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Routing Requirements in Matrix Production Systems

Anforderungen an die Tourenplanung in Matrixproduktionssystemen

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Flexible manufacturing systems like Matrix Production Systems are enabling companies to manufacture mass customized products demanded by customers. Consequently, they require a highly productive and flexible transport system, as products do not follow a fixed route through production. Autonomous Mobile Robots, being able to navigate freely within the shop floor, present a promising technical solution meeting these requirements. This is especially true, if they are able to transport multiple loads at once. However, the fact that every process module is simultaneously a source and a sink of transport demands introduces a variant of the Vehicle Routing Problem that has not yet appeared in intralogistics, called Pickup and Delivery Problem (PDP). This contribution investigates how to adapt the PDP to represent the particular requirements of intralogistics, forming the foundation for developing efficient control strategies.

[Keywords: Routing, Pickup and Delivery Problem, Matrix Production System, Intralogistics, Autonomous Mobile Robots]

Flexible Produktionssysteme wie die Matrixproduktion ermöglichen es Unternehmen, vom Markt nachgefragte kundenindividuelle Produkte herzustellen. Um den hohen Anforderungen dieser Systeme an die Materialbereitstellung gerecht zu werden, ist eine leistungsfähige Produktionsversorgung erforderlich. Dies kann z. B. durch autonome mobile Roboter erfolgen, insbesondere, wenn diese mehrere Ladeeinheiten zeitgleich transportieren können. Dadurch, dass die einzelnen Module einer Matrixproduktion gleichzeitig Quellen und Senken für Transportaufträge darstellen, muss in der Tourenplanung der Transportressourcen das in der Intralogistik bislang kaum aufgetretene Pickup and Delivery Problem (PDP) gelöst werden. Dieser Beitrag stellt eine Formulierung des PDP unter Berücksichtigung der Anforderungen der Matrixproduktion vor, auf deren Basis effiziente Steuerungsstrategien entwickelt werden können.

[Schlüsselwörter: Tourenplanung, Pickup and Delivery Problem, Matrixproduktion, Intralogistik, Autonome Mobile Roboter]

1 INTRODUCTION

Global manufacturing is in midst of a fourth industrial revolution. After steam engines in the late 1700s, assembly lines in the early 1900s and microprocessors in the 1960s, nowadays it is digitization and automation disrupting production processes once again [1]. Consequently, companies are able to meet customer demand for mass customized products, in some cases decreasing batch sizes all the way down to one [2]. However, this development poses a significant challenge to production systems and, in extension, to production supply. Instead of merely optimizing existing assembly line based systems, using Matrix Production Systems (MPS) offers an alternative approach to face these challenges. Derived from a history of an ever increasing need for flexibility, in MPS products do not follow one singular predetermined path from process module to process module. Instead, each product follows its individual route skipping and/or looping back to specific modules [3]. To perform the necessary transports between process modules, a highly flexible transport system is required. With recent advances in the field of mobile robotics resulting in increasing capabilities and decreasing prices, Autonomous Mobile Robots (AMR) are predominantly suited for this task [4]. They are able to navigate freely within manufacturing systems and can load and unload single parts and/or crates autonomously [5].

While companies already adopted physical transport via AMR carrying multiple loads at once within production systems, the control of these mobile robots in MPS presents a previously unfamiliar challenge. In conventional production systems, working stations are usually supplied from one or more depots with supply runs of multiple loads starting and ending in the same depot [6]. In contrast, products in MPS take individual routes through the production system, causing process modules to simultaneously act as sources and sinks of transport demands [3]. These kind of routing problems are subsumed as Pickup and Delivery Problems (PDP), which existing fleet managing systems, assigning transport demands to AMR, lack efficient routing strategies for. PDP are, however, a topic of intense research

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activities in transport logistics, concerned with road, rail, ship and air transport, but have only rarely been applied in intralogistics, concerned with in-plant transports. Due to the significantly different requirements and constraints of intralogistics in comparison to transport logistics, research is required to investigate how PDP strategies can be adapted for production supply in MPS.

To lay the foundation for this research, the specific requirements of intralogistics in general and MPS in particular have to be analyzed. This allows to obtain a formulation of the PDP in the context of production supply, which is the aim of this contribution. Therefore, it firstly covers the state of the art regarding MPS and the general PDP. Secondly, requirements and differences between intralogistics and transport logistics are analyzed to, thirdly, define the resulting PDP variant. We conclude with a summary and an outlook for further research.

2 STATE OF THE ART

2.1 MATRIX PRODUCTION SYSTEMS

The demand for flexibility in production systems introduced a variety of different approaches over the past decades. They include Flexible Manufacturing Systems (FMS), Reconfigurable Manufacturing Systems (RMS) and Matrix Production Systems. These systems consist of independent process modules where manufacturing or assembly tasks are performed. In contrast to more traditional Designated Manufacturing Lines (DML), none of them require products to move from station to station in an immutable sequence but offer multiple possible routes between stations, depending on a specific product's requirements, as shown in Figure 1 [7]. While in FMS and RMS transport is usually conducted by more restrictive stationary conveying equipment, MPS use an AMR-based production supply, further increasing their flexibility and productivity [3, 7]. As their name suggests, process modules in MPS are fully modular, offering interaction with the transport system via well-defined interfaces for loading and unloading [3]. This allows a high degree of reconfigurability for individual modules internally as well as for the overall system to easily add and remove modules, when faced with fluctuations in demand or changing requirements [7, 8].

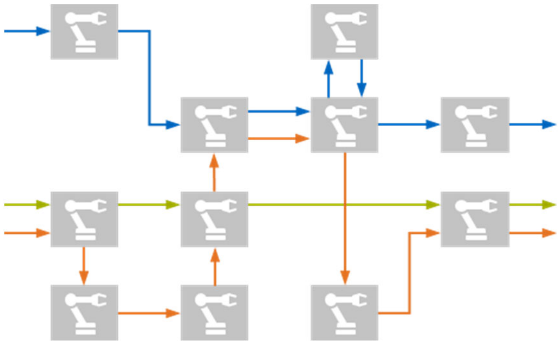


Figure 1. Individual job routes of products in an MPS

In addition to their increased flexibility regarding both production processes and scalability, MPS offer some unique advantages. Due to their inherent characteristic of individualized routes for every product, each product only visits process modules it requires operations from. This increases the utilization of process modules in comparison to traditional DML, where modules cannot be skipped, regardless of whether they are required for a specific product or not [8]. The products' routing flexibility also renders the need for uniform cycle times across all process modules obsolete, further increasing their utilization [9, 10]. Additionally, in case of breakdowns of singular process modules, products can be rerouted to modules offering a similar or even identical skill set, building up resilience of the overall system [8]. All in all, these factors suggest an increase in overall productivity of MPS compared to DML [8].

As in most cases, these benefits come with a cost in form of some limitations and challenges to be considered. The arguably most significant among those being the high operative complexity of MPS [11]. Both the planning of the products' job routes and the transport routes of AMR are complex and dynamic optimization problems that are highly dependent on the current system state. This complexity is reflected in increased operational costs [7]. Because process modules in MPS are completely decoupled, each of them need at least small buffers for incoming and outgoing products, leading to overall higher inventory in the production system and longer throughput times [9].

Even considering these drawbacks, in variant-rich production systems in particular the benefits of MPS already outweigh the disadvantages. Nevertheless, there still is a lot of untapped potential for increased efficiency in MPS with this contribution focusing on the logistical aspects.

2.2 THE PICKUP AND DELIVERY PROBLEM

The question, how to transport goods to their designated destination as effectively as possible, has been a challenge ever since humanity became sedentary. However, it took until the midst of the 20th century before a systematic scientific analysis started with FLOOD's mathematical formulation of the so called Travelling Salesman Problem (TSP) in 1956 and its generalization to the Vehicle Routing Problem (VRP) by DANTZIG AND RAMSER in 1959 [12, 13]. Ever since, a virtually countless number of publications explored various approaches to solve this question for specific logistics systems and sets of constraints [14].

Starting with a given set of transport demands and an available fleet of transport resources, the overarching goal of the VRP is to determine a route for each transport resource in a way that all transport demands are satisfied at a minimum value of an objective function [15]. The objective function to be minimized varies based on the characteristics of the particular problem. Popular metrics include, for example, cost, time or distance travelled. In addition to optimizing for a singular criterion, hierarchical and multiple-criteria optimization can be applied. [15] The effort of solving a VRP can be subdivided into three problems. *Dispatching* determines which transport demand is assigned to which transport resource. In the *routing* step (that pars pro toto also names the overall problem), specific paths in between waypoints for the individual transport resources are selected. *Scheduling* refers to the decision at what time transport resources are to arrive and leave at their respective stops within their route. [16]

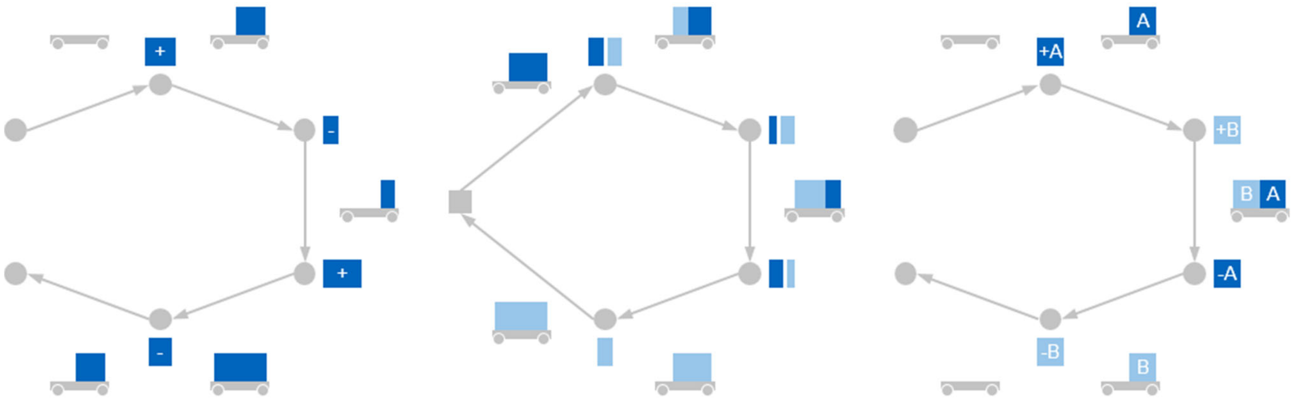
Most variants of the VRP assume a single depot supplying all customers, which act exclusively as sinks for transport demands. Therefore, all transport resources both start and end their routes at that depot [15]. If multiple depots do exist, each sink is usually exclusively supplied from a single depot. These assumptions, of course, are not suitable to accurately describe the desired properties of production supply in MPS. Due to process modules simultaneously acting as sources and sinks of transport demands, a possibility to include transport demands in between process modules is needed. This requirement is met by the VRP subclass of Pickup and Delivery Problems, first formulated by Savelsbergh and Sol in its general form in 1995 [17]. PDP, in turn, distinguish Many-to-Many (M-M) problems, where each commodity can have multiple origins and destinations, One-to-Many-to-One (1-M-1) problems, where some commodities are delivered from a depot to multiple customers and others are collected from customers and transported back to the depot, and One-to-One (1-1) problems, where each commodity has a single origin and single destination (see Figure 2) [18]. If people instead of goods are being transported (e. g. in case of shared taxis), the problem is instead referred to as Dial-a-Ride Problem (DARP). Except from specific constraints regarding customer satisfaction it is identical to PDP [19]. As shown in a 2022 bibliometric analysis by Zang et al., research on PDP is rapidly developing [20]. However, it is still almost exclusively focused on transport logistics, leaving a research gap in intralogistics use cases like MPS to be closed.

3 REQUIREMENT ANALYSIS OF ROUTING IN MATRIX PRODUCTION SYSTEMS

To determine which elements of existing PDP literature on transport logistics can be directly adopted and which ones have to be adapted for MPS, requirements of production supply in MPS need to be identified. Like all intralogistics processes, the objectives of MPS supply operate in a trade-off between performance, quality, and cost [21].

The performance aspect is primarily characterized by providing the throughput demanded by the MPS with flexibility and scalability to match the corresponding qualities of MPS being secondary performance requirements. This implicitly also includes the prevention of deadlocks in production supply by the fleet managing system's routing module to be able to achieve the required throughput. Additionally, routing in MPS needs to be able to react quickly to short-term changes within the production system. These changes can either be intentional, e. g. if new high-priority orders arrive, or unintentional due to breakdowns of either process modules or transport resources. Consequently, a static approach to transport orders is not sufficient so a dynamic variant of the PDP needs to be employed. This allows the fleet managing system to optimize the routing according to disruptions and ensure a consistent performance level of production supply. Simultaneously, a dynamic PDP also accommodates for stochastic variation in processing and handling times.

In terms of logistics quality in MPS, the most important requirements are to ensure that goods reach their designated destinations and that they do so in time to prevent stops in production. The latter suggests the use of time windows in the routing problem, defining the latest time of arrival of a transport demand at its destination and penalizing any violation of time windows in the objective function of the PDP.



M-M 1-M-1 1-1

Figure 2. The three types of PDP, adapted from [18]

Cost of production supply in MPS is mainly influenced by costs for transport resources, in this case AMR, and inventory costs. Therefore, developing and implementing more efficient routing strategies provides significant leverage to decreasing cost while simultaneously keeping logistics performance and quality at the required level. By increasing utilization and performance rates through improved routing, a lower number of AMR needs to be used, which decreases both fixed costs for acquiring AMR as well as variable costs for servicing and monitoring. Using multi-load AMR can increase the performance rate of single robots further by reducing empty trips, allowing to keep up the required logistics performance with an even smaller AMR fleet. However, it needs to be noted that multi-load AMR are likely to also cause additional cost due to their more sophisticated hardware and increased complexity in routing as well as possibly increasing throughput times.

While the overall goals in transport logistics and intralogistics match for the most part, there are some significant differences to be considered, crucially influencing routing requirements. The most obvious one being the immense difference in travel distance and travel time of transport resources. Consequently, the ratio of handling times to total transport time is much higher in intralogistics, placing more emphasis on the dispatching part of the routing problem than the actual routing itself. With transport times being lower in general, computing time for fleet management systems, not statically preplanning routing of production supply entire shifts or days of production, to produce valid and efficient routes is equally reduced. Since the PDP in MPS is dynamic, appropriately quick algorithms for solving the PDP are required.

Being operated by humans, transport resources in transport logistics usually loop back to their initial location eventually for drivers to return to their homes. This constraint does, of course, not apply to the routing of AMR in MPS. While mobile robots do need to interrupt operations periodically to recharge their batteries, the selection of a recharging location is free of any comparable constraints.

The recharging process does, however, introduce an additional constraint, lacking a counterpart in transport logistics. When an AMR starts recharging, it is beneficial not to interrupt charging until the process is complete. Even though AMR nowadays predominantly use Li-Ion batteries that do not suffer any substantial loss of capacity by partially recharging, routes of AMR with decreased range due to a low state of charge tend to yield less optimal results. Since in shorter routes driving from and to a charging station takes up a bigger proportion of overall route time, a correspondingly smaller portion remains for actually fulfilling transport demands, decreasing efficiency of the AMR. Therefore, the PDP should incentivize not to interrupt the recharging process of AMR.

4 CHARACTERISTICS AND MATHEMATICAL FORMULATION OF THE PICKUP AND DELIVERY PROBLEM IN MATRIX PRODUCTION SYSTEMS

Based on requirements of production supply in MPS established in the previous section, we can conclude the following characteristics of the underlying PDP:

- It is considered a 1-1 problem with each transport demand having a single origin and a single destination. Prima facie, this may seem counterintuitive regarding the flexibility, reconfigurability, and redundancy MPS offer. However, we assume a manufacturing execution system (MES) that includes these properties in production planning and scheduling, providing corresponding transport demands as input data for the PDP.
- To enable the MES to fully utilize the flexibility of production planning in MPS as well as accommodate for breakdowns, the PDP is considered dynamic.
- The PDP includes time windows with a hard beginning (product has to be available at origin) and a soft ending, allowing delayed deliveries to prevent being unable to produce valid routes and thus halting production supply as a whole. To simultaneously avoid the violation of time windows, it is penalized by the objective function.
- The higher relative influence of handling times on total transport time is reflected by explicitly considering them within the PDP.
- Transport resources have a transport capacity greater than one to include multi-load AMR and are able to access any load at any time, regardless of loading sequence. Allowing for multi-load AMR still includes the possibility to investigate single-load AMR.
- We assume a homogenous fleet of AMR, meaning all mobile robots share identical properties. This also implies that every transport demand can be executed by every AMR.
- Interrupting the charging process of AMR is to be avoided as long as it does not result in delayed deliveries.

The objective function of the PDP therefore follows a multi-criterial approach to represent the abovementioned characteristics. These criteria are to comply with time windows, not to interrupt the charging process of AMR, and to reduce the time required for routes. Since these criteria are not equally important to obtain the best possible results in routing, their proportions relative to one another are adjustable via weighing factors, increasing or decreasing their influence on the objective function's overall result. A reasonable a priori assumption seems to be ranking compliance with time windows highest, followed by uninterrupted charging and reducing route time. The optimal dimensioning of the weighing factors is subject to further investigation and may differ across various MPS.

In mathematical terms, this leads to the following description of the objective function:

$$min\left(\sum_{k\in M}\left(\sum_{(i,j)\in V\cup W}\left(\lambda_T\tau_{ij}^k x_{ij}^k\right)+\lambda_C A_k B_k^{-1}\right)+\sum_{i\in V}\lambda_D\delta_i\right) \quad (1)$$

with M being the set of AMR, V the set of visited process modules and W the set of start and end points of routes. The first part of the formula describes the time required for completing the routes. The transport time τ_{ij}^k from location i to location j is calculated as:

$$\tau_{ij} = t_{ij} + t_H \quad \forall i \in V \cup M^+, j \in V \quad (2)$$

$$\tau_{ij} = t_{ij} \quad \forall i \in V, j \in M^- \quad (3)$$

with t_{ij} being the travel time from i to j and t_H the handling time. At the route's end point $M^- \in W$ the handling time is not considered, as equation (3) describes. x_{ij}^k is a decision variable, indicating whether the trip from i to j is part of the route of AMR k, and λ_T the weighing factor for route time.

The second part of the objective function is concerned with AMR charging. A_k is a variable that assumes 1, if AMR k is currently charging, and assumes 0, if it is on an active route. In the latter case, the whole term equals 0, meaning no extra cost is added. In the former, its multiplication by the inverse of the current battery level B_k and the weighing factor for charging λ_C results in increasingly higher costs the closer B_k is to 0.

The last term of the objective function describes how the violation of time windows is penalized. It is calculated by multiplying the accumulated delay δ_i at process module i by the weighing factor for delays λ_D.

A number of the constraints that apply to the PDP in MPS can be directly adopted from the general PDP formulated by Savelsbergh and Sol [17]:

- Each transport demand is only assigned to a single AMR
- AMR only visit locations that are origins or destinations of transport demands
- For each route a start and an end point are defined
- The pickup part of a transport demand is executed prior to the delivery part
- Locations along the route are visited by the AMR in the assigned sequence
- AMR do not carry any loads when they start and end a route
- Maximum transport capacity of AMR is never exceeded and current load is always non-negative

To describe the remaining characteristics of the PDP in MPS, some additional constraints have to be defined:

$$x_{ij}^k = 1 \Rightarrow D_i + \tau_{ij} \leq D_j \quad \forall i,j \in V \cup W, k \in M \quad (4)$$

$$a_i \leq D_i \quad \forall i \in V \quad (5)$$

$$\delta_i = max(0, D_i - b_i) \quad \forall i \in V \quad (6)$$

$$D_{k^-} \leq L_k \quad \forall k \in M \quad (7)$$

with D_i being the departure time at location i. Equation (4) adjusts an original constraint from the general PDP regarding travel time to also include handling times. The following two equations describe time windows with a hard beginning a_i (5) and a soft end b_i that is used to calculate the delay (6), considered in the objective function. Constraint (7) defines a maximum duration of the route L_k depending on the battery level of AMR k.

5 CONCLUSION AND OUTLOOK

MPS offer an intriguing approach to solve current challenges in mass customization manufacturing. However, the emerging discussion of this novel production system does not yet focus on logistical aspects, leaving a lot of potential untapped. To start closing that research gap, this contribution formulates an optimization problem for AMR routing in MPS. To that effect, it analyzes logistics requirements of MPS and their influence on routing to supply production. Due to process stations in MPS simultaneously being sources and sinks of transport demands, the underlying optimization problem can be described as a PDP. Being originally developed to be applied in transport logistics, relevant differences between transport logistics and production supply have been investigated to identify in what ways the PDP has to be adapted for MPS, and included into the problem formulation. Its objective function considers penalties for the violation of time windows and premature interruptions of charging processes as well as a minimization of route times as optimization criteria.

This formulation of a PDP in MPS is primarily targeted towards exclusively using AMR as transport resources. Nevertheless, it is transferable to MPS using human-operated transport resources requiring only minor adjustments, especially regarding charging processes. Furthermore, alternative possible scenarios to supply MPS exist, resulting in slightly different variants of the PDP. However, the overall notion remains identical, allowing the findings of this contribution to be applied across many use cases in MPS.

After having defined the optimization problem, the next logical step in researching routing in MPS is to develop effective strategies to solve this particular PDP efficiently. As concluded above, lower travel times between destinations cause the ratio of handling time to transport time to be higher in MPS. Therefore, focusing on dispatching suggests to be the most promising initial direction. Literature on PDP in transport logistics provides a plethora of potentially suitable algorithms that need to be reviewed, clustered, and ranked to identify fitting candidates for MPS. The chosen algorithms can then be evaluated using e. g. discrete event simulation. With the definition of representative reference MPS, the impact of system properties such as size and complexity on the performance of various routing strategies can be investigated. This not only includes different algorithms, but also other characteristics like the use of multi-load AMR discussed in section 3 and the number and placement of charging stations, all of which can influence system performance.

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