CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2020

1st Conference on Production Systems and Logistics

Optimization approach for the combined planning and control of an agile assembly system for electric vehicles

Peter Burggräf[1,2], Matthias Dannapfel[1], Tobias Adlon[1], Aaron Riegauf[3], Esben Schukat[1], Felix Schuster[3]

[1]*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Campus Boulevard 30, 52074 Aachen, Germany*
[2]*Chair of International Production Engineering and Management (IPEM), University of Siegen, Paul-Bonatz-Straße 9-11, 57076 Siegen, Germany*
[3]*Chair of Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Campus Boulevard 30, 52074 Aachen, Germany*

Abstract

For some years now, the automotive industry has been challenged by growing market dynamics, shorter product lifecycles and customers' increasing demands for individualization. In order to cope with this development, the automotive assembly needs to adapt quickly to changing demands with a low level of investment in the future. Under the current circumstances, the traditional line assembly for high volume production is reaching its limits in terms of adaptability and scalability. A promising solution to address the current challenges is the concept of the agile assembly. The concept of agile assembly breaks up the rigid linkage of assembly stations and, thus, enables full flexibility in the sequence of assembly operations only limited by the precedence graph. Therefore, the routing of electric vehicles in the agile assembly is based on the availability of resources such as assembly stations and automated guided vehicles that handle the material supply. Further, by transferring the transport function to the vehicle itself, investments for convey or systems are eliminated. This research work presents an optimization approach for the machine scheduling and transportation planning, which derives instructions for electric vehicles, assembly stations as well as automated guided vehicles. For each electric vehicle, an optimized route is calculated, taking into account product-specific precedence graphs and minimizing the overall makespan. In addition, the machine scheduling and transportation planning is integrated into a combined planning and control concept which covers the allocation of resources and the assignment of capabilities of the entire assembly system. The approach is implemented and applied to a practical case of a compact electric vehicle. Thus, the work contributes to the evaluation of agile assembly systems in automotive production.

Keywords

Automotive assembly; Agile assembly; Assembly control; E-mobility production; Factory planning; Assembly planning

1. Introduction

Shorter product life cycles, an increasing variety of variants, growing uncertainty about sales forecasts and rising demand for electric vehicles (EVs) are the main challenges of today's automotive production [1,2]. Automotive manufacturers are thus in constant conflict between short product life cycles and low investment costs for the production. To address these challenges, production systems in the automotive industry must

DOI: https://doi.org/10.15488/9655

be able to adapt quickly and with low investment within their existing infrastructure in order to respond to changing market and demand conditions [3,4].

Until now, automotive assembly has mainly been characterized by line assembly. Line assembly is particularly efficient in the production of large quantities due to specialization advantages and continuous flow. However, it has low flexibility regarding changes in production volume and is rather limited in terms of line balancing, which makes it challenging to integrate new variants or products. Large differences in cycle times in the mixed model production lead to significant inefficiencies due to lower utilization of assembly stations (ASs). These disadvantages are particularly evident in production systems for EVs. Future market demands for EVs are uncertain and difficult to predict. Therefore, established automotive manufacturers are reluctant to make major investments in the production of EVs. In order to minimize the investment risk, the manufactures tend to integrate the assembly of EVs in existing lines that were initially designed for vehicles with an internal combustion engine. This leads to increasing planning efforts and cycle time losses due to fundamental differences in the assembly processes [5,6].

The Chair of Production Engineering of E-Mobility Components (PEM) and the Laboratory of Machine Tools and Production Engineering (WZL) at RWTH Aachen University have developed the concept of the agile assembly to address the above stated challenges in order to enable the economic small batch production of EVs. One of the main pillars of the concept is the transfer of the transport function within production from the conveyor system to the EV itself. Shifting the mounting and the commissioning of the powertrain into the early phase of assembly, the EVs become self-driving. The breakup of the rigid line structure enables a flexible sequence of assembly processes, which is only determined by restrictions of the product-specific precedence graph. Thus, agile assembly achieves scalability in terms of quantity and variance as well as significantly lower structural investments. With the flexible flow of EVs in the production, however, the requirements for the assembly control and its complexity increase. The elementary premise for the operation of the agile assembly is the creation of a network that links all participating resources within an assembly ecosystem. Automated guided vehicles (AGVs) in intralogistics, assembly stations and self-driving EVs need to act as cyber physical systems.

This work aims at the conception and demonstration of a combined assembly planning and control framework for the agile assembly. The assembly planning and control includes a machine scheduling approach that determines the assembly sequence of the EVs considering the product-specific precedence graph and material supply by AGVs.

2. State of the art

In order to lay the foundation for the assembly control system for the agile assembly of EVs, existing approaches for flexible assembly systems were examined. The primary object of consideration were principles for decision-making in the flexible assembly in the form of algorithms and constraints for the vehicle routing. In addition, the material supply by AGVs was taken into account. Attention was also paid to the classification of approaches in the overall context of production planning. Production planning in general involves preserving and enhancing all production processes while adapting to changes of the product portfolio or demand [7]. The projects freeMoVe, SmartFace and the approach of Bochmann were particularly relevant for this scientific work and are therefore explained in the following.

The research project freeMoVe covers the development of an ideal concept of flexible assembly as a new assembly organization form and includes the design of a control system, material supply and layout. It focuses on the development of a control system architecture for machine scheduling [8,9]. However, the scheduling of assembly tasks is not integrated into the overall planning process of the production. Furthermore, no concrete algorithms for implementing decision-making in the control system are presented. The developed concept of the control system architecture does not take any AGVs into account.

The SmartFace project develops a production planning concept for the final assembly of EVs according to the principles of flexible assembly. The goal of the project is the breakup of the fixed cycle times in the assembly and a transfer into a self-organizing cyber-physical system. As an interface between production program planning and production control, the concept of the volume cycle is presented. Instead of defining a specific production time, a production volume for a certain period of time is planned [10]. Thus, the material supply can continue to be provided just-in-time. The production control translates the processing jobs of the volume cycle into assembly orders and transport requests. The control is no longer carried out by a central planning and control system, but by a multi-agent system, which is composed of independent software agents. Each software agent performs its activities on the basis of limited information, such as its environment and its own capabilities [10,11,12]. The developed principle of a combined production planning and control remains conceptual while no specific algorithms for decision making are presented. Furthermore, the decentral approach based on a multi-agent system cannot ensure that a globally optimal solution is found [13].

The approach by Bochmann focusses on layout planning, machine scheduling and transport route planning of a flexible assembly system. The goal of the layout planning is to minimize transport costs within the assembly system. For this purpose, the statistical transport intensity between ASs is derived on the basis of the capability profiles of each AS. The assignment of assembly tasks to stations is based on machine scheduling model and solved with a Tabu-Search heuristic. Eventually, Bochmann concludes that the investment costs for the investigated concept of agile assembly may exceed those of a classic line assembly [14]. However, this approach does not provide any integration of the presented planning tasks into a broader concept of assembly planning. Furthermore, the machine scheduling does not take the utilization of AGVs into account, which restrict solid cost analysis.

The discussed assembly control approaches lack in setting the developed methods in the context of the overall assembly planning. Therefore, no clear planning horizons and interrelations for layout planning, required production resources or production program planning are provided. Moreover, neither of the approaches presents specific methods of decision-making and algorithms or further considerations of AGVs in the scheduling approaches. In order to address the deficits of the existing approaches, a framework for combined assembly planning and control is presented in the following. This framework lays the fundament for the later implementation of a comprehensive machine scheduling approach for the agile assembly that includes the planning of EVs, ASs and AGVs.

3. Combined assembly planning and control

In a monolithic approach, increased flexibility requirements in agile assembly lead to a significant increase in complexity. To ensure that the overall assembly planning and control can be solved, the concept of hierarchical planning from operations management is applied. Hierarchical planning separates all process tasks and decisions into subtasks with defined interfaces between the subtasks. As the subtask level decreases, the level of detail increases while the observation horizon decreases. Decisions and solutions on higher planning layers are passed down as instructions for more detailed planning. Feedback is returned to upper layers in order to enhance the planning and decision quality in future iterations [15].

Two main goals of an assembly control are optimized efficiency and real-time performance, which contradict each other. Thus, specific time intervals for the transmission of instructions and feedback are defined for a rolling planning. It features a temporal disaggregation when passing down tasks. Upper planning layers have long planning horizons with rough resolutions of quarters or years. Once their planning is completed, decisions are fixed and passed down as instructions. The receiving layer disaggregates the planning interval into smaller units with higher resolutions. In general, planning horizons are shorter in agile assembly than in classic assembly due to higher flexibility. The developed model for a combined assembly planning and control is shown in Figure 1.

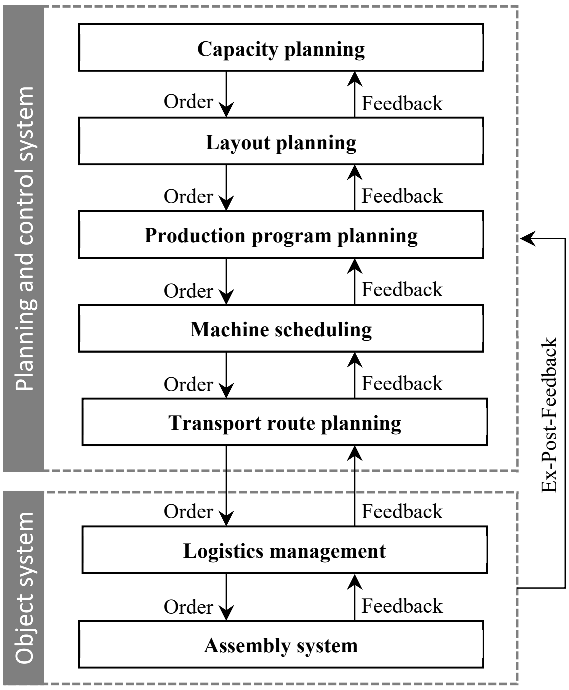


Figure 1: Structure of the combined assembly planning and control system

The developed framework consists of a planning and control system as well as an object system. While the object system represents the physical production resources through cyber-physical instances, the planning and control system include more abstract planning layers.

Capacity planning is the top-level task and is executed first. The purpose of capacity planning is the strategic procurement of production resources within time horizons of quarters to years. It is based on long-term sales forecasts and the feedback from lower planning levels such as occupation rates from the machine scheduling. As a result, the layout planning layer may be instructed to introduce, remove or reallocate resources. The **layout planning** consists of the allocation of resources within the physical factory layout as well as the optimization of transportation routes and material flows. Its output are the availability of physical resources and capability profiles for each AS. To achieve this, further feedback is gathered from the object system containing information about transport intensity and time. The next layer is the **production program planning**. Its goal is to determine a profit-optimized material demand and delivery schedule for the products. Hence, outputs are both just-in-time material orders and the volume cycles, which contain all information about type and variation of the order in a specific timeframe. On this layer, planning horizons equal weeks and each production sequence is determined for time frames of shifts or working days. The process is similar for line and agile assembly concepts and relies on input data regarding capacity, orders and short-term prognoses. **Machine scheduling** then distributes the orders from the production program planning to the available production resources. Timed output commands comprise operations to ASs as well as material delivery assignments to AGVs. Key goal is a short makespan for the volume cycle. This planning step is unique to agile assembly as the classic line assembly features an already predetermined order of operations. The scheduling is discussed in detail in the following chapter. Top-down inputs are the planned volume cycle, available resources and capability profiles. The actual transport times are fed back from the object system to the upper levels. Interruptions such as defect stations or missing parts are countered through a fall back strategy, which is an interface between the scheduling and lower decision layers. Short-term rescheduling should only take minutes, thus ensuring a continuous production until the scheduling level has recalculated the entire volume cycle.

The final process step is the **transport route planning** for the EVs and AGVs. Transport instructions for both AGVs and the EVs are given to the system along with the current position of the physical objects. The route planning process is divided into rough and detailed path planning. Collisions with static and dynamic objects, buffer areas and avoidance of congestion must be considered within the time intervals of several seconds. The calculated trajectories are forwarded to the instances of the object system as the final result of the planning process. In the object system, the physical trajectories of the EVs and AGVs as well as the assembly operations are executed.

As one of the major challenges in the transition from a classical line to an agile assembly, the layer of the machine scheduling and its decision making algorithms will be detailed in the following section.

4. Machine scheduling for the agile assembly

In the concept of agile assembly the machine scheduling will replace the planning tasks of line balancing and the sequence planning of classic line assembly. While the classical line assembly offers limited possibilities for the resequencing of ASs and operations, the agile assembly enables a flexible flow of the assembly objects. The holistic concept for the control system is visualized in Figure 2 and describes the relationship between production program planning, machine scheduling and the object system including the flexible flow of the assembly objects.

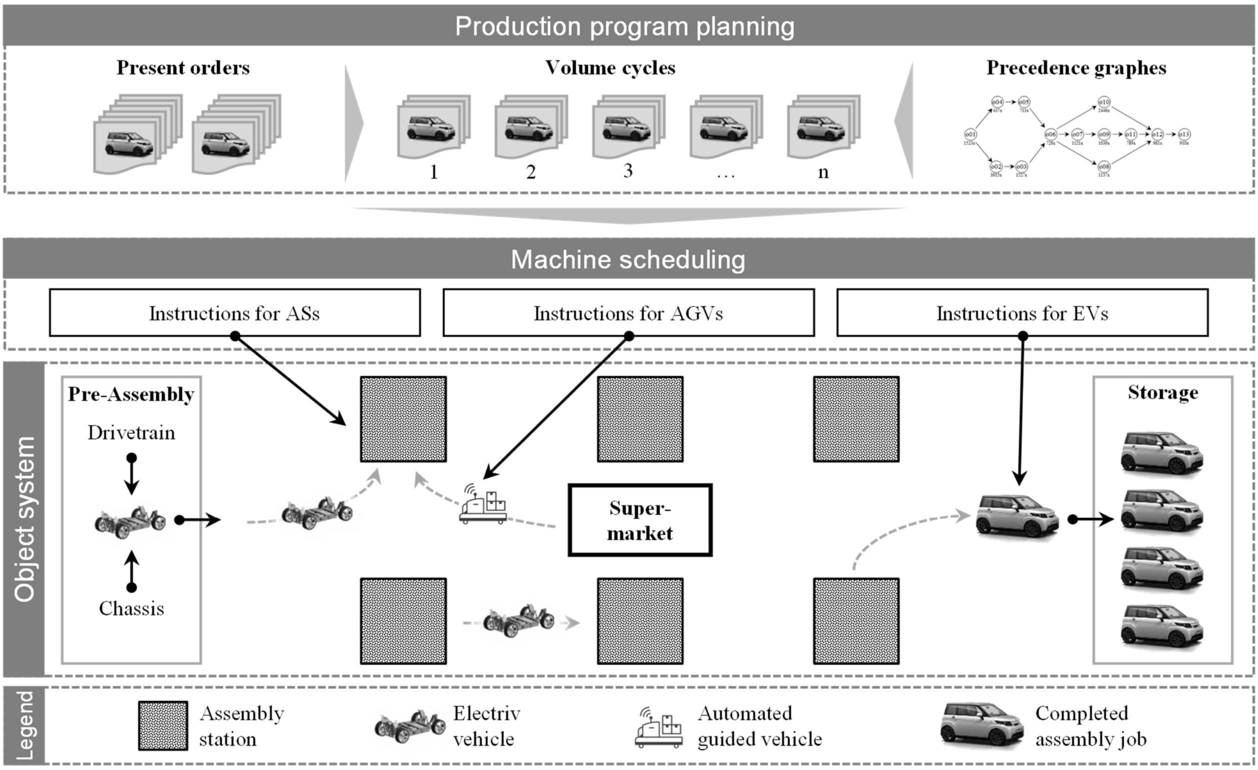


Figure 2: Interconnection of the machine scheduling in the concept of agile assembly

The production program planning manages the existing orders and groups them to volume cycles which represent a set of orders to be produced in a specific time horizon. The machine scheduling receives a specific volume cycle from the production program planning. Each order within the volume cycle is described by a precedence graph as well as a set of required assembly operations. In addition, the machine scheduling planning requires deterministic information about the object system. This includes the capability profile, the availability of resources as well as the transport times. The capability profiles describe which assembly operations can be performed by which ASs. This ensures, for example, that a lifting platform is available at the respective AS for underfloor work. Resources are defined as ASs and AGVs. Transport times quantify the distance between two ASs for EVs or between the supermarket and an AS for AGVs, respectively. The machine scheduling then derives the instructions for the ASs, AGVs and EVs. These instructions represent the control of the physical object systems and determine which EV is at which station at which time. The same applies to AGVs.

This implies first of all that the machine scheduling includes a combination of a scheduling and a routing problem. The scheduling problem is the creation of a sequence in the number of required operations (assembly tasks) to process EVs while the routing problem consists of the assignment of these operations to the ASs. In order to solve the combination of this scheduling and routing problem, a method for model-based decision making is required. Mönch (2006) classifies the methods of model-based decision making into priority rules, simulation approaches and deterministic machine scheduling, which will be used in this work [13]. Such machine scheduling problems with jobs consisting of multiple operations performed on different machines (such as ASs) are named Shop-Problem [16]. An extension of the general Shop-Problem is the Flexible Job Shop Problem (FJSP). Each job has its own individual material flow path and is not transferred to every machine [17]. Özgüven et al. (2010) extended the FJSP to the FJSP-PPF by introducing full routing and process plan flexibility (PPF) [18]. Routing flexibility means that multiple or redundant machines may be available for the execution of assembly operations. Process plan flexibility means that different process sequences can exist for different machining jobs. This is required as we assume that a few ASs will have an overlap in their capability profiles. The FJSP-PPF comes closest to the requirements of the control system in agile assembly. A major advantage of the FJSP class is the availability of heuristics for solving [19,20].

However, the control system is also supposed to generate instructions for the AGVs and EVs. AGVs are major cost drivers in the assembly and, thus, their utilization must be considered in the assembly control. For this reason, the formulation of the FJSP-PPF will be extended to include the consideration of transport times (TT) to the FJSP-PPF-TT. The extension of the FJSP-PPF to the FJSP-PPF-TT does not only imply additional constraints, but also requires an extension of the indexing and an introduction of new variables. However, since no research results exist yet on this subject, a novel approach has been developed. This approach suggests a specific distinction between the transport processes of materials (AGV transport) and the transport of the EV itself. This distinction is necessary, since the two transport procedures differ from each other. Furthermore, they do not reflect regular set-up procedures. Figure 3 visualizes the transport processes.

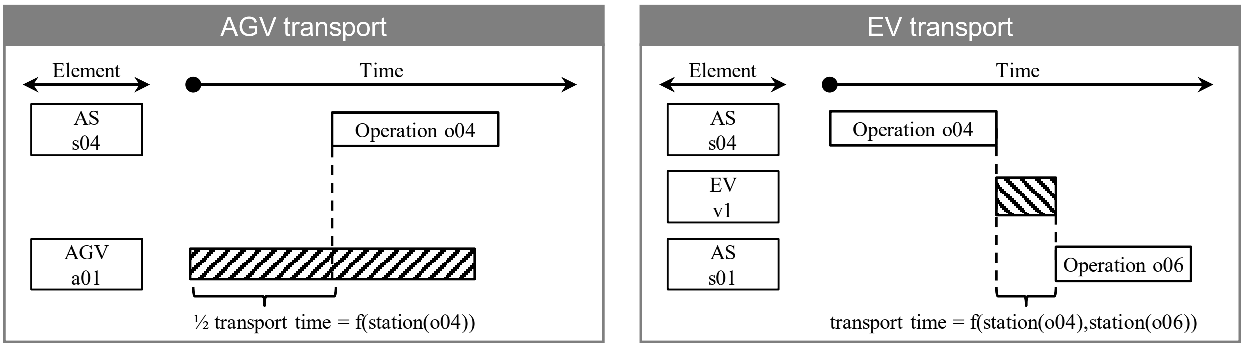


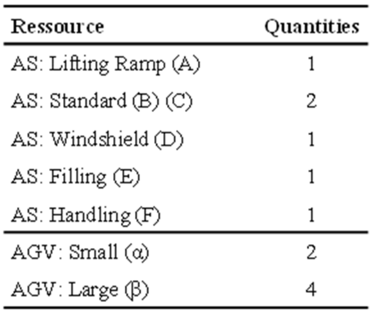
Figure 3: Distinction AGV transport and EV transport

Before an assembly operation can be performed at a certain AS, material may need to be transported from the supermarket to the AS. In this example, operation "o04" is executed on AS "s04". The necessary material supply by an AGV has to finish before the operation starts. This requirement cannot be represented by corresponding entries in the precedence graph since the transport operation and the assembly operation may overlap under certain circumstances. Instead, new constraints must be defined in order to take the transport of material into account. It must be considered that the AGV will return to the supermarket after the material has been delivered and is blocked for the full transport time from the supermarket to the AS and back. Therefore, the operation "o04" can start after half of the transport time assuming a constant speed of the AGV. It should be noted that the transport time does not depend on the type of operation, but on the destination, which is related to the location of the AS (here “s04”). The example for the EV transport includes two consecutive operations ("o04" and "o06") to be executed at two different ASs ("s04" and "s01"). The EV (“v1”) thus needs to move from one AS to another. As the used ASs are not occupied during EV transports they can be used to execute operations on other EVs. However, the EV is locked for the duration of the transport and cannot be processed. In contrast to AGV transport, the transport time of the EV depends both on the current AS as well as the destination AS.

The developed model was validated with a reference data set developed by Özbakır (2004) which has been adapted to the formulation of the FJSP-PPF-TT [21]. To show the practical relevance and the possibility of exploiting flexibility potentials, the machine scheduling model will be applied to a concrete example below.

5. Practical Application

To further demonstrate the capabilities of the developed model, a relevant scenario configuration and the assembly description for the agile assembly of a compact EV have been designed. Figure 4 shows the resources of the scenario. The setup consists of five different types of ASs (A)-(F) as well as two different types of AGVs (α)-(β). Figure 5 presents the precedence graph for the EV. The assembly process of the EV consists of 13 operations (“o01” to “o13”).



Ressource	Quantities
AS: Lifting Ramp (A)	1
AS: Standard (B) (C)	2
AS: Windshield (D)	1
AS: Filling (E)	1
AS: Handling (F)	1
AGV: Small (α)	2
AGV: Large (β)	4

Figure 4: Scenario resources

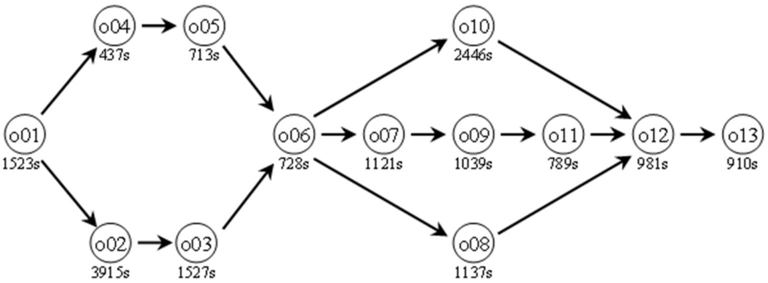


Figure 5: Scenario precedence graph

The necessary assembly operations of the EV are detailed in Table 1. For each operation, a specific amount of AGV transportations is given. Additionally, process times were assigned to each operation as well as ASs that are capable of performing the operation, marked by the dots in Table 1.

Table 1: Operations and resources needed to assemble the compact EV

Number	Description	(α)	(β)	Process time [s]	(A)	(B) (C)	(D)	(E)	(F)
o01	Assembly Chassis, Spaceframe & Backend	0	1	1513	○	○	○	○	○
o02	Wire Harness & Control Unit Assembly	1	0	3915	○	○	○	○	○
o03	Dashboard Assembly	0	1	1527					○
o04	Side Covering Assembly	0	1	437	○	○	○	○	○
o05	Side Windows & Roof Assembly	1	1	713	○	○	○	○	○
o06	Windshield Assembly	0	1	728			○		
o07	Interior & Safety Belt Assembly	1	1	1121	○	○	○	○	○
o08	Rear Body Assembly	0	1	1137	○	○	○	○	○
o09	Seats Assembly	0	2	1039					○
o10	Frontend & Front Hood Assembly	0	1	2446					○
o11	Doors Assembly	0	1	789					○
o12	Underbody Assembly	0	1	981	○				
o13	Fluid Filling	0	0	910				○	

In order to solve the introduced scenario, the machine scheduling algorithm was implemented in Python using the high performance MIP-Solver Gurobi. On an Intel Core i7-3612QM 2.1 GHz CPU and 8 GB RAM, the calculation time for the scheduling of one EV was 435.66 s, whereby the global optimum was already found after 25 s. Thus, an explicit solution for more than one EV is not feasible within relevant time. To overcome this constraint, the problem is solved sequentially. At the beginning, the scheduling is solved for the first EV and the results are stored. Then, the second EV is added to the scheduling problem with the previously generated results as additional constrains. This procedure is repeated for each newly added EV. The downside of this technique is that reaching the global optimum cannot be ensured. The resulting schedule of the exemplary application for four EVs is shown in the Gantt-Chart in Figure 6.

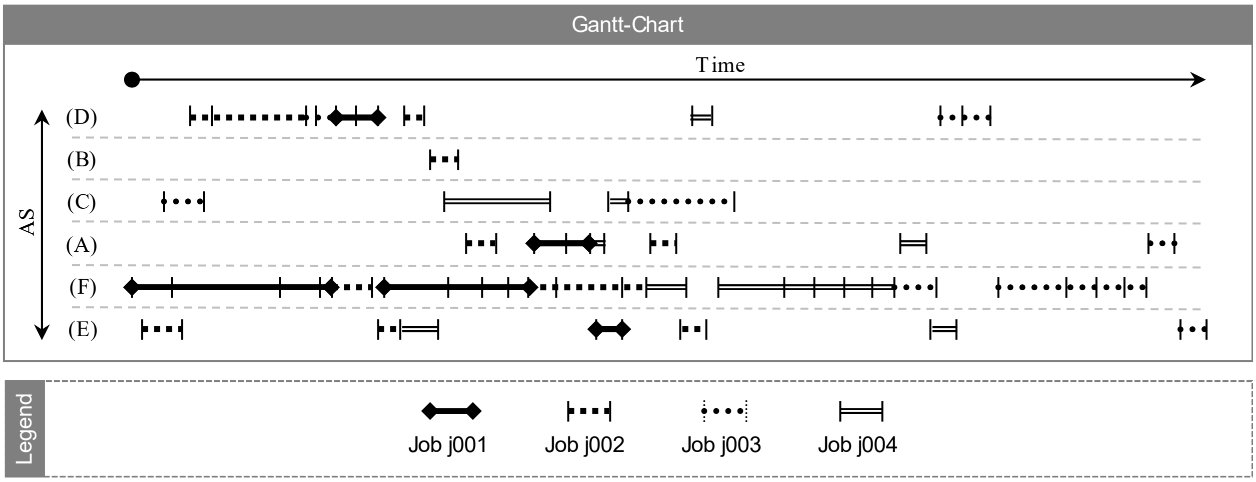


Figure 6: Result of the machine scheduling

The rows represent the schedule for each AS (A)-(F) and each EV represents an assembly job. For instance, job j001 starts at AS (F) where 4 assembly operations are executed (separated by vertical lines). Then, job j001 performs a transport operation to AS (D) where another 2 assembly operations are executed that are followed by another transport operation back at AS (F). This transfer is required due to varying capability profiles of AS (D) and (F).

The result of the machine scheduling exposes that the assumed quantity of AGVs is significantly too high and hence no limiting resource. Therefore, the schedule for the AGVs is not visualized here. As a result of the sequential scheduling, the most versatile station (F) has the highest utilization rate and, thus, represents a critical resource. Embedded in the combined assembly planning and control framework, this information can be used to re-evaluate the allocated resources and the layout. Moreover, the missing global optimum can be seen in the schedule. Job j001 is mainly processed at station (F), since this station (F) has a far-reaching capability profile and, thus, transport times can be minimized. However, the utilization of station (F) increases with each additionally dispatched EV whereas station (B) has an overall low utilization. Therefore, bottleneck stations and recommendations for the duplication or removal of certain assembly stations as well as required capability profiles can be derived from the schedule.

6. Conclusion and outlook

This research work presented a combined planning and control concept for the flexible and scalable assembly of electric vehicles: the agile assembly. In agile assembly, self-driving electric vehicles get routed to assembly stations depending on their order-specific equipment features. Automated guided vehicles provide the material required for an individual assembly operation to the assembly stations. The flow of electric vehicles and automated guided vehicles as well as the sequence of assembly tasks in the agile assembly is determined by machine scheduling. For this purpose, an enhanced Job Shop Problem taking into account transport times of electric vehicles and automated guided vehicles was formulated and applied to a practical use case. The application has shown that valid schedules and routes can be generated for electric vehicles and automated guided vehicles. Furthermore, statements can be made about resource utilization and bottlenecks. However, further research is needed to develop heuristics as a solving method to improve the solvability for larger volume cycles as the current computing time does not yet meet future requirements of a real-time control. In addition, the related planning activities described in the combined planning and control concept such as capacity planning, layout planning and production program planning must be algorithmically detailed in order to quantify the entire system behaviour of agile assembly. This scientific work constitutes a significant added value by presenting a machine scheduling approach for the agile assembly, which enables the economic evaluation of agile assembly.

Acknowledgement

The research work has been conducted by the Laboratory of Machine Tools and Production Engineering (WZL) and the chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University within the research project LoCoMo, funded by the German Federal Ministry for Economic Affairs and Energy (BMWi); Grant Agreement No. 01MX15008A

References

[1] Kampker, A., Kreisköther, K., Burggräf, P., Dannapfel, M., Bertram, S., Wagner, J., Fischer, A., Knau, J., Grams J., Bartl, M., 2017. Agile Low-Cost Montage. Internet of Production für agile Unternehmen. AWK Aachener Werkzeugmaschinen-Kolloquium, Aachen, Germany. Apprimus Verlag, pp. 231-259.

[2] Grinninger, J., 2012. Schlanke Produktionssteuerung zur Stabilisierung von Auftragsfolgen in der Automobilproduktion (Doctoral dissertation). Lehrstuhl für Fördertechnik Materialfluss Logistik, Munich, Germany.

[3] Mößmer, H. E., Schedlbauer, M., Günthner, W. A., 2007. Die automobile Welt im Umbruch. Neue Wege in der Automobillogistik. VDI-Buch. Springer, Berlin, Heidelberg, Germany, pp. 3-15.

[4] Hofmann, M., 2016. Montage- und Logistik-FTF für die Automobilproduktion ohne Band und Takt. Logistics Journal.

[5] Dijk, M., Orsato, R. J., Kemp, R., 2013. The emergence of an electric mobility trajectory. Energy Policy 52, 135-145.

[6] Kampker, A., Wagner, J., Kreisköther, K., Fluchs S., 2016. Mobile Assembly of Electric Vehicles: Decentralized, Low-Invest and Flexible. World Academy of Science, Engineering and Technology 10 (12), 1926-1932.

[7] Vollmann, T. E., Berry, L. B., Whybark, D. C., 1997. Manufacturing Planning & Control Systems, 4th ed. McGraw-Hill, New York.

[8] Göppert, A., Hüttemann, G., Jung, S., Grunert, D., Schmitt, R., 2018. Frei verkettete Montagesysteme. Zeitschrift für wirtschaftlichen Fabrikbetrieb 113 (3), 151-155.

[9] Schmitt, R., Göppert, A., Hüttemann, G., Lettmann, P., Rook-Weiler, K., Schönstein, D., Schreiber, A., Serbest, E., Steffens, M., Tomys-Brummerloh, A., 2017. Frei verkettete wandlungsfähige Montage. Internet of Production für agile Unternehmen. AWK Aachener Werkzeugmaschinen-Kolloquium, Aachen, Germany. Apprimus Verlag, pp. 339-368.

[10] Bochmann, L., Gehrke, L., Böckenkamp, A., Weichert, F., Albersmann, R., Prasse, C., Mertens, C., Motta, M., Wegener, K., 2015. Towards Decentralized Production: A Novel Method to Identify Flexibility Potentials in Production Sequences Based on Flexibility Graphs. Automation Technology 9 (3), 270-282.

[11] Böckenkamp, A., Mertens, C., Prasse, C., Stenzel, J., Weichert, F., 2017. A Versatile and Scalable Production Planning and Control System for Small Batch Series. Industrial Internet of Things. Springer, pp. 541-559.

[12] Gehrke, N., Seiss, O., Bochmann, L. S., Mertens, C., Gehrke, L., 2016. Innovative Konzepte einer sich selbstorganisierenden Fahrzeugmontage am Beispiel des Forschungsprojekts SMART FACE. Einführung und Umsetzung von Industrie 4.0: Grundlagen, Vorgehensmodell und Use Cases aus der Praxis. Springer, Heidelberg, Germany, pp. 172-191.

[13] Mönch, L., 2006. Agentenbasierte Produktionssteuerung komplexer Produktionssysteme. Deutscher Universitäts-Verlag, Wiesbaden, Germany.

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

[15] Britan, G. R., Hax, A. C., 1977. On the design of hierarchical production planning systems. Decision Sciences 8 (1), 29.

[16] Dempster, M. A. H., Lenstra, J. K., Rinnooy Kann, A. H. G., 1982. Deterministic and Stochastic Scheduling. Springer, Dordrecht, Netherlands.

[17] Brandimarte, P., 1993. Routing and scheduling in a flexible Job Shop by Tabu Search. Annals of Operations Research 41 (3), 157-183.

[18] Özgüven, C., Özbakır, L., Yavuz, Y., 2010. Mathematical models for job-shop scheduling problems with routing and process plan flexibility. Applied Mathematical Modelling 34 (6), 1539-1548.

[19] Çaliş, B., Bulkan, S., 2015. A research survey: review of AI solution strategies of job shop scheduling problem. Journal of Intelligent Manufacturing 26 (5), 961-973.

[20] Chaudhry, I. A., Khan, A. A., 2016. A research survey: review of flexible job shop scheduling techniques. International Transactions in Operational Research 23 (3), 551-591.

[21] 2004. Modeling, Analyzing and Solution of Multiple Objective Flexible Job Shop Scheduling Problems by Using Meta-heuristic Algorithms.

Biography

Peter Burggräf (*1980) has been head of the Institute of International Production Engineering and Management at the University of Siegen since 2017. Prof. Dr.-Ing. Peter Burggräf is a member of the Supervisory Board of the electric vehicle manufacturer e.GO Mobile AG and Managing Director of StreetScooter Research GmbH.

Matthias Dannapfel (*1986) has been head of department of Factory Planning at Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2017.

Tobias Adlon (*1989) has been research associate at department of Factory Planning at Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2015.

Aaron Riegauf (*1990) has been research associate at the chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen RWTH Aachen University since 2017.

Esben Schukat (*1993) has been research associate at department of Factory Planning at Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2019.

Felix Schuster (*1992) was a master thesis student at the chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen RWTH Aachen University and has been a Global Trainee at ZF Friedrichshafen AG since 2019.