA) that specifically takes control of order release. To do so, the ORA communicates with a manager agent, which triggers the ORA. The ORA retrieves information from the environment and evaluates the system based on the available capacity. Once the capacity situation is evaluated, it communicates in case a suitable order for release was found.

To evaluate the capacity situation of the assembly system and take release decisions, the ORA creates capacity profiles for each order already released and for each possible release candidate. A capacity profile describes the time-specific demand for assembly operations of an order. These are represented as a matrix, where each column represents a unit of time and each row represents the demand for an assembly operation as a binary variable. The number of columns covers the entire time horizon until the completion of an order. The sequence of assembly operations is based on the assembly precedence graph. A widely branched precedence graph offers more possibilities for different assembly sequences resulting in a higher number of capacity profiles per order. Thus, one capacity profile is created for every valid sequence of assembly operations for each order. Capacity profiles also present the current state of the job. Accordingly, orders with completed assembly operations have less capacity profiles than unprocessed orders while also having fever filled columns as the time horizon until completion is shorter. In order to keep calculations between matrices possible, the size of every capacity profile is stretched to the longest possible sequence in the system and filled with zeroes in time steps that exceed the actual demand for assembly operations.

Each capacity profile thus reflects a possible load of the assembly system by an order. Since all assembly sequences and thus all capacity profiles can occur in reactive assembly control, all capacity profiles are still taken into account. In order to map the current capacity load of the assembly system, all combinations of the capacity profiles of the orders currently being processed are added up. This results in an operation- and time-specific prediction of the system load. All these combinations are then extended with capacity profiles of unprocessed orders. Those so-called matched capacity profiles must be compared with the available processing capacity of the assembly system. The available processing capacity of one assembly station is described with a vector containing the operation-specific capability. By summing of those vectors, the overall processing capacity of the system can be described. The resulting vector describes the system supply. Now, for each time unit, the overall system supply can be compared column-wise with the matched capacity profiles. If the demand for a certain operation exceeds the available processing capacity, the matched capacity profiles is rejected. Nevertheless, a different matched capacity profile of the same order may be accepted.

The non-rejected profiles or rather their unprocessed orders are then evaluated in terms of best capacity fit. For this purpose, these orders are initially distinguished exclusively by the assembly operations they contain. Identical assembly operations of an order are interpreted as identical products. Thus, these orders are equated at first. The capacity fit is the sum the free capacity of the system for all operations, calculated by subtracting the matched capacity profile from the available processing capacity over all time steps. The product which utilizes the system the most is then selected for further evaluation on order specific level. Here, a scored-based decision considering due dates or expected profit is used to select a specific job for release. When no order was selected due to the overload constraint, no order is dispatched and the agent goes into standby.

2.3 Limitations of capacity evaluation regarding path planning

The presented ORA as part of the assembly control provides a framework to perform release decisions based on current system information. Therefore, all released and waiting orders are considered with their potential sequences and capacity implications by the ORA. However, this leads to NP-hardness. If an additional order is considered, not only one further capacity profile is calculated. Instead, the matched capacity profiles are multiplied by the factor of the possible capacity profiles of the additional order. Thus, this profile combination scales exponentially when adding orders, but also operations or assembly stations. Consequently, it is expected that the approach fails for large problem instances. In order to circumvent the NP-hardness, SCHUKAT et al. suggested to reduce the number of capacity profiles e.g. by taking a limited number of randomly selected capacity profiles instead of calculating all capacity profiles. [13] However, this can lead to matching orders being excluded at random. Likewise, no linear scaling is achieved. In the following, a different approach will be introduced. To reduce the number of created and evaluated (matched) capacity profiles, possible operation sequences of orders are analyzed with respect to the resulting path through the assembly system. To do so, the transport times are estimated based on current routing algorithms of the order agent using the given sequences. This approach is further detailed in the next chapter.

3. Approach

3.1 Correlation of sequences and lead time

Although it seems evident that the assembly sequence impacts the lead time, a statistical analysis was performed to prove the correlation between those. In a matrix-structured assembly system, a product can have multiple assembly sequences. Consequently, completed orders containing the same product may show different assembly sequences after being processed. Same applies for the paths that describe the actual route an order takes through an assembly system. If several assembly station offer the same operation, orders with the same sequences might face different paths through the system and visit different assembly stations.

The lead time consists of three elements: working time, transport time and waiting time. The working time is the sum of all operation processing times at all stations that an order passes through. The transport time is the time that an order takes moving from one destination to another. The waiting time is the time an order spends waiting in queues at stations. While the working time for similar products remain the same, the waiting and transport time can vary depending on the chosen sequence and resulting path. The selection of the next assembly station is carried out by an order agent, considering real-time factors such as the estimated transport time to the available assembly stations. Besides the estimated transport time, the current waiting time at possible next assembly stations are taken into account. Depending on the strategy of an order agent, a shorter route to the next work station can be prioritized. However, to avoid long queues, longer routes might be accepted nevertheless. This lead to varying assembly sequences, depending on the current occupation and availability of the assembly stations.

To conduct the analysis, a basic test case was simulated matrix-structured assembly system. The test case consists of 16 stations, one product type and 1000 orders. The product requires four operations that can result in 12 different sequences total. The simulation environment is a MAS containing an assembly control system based on the proposed model by BURGGRÄF et al. [8] While 12 sequences are theoretically possible for the given product, only 8 actually occurred in the simulation run. The frequency of occurrence of the sequences followed the Pareto principle with 20% of the sequences accounting for 80% of the jobs. It also has the lowest minimal transport time and generally the lowest quartile of all sequences and the lowest median transport time. Furthermore it has the lowest estimated impact on the transport time. This finding correlates with the logic of the assembly job agents as they try to choose operations in such a way that optimizes the potential transport time, while considering other factors as well.

These results highlight that the transport time and related path depends on the chosen sequence. Furthermore, the frequency of an individual assembly sequence correlates with the average transport time that results from a sequence. That means that an assembly sequence appears more frequent if it results in a lower average transport time. This matches the intuitive thought that the assembly sequence directly impacts the transportation time of a job. These findings can be used to develop a method to limit the sequences that are used to calculate the capacity profiles of the ORA.

3.2 Approach for capacity profile limitation

This work proposes selecting only one sequence for every job in the capacity profile generation by anticipating the estimated transport times. Selecting only one sequence means that no matter how many jobs are released in the system or how many different sequences are possible, it will always result in one capacity profile per product and order, and thus only one matched capacity profile being calculated for the release decision. Within this paper, the estimation of the transport time will be done using the routing algorithms of the agents. The routing algorithms already include the planning of a trajectory that an order can take to be transported between to assembly stations without crossing another assembly station directly. For every operation in a sequence, there is a certain number of assembly stations that can process that operation. Using the current location of the assembly job agent, the distance and resulting transport time to these stations can be calculated. One station will be selected according to a selection criterion and it will act as the origin coordinate for the next assembly operation. This process repeats for every assembly operation in a given sequence. The process can be summarized with the following steps:

1. Retrieve all capable assembly stations for the first operation in the assembly sequence
2. Take the current position of the job and calculate the transport time to all capable stations
3. Select a station according to a selection criterion and use its position in the system as the next position of the job
4. Add the transport time of the selected station to the sequence's total transport time estimate
5. Retrieve all capable assembly stations for the next operation
6. Calculate the transport time to all capable stations using the updated position of the job and repeat the process until all operations of a sequence are accounted for

This process is done for every job's possible sequence. Once the transport time estimate has been calculated for every sequence, the algorithm selects the sequence with the lowest transport time estimate and passes it to the capacity profile generation.

3.3 Transport time estimation

Similar to *branch and bound algorithms*, the shortest path to complete an order does not necessarily result from always taking the shortest route to the next available assembly station. Thus, the criterion used to estimate the overall transport time is a crucial aspect. It should be noted that finding the shortest path in graph theory is called *shortest path problem*. To solve basic variation of this problem, there are multiple established algorithms such as *Dijkstra's algorithm*. [26] In a dynamic environment, with additional constraints this problem becomes NP-hard and additional computational resources are required to solve this issue. As the matrix-structured assembly is a dynamic environment and additional constraints other than the transport time are considered in the routing of the agents, finding the actual smallest transport time becomes another NP-hard optimization problem. As the main goal of this approach is to circumvent the NP-hardness of the capacity profile creation and selection, creating another NP-hard problem contradicts the goal. Because of this, an estimation is chosen that doesn't result in an NP-hard solution.

The selection criterion consists of four calculated paths to avoid the issue that may result when only choosing the next assembly station showing the lowest transport time. The calculated paths are created with the help of all possible operation sequences from the assembly precedence graph, which are related to the assembly stations and layout of the assembly system. Accordingly, the capabilities of assembly stations are taken into account. The first path is calculated by always choosing the station with the lowest transport time. The second path is calculated by always choosing the station with the highest transport time. The third and fourth paths are alternating between lowest and highest transport times. The third path starts with the station that has the shortest transport time and continues to alternate from there. The fourth path starts with the station that has the highest transport time and continues to alternate from there. This results in four calculated transport times for each sequence. These times are then added up for every sequence and then compared with each other. Afterwards, the sequence with the lowest sum of its four paths is used for the capacity profile calculation. Due to the dynamic behavior of the assembly system, it is crucial to consider the paths with potential higher transport times as they might become relevant in case of malfunctions and station breakdowns. In these situations, job agents may decide to take longer routes to avoid unnecessary waiting times.

4. Evaluation

4.1 Framework and Test case

To evaluate the functionality of the proposed approach, a simulation-based comparison with the random profile selection was conducted. For this, the ORA was implemented in an evaluation environment. In general, an evaluation environment is defined as a technology platform that serves the purpose of validating methodologies, models and theories developed in innovation projects. By integrating these into a common environment, the acceptance of new approaches can be increased. An evaluation environment allows multiple stakeholders to gain a common understanding of a program and the evaluation process. [27,28] In the present context, an evaluation environment must include an agent-based assembly control for matrix-structured assembly systems, provide an order pool, simulate the assembly processes, and also record all results and make them available for output. Such an evaluation environment was developed accordingly based on the logic for assembly control suggested by BURGGRÄF et al. [8] The evaluation environment was coded in TypeScript. It allows users to set specific production programs, assembly system configuration as well as export key figures after simulation.

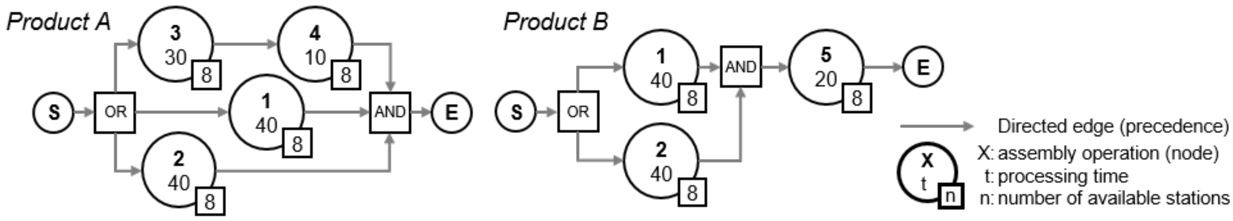

Figure 1: Assembly precedence graphs of Product A and Product B

For this paper, the production program contains two fictional product namely Product A and Product B, each having its individual precedence graph. A total of 30 products is assembled per simulation run: 10 of Product A and 20 of Product B. Product A was also used for the statistical analysis of the transport times in Chapter 3.1. Product A requires operations 1, 2, 3 and 4 while Product B requires operations 1, 2 and 5. This results in a total processing time of 120 seconds for Product A and 100 seconds for Product B.

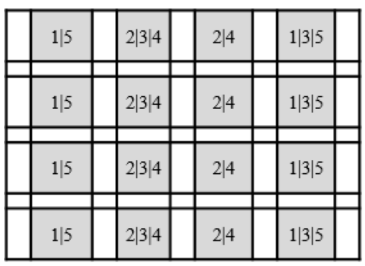

Figure 2: Station layout

The assembly system configuration is defined by the layout, assembly stations as well as their capabilities. The layout shows a total of 16 stations, which are all arranged in a matrix form leaving space for transportation between the assembly stations. The distances in x and y direction are all equal for each neighboring station. The stations are fitted to carry out multiple operations with 8 stations being able to perform three different operations and the other 8 stations being able to carry out two operations. When a station switches between operations it requires a certain setup time to change the tools required.

The key figure system was defined to quantitatively evaluate the behavior and impact of the ORA for each simulation run. The following key indicators for the test case were defined:

- Total assembly run time [s]
- Average lead time [s]
- Average transport time [s]
- Average waiting time [s]
- Total utilization rate [%]
- Percentage of waiting time [%]
- Percentage of processing time [%]

4.2 Results

To test the suggested approach, it was implemented and compared to the former approach for capacity-based order release in matrix-structured assembly systems. To circumvent the known shortcoming of the former approach, the generation of matched capacity profiles was limited using a threshold while creating capacity profiles randomly. In total, four simulation runs were analyzed. The used thresholds for the generation of matched capacity profiles were 1 (ORA-1), 50 (ORA-50) and 100(ORA-100). The newly suggested approach is referred to as ORA-P. The simulations were carried out on an Intel® Core™ i5-8600 6 core CPU at a base clock of 3.1 GHz and 8GB of RAM. The results are summarized in figure 3.

Dispatcher type	Total assembly run time [s]	Average lead time [s]	Average transport time [s]	Average waiting time [s]	Total utilization rate [%]	Waiting time [%]	Processing time [%]	Relative difference of total assembly run time [%]	Relative difference of average lead time [%]	Relative difference of average transport time [%]	Relative difference of average waiting time [%]	Relative difference of total utilization rate [%]
ORA-1	506	210	62	42	47	11	50	8	4	2	22	8
ORA-50	479	211	65	40	50	20	50	3	4	6	18	3
ORA-100	466	210	63	41	51	20	50	0	4	4	21	0
ORAP	465	201	61	33	51	16	53	-	-	-	-	-

Figure 3: Testing results

The total assembly run time to process all orders for ORAP was slightly less compared to ORA-1 (~8%) and ORA-50 (~3%). For ORA-100, no effect can be seen. Using ORAP leads to decrease of average lead time per job by 9 seconds. The average transport time was about 6% slower for ORA-50, 4% for ORA-100 and 2% for ORA-1 compared to ORAP. The most significant difference was found in the average waiting time. The ORAP outperformed the other simulation runs by 18-22%. Using ORAP the waiting time amounted for 16% of the total time while for the other runs it was 20%. The percentage of the processing time on the total time also improved using ORAP from 50% to 52%. ORAP shows a higher total utilization rate of the assembly stations than ORA-1 and ORA-50 and about the same rate as ORA-100. Given the shown performance indicators, the results demonstrate an overall better performance using ORAP.

5. Discussion and limitations

In matrix-structured assembly systems with multifunctional assembly stations, it is not possible to predict the exact path of an order when using reactive assembly control. This is a challenge not only for the determination of material supply positions, but also for the capacity evaluation of the order release. While the authors' previous work on capacity evaluation suggests considering all possible sequences, the transport time estimation approach developed in this paper allows limiting the sequences considered in capacity evaluation. By estimating the possible transport time through the average between four probable path finding methods, the approach determines exactly one sequence per order that can be used for the generation of the order's capacity profile. The simulations performed indicate the ORA. The simulations indicate improved scalability, more consistent results and greater reproducibility, while significantly reducing the waiting times of orders at stations. Accordingly, the developed approach can be used as basis for further evaluation, improvement and additions to the ORA compared to the former approach. Furthermore, limiting the number of capacity profiles, the inherent NP-hardness of the previous research is addressed. This allows to test larger problem instances using an advanced order release logic.

However, the presented approach is subject to the constraint that assembly control is designed to reduce transportation times. The current transport time estimation was only tested for a rather simple and consistent layout. Complex assembly layouts could lead to inaccurate predictions. Therefore, the developed profile limiting approach should be considered primarily as a prototype demonstration rather than an optimal solution.

6. Summary and outlook

This paper presents an approach to improve the capacity evaluation in order release for matrix-structured assembly systems. The approach determines one assembly sequences for each order that can be used to assess the capacity fit within order release.

To show the potential of the suggested approach, it has been implemented in an evaluation environment containing an agent-based assembly control. It was compared to the former approach for capacity-oriented order release. For the former approach, random sequence selection was used to reduce the number of sequences and thus calculations. The simulation results show that newly developed approach outperforms the former approach, e.g. by a reduction of 20% of waiting time. However, with more random profiles being considered, this effect declines. Thus, it can be assumed that the random profile selection outperforms the suggested profile limiting approach if the number of random profiles selection covers almost all possible sequences. This can be explained with the nature of the random profile generation. As the number of matched capacity profiles increases, so does the probability that a combination leading to an optimal order release decision occurs. However, this still has the downside of requiring significantly more computational power.

Further research should transfer the routing algorithms from assembly control into the path prediction. This potentially improves the transport time estimation and sequence selection. Consequently, the agent-based order will obtain better results, while maintaining its flexibility and real-time capability. Furthermore, the use of a deep neural network should be considered, as it can extract hidden features of the system and estimate path finding functions.

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Biography

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