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Abstract. Due to increasing product variety and uncertain demand for highly individualized products, a rising need for flexibility of manufacturing systems can be observed. In this context, the concept of matrix-structured manufacturing systems (MMS) has attracted increasing consideration. MMS aim to achieve high operational flexibility by implementing a flexible product flow between stations with automated guided vehicles and by providing redundant resources for each operation, thus eliminating constant cycle times and the serial arrangement of stations. This paper investigates the design of MMS pursuing an economic objective. We formulate a mixed-integer program for the design of MMS. Introducing a numerical example, we illustrate the effectiveness of our approach and derive future research opportunities.

Keywords: Matrix-structured Manufacturing System, Flexible Manufacturing System, Mass Customization.

1   Introduction

Manufacturing companies face different trends such as individualized customer demand, an increased level of global competition, and rapid technological progress. These trends result in a higher product variety and uncertain demand. [1] Thus, a change of the production paradigm from mass production to personalized production can be observed. [2] Conventional manufacturing systems (MS) such as mixed-model assembly lines or job shops are either capable of handling high product volumes or a high product variety but struggle to cope with both requirements simultaneously. Manufacturing companies are therefore confronted with the challenge of designing MS which can reliably produce a high volume of products with a high product variety in an economic way. Due to the digitization in the manufacturing sector (frequently referred to as Industry 4.0), novel technologies arise which may serve as drivers of increasing flexibility at reasonable costs. [3] The use of automated guided vehicles (AGVs), for example, enables flexible routing between stations of a MS. One concept of manufacturing systems that emerged from the use of these new technologies is the concept of matrix-structured manufacturing systems (MMS).

MMS describes the concept of a MS capable of producing high volumes of multiple products by using a flexible material flow through the manufacturing system while redundant resources allow for alternative paths through the MS. The basic elements of the MMS are stations, each of which is an autonomous subsystem and may operate at an individual pace. By allowing an individual pace for every station, a constant cycle time can be avoided. This is desirable as different processing times for different products lead to unbalanced utilization of stations and may result in starving or blocking of stations in conventional MS. [4] Different resources, i.e., human workers, autonomous machines, or collaborative robots operate in the stations of the MMS. Each resource is characterized by the capability to complete specific operations for certain products with a corresponding processing time. As the resources are used redundantly, not only a single station is capable to execute a specific operation for a product, but several stations are. Therefore, starving and blocking effects can be avoided. [1] To fully utilize the advantages of dynamic cycle times and redundant resources, a flexible material flow is required. AGVs transport the products through the MMS until their assembly is completed. Thus, products can skip stations that are not required for the assembly, which leads to routing flexibility as redundant resources in different stations can be used for the processing of specific operations. [5] By combining the advantages of job shops and assembly lines, MMS aim to efficiently produce a high volume of products with a high variety. [1]

First pioneer implementations demonstrate the industries' interest in MMS. The mechanical engineering company KUKA AG advertises the concept of MMS [6] and the automotive company Audi AG already uses a MMS for the assembly of the Audi R8, resulting in an estimated efficiency gain of 20% in comparison with the former mixed-model assembly line. [7] However, the increased flexibility of MMS might result in higher production costs compared to more efficient means of production. Thus, an evaluation of the initial configuration decisions in the design phase of MMS becomes necessary. In this contribution, we, therefore, present a cost-oriented approach to this long-term planning problem, as these objectives have been commonly considered in the design of other MS. [8] Therefore, we formulate a mathematical optimization model to obtain cost-efficient initial designs for MMS. We illustrate the effectiveness of our approach by providing a numerical example.

The remainder of this contribution is structured as follows. In Section 2, a literature review considering related contributions is given. In Section 3, the decision-making situation of the problem is described in detail. Our developed mathematical model is presented in Section 4. A numerical example is presented in Section 5. Finally, we conclude our contribution in Section 6.

2   Literature Review

Although capacity-oriented approaches for MS design are more frequently found in the literature, cost-oriented approaches are increasingly used to evaluate the initial configuration of different types of MS. [9] As the initial design of a MS is a long-term planning problem, costs are usually subdivided by the capital cost and the operating cost.

Capital costs are associated with the investment in the basic elements of the MS, whereas operating costs include the costs incurred during the operation of the MS. [8, 10] For MMS, the capital cost is associated with the number of stations that are opened and the resources that operate in the stations. The operating costs mainly consist of the costs occurring for the transportation of products between the stations and the resource usage costs. Additional costs as failure cost, idle-time cost, or reconfiguration cost are mainly investigated in tactical decisions regarding the design of MS and are therefore out of the scope of this contribution. [9] To the best of the authors' knowledge, a cost-oriented design approach for MMS has not yet been addressed in the literature. For comprehensive literature reviews on cost-oriented design approaches of MS, we refer to Hazır, Delorme, Dolgui [9] and Yelles-Chaouche, Gurevsky, Brahimi, Dolgui [8].

The first mathematical formalization of a problem that is related to the design of MMS is the Simple Assembly Line Balancing Problem (SALBP). [11] In SALBP, operations are assigned to serially arranged stations considering capacity restrictions and precedence relations between production operations. As the assumptions of SALBP are very restrictive, many contributions generalize the problem to enable the consideration of practical aspects in their mathematical formulations. Those contributions are often referred to as General Assembly Line Balancing Problems (GALBP). [12] Many of those generalizations are linked to the problem considered in this contribution. In Mixed Model Assembly Line Balancing, two or more products are produced in the same MS. [12] This is also a key characteristic of MMS. The multi-manned Assembly Line Balancing Problem additionally considers the parallel execution of operations by different resources positioned in the same station. [13] As several resources can be assigned to every station, the parallel execution of operations is also considered during the design of MMS. The Robotic Assembly Line Balancing Problem (RALBP) investigates the design of automated assembly lines by assigning automated robots to the stations while predominantly pursuing a minimization of used stations or minimization of capital cost for the assigned robots. [14, 15] Resource selection and assignment are also considered during the design of MMS. Thus, in GALBP several aspects of the optimal design of MMS are investigated. However, a serial connection between stations is always assumed. Therefore, GALBP approaches cannot be applied to the design of MMS as the problem of designing MMS requires flexible material transport between stations. For comprehensive literature reviews on GALBP, we refer to Baybars [12], Boysen, Fliedner, Scholl [16] and Boysen, Fliedner, Scholl [17].

Two MS concepts that include a flexible material flow often considered in the literature are Flexible Manufacturing Systems (FMS) and Reconfigurable Manufacturing Systems (RMS). A FMS can be described as a computer-controlled and integrated complex of machines, which operate in different stations connected by an autonomous material handling system. The operations of the different machines and the material flows are coordinated and controlled by the central computer. [18] In comparison to the concept of MMS, the stations in FMS are not operated independently and therefore a common cycle time cannot necessarily be avoided. Moreover, only machines are used as resources in FMS, making MMS more suitable for applications in industries with a high amount of manual operations. A RMS is composed of several reconfigurable machines that can be easily added, removed, or reconfigured to execute different operations

during the lifecycle of the RMS due to the modular structure of the machines. The modular structure also allows scaling the RMS to cope with increasing or decreasing capacities. The machines are connected and are operated through control software. [8] In contrast to the concept of MMS, the resources in RMS operate without being grouped into stations. Thus, resources can only be used sequentially and not simultaneously. Moreover, as already observed for FMS, only machines are used as resources in RMS, making MMS more suitable for use in industries with a high amount of manual operations. Therefore, approaches for the design of FMS or RMS differ from our approach as they either exclude crucial assumptions of the concept of MMS or include assumptions that are too narrow. For comprehensive literature reviews on the design of FMS and RMS, we refer to Bortolini, Galizia, Mora [19] and Yelles-Chaouche, Gurevsky, Brahimi, Dolgui [8].

Only a few contributions are investigating on MMS explicitly. Greschke, Schönemann, Thiede, Herrmann [4] and Schönemann, Herrmann, Greschke, Thiede [1] elaborate on the concept of MMS and propose a simulation-based approach for the evaluation of MMS designs. However, those contributions do not investigate the optimal design of MMS. Hottenrott, Grunow [5] propose a mixed-integer linear program and a decomposition-based solution approach for the design of flexible segments for the assembly of products. Although the contribution investigates the design of MMS, the selection of different resources is not considered. Moreover, no cost-oriented objective is pursued. To the best of the authors' knowledge, a cost-oriented design approach for MMS, as presented in Section 3, has not yet been addressed in the literature.

3   Problem Description

We investigate the design of MMS, in which a set of $p \in P$ products with high product variety and a given demand D_p for the respective products is to be produced in a certain time interval. During this time interval, the MMS may operate upmost Q time units. The shop floor is represented by $l \in L$ locations, at which stations could be opened. The stations are of the same size and are arranged in a grid, i.e., they can be identified by height and length coordinates to determine the distance between the individual stations. The distance between two stations l and l' is denoted $d_{l,l'}$. For the production of all products, a set of $o \in O$ operations have to be executed, where every product requires a subset $O_p \in O$ operations to be executed while complying with the known precedence relations of each operation for each product. A set $r \in R$ of resources are available and can operate in the stations. Due to the standardized station design, every resource can be operated in every opened station, but only a maximum of K resources can be assigned to each station. The capability of resources is limited. Whether a resource is capable of performing a specific operation is depicted in binary parameters $a_{r,o}$. The parameters $\beta_{r,o,p}$ indicate the processing time resource r requires to process operation o for product p. The products are transported through the shop floor by AGVs on sets $n \in N_p$ of routes, where each product may have its individual set. A route consists of several operations that are executed by the resources in a specific sequence. The binary parameters e_{oqn}^p indicate whether operation o precedes operation q in route n. Every

route consists of a sequence of all required operations for the corresponding product, complying with the known precedence relations of the operations. Common dummy start and end operations (O^{S} and O^{E}) as well as common dummy start and end resources (R^{S} and R^{E}) exist as start points and endpoints of every route. Moreover, cost rates induced by opening a station at a location (ic), induced by resources (c_r), and a cost rate for material transport (ct) are known.

We decide whether a station is opened at location l (binary variables x_l) and whether a resource r is assigned to location l (binary variables $y_{l,r}$). The auxiliary variables $y_{l,r,l',s}$ are used for the connection of the variables $y_{l,r}$. Moreover, the volume of products p assigned to the routes n (variables f_{pn}) are determined. Finally, we determine the flows of units of product p from operation o performed by resource r to operation q performed by resource s on route n (variables v_{orqspn}). The objective is to minimize the sum of costs for stations and resources and costs for transportation of the products within the MMS.

We make six further assumptions: First, common entry and exit locations are required for the MMS to enable a stable connection to adjacent production stages. The exact locations of the entry and exit points are known. Second, we assume constant cost rates for stations, resources, and transportation, i.e., a linear depreciation of necessary investments and constant interest rates are assumed. Third, we assume that no failures occur while executing operations. Fourth, we assume the demand D_p for each product is known. Fifth, we assume that operations executed in the same station can be executed simultaneously. Therefore, no scheduling of the operations inside of the stations is required. Finally, we assume that processing times and the demand for each product are deterministic.

4   Model Formulation

To provide a formalized description of the problem, a mathematical model formulation is developed in this section using the notation introduced in Section 2.

$$Minimize \sum_{l \in L} x_l \cdot ic + \sum_{l \in L} \sum_{r \in R} y_{l,r} \cdot c_r + \sum_{p \in P} \sum_{r \in R} \sum_{s \in R} \sum_{l \in L} \sum_{l' \in L} ct \cdot d_{l,l'} \cdot y_{l,r,l',s} \cdot \sum_{o \in O_p} \sum_{q \in O_p} \sum_{n \in N_p} v_{orqspn} \quad (1)$$

Subject to:

$$\sum_{r \in R} y_{l,r} \leq K \cdot x_l \qquad\qquad \forall\, l \in L \qquad\qquad (2)$$

$$\sum_{l \in L} y_{l,r} \leq 1 \qquad\qquad \forall\, r \in R \qquad\qquad (3)$$

$$y_{l,r,l',s} = y_{l,r} \cdot y_{l',s} \qquad\qquad \forall\, l \in L, l' \in L, r \in R, s \in R \qquad\qquad (4)$$

$$\sum_{n \in N_p} \sum_{p \in P} \sum_{r \in R} \sum_{o \in O_p} \sum_{q \in O_p} v_{orqspn} \cdot \beta_{s,q,p} \leq Q \qquad \forall \, s \in R \qquad (5)$$

$$\sum_{n \in N_p} \sum_{p \in P} \sum_{r \in R} \sum_{o \in O_p} v_{orqspn} \leq a_{s,q} \cdot \sum_{l \in L} y_{l,s} \cdot \sum_{p=1}^{P} D_p \qquad \forall \, s \in R, q \in O_p \qquad (6)$$

$$\sum_{r \in R} \sum_{s \in R} v_{orqspn} = f_{pn} \cdot e_{oqn}^p \qquad \begin{aligned} &\forall \, q \in O_p\,, o \in O_p\,, o \neq q, \\ &\quad p \in P, n \in N_p \end{aligned} \qquad (7)$$

$$D_p = \sum_{n \in N_p} f_{pn} \qquad \forall \, p \in P \qquad (8)$$

$$\sum_{r \in R} \sum_{o \in O_p} v_{orqspn} = \sum_{t \in R} \sum_{u \in O_p} v_{qsutpn} \qquad \forall \, q \in O_p, s \in R, p \in P, n \in N_p \qquad (9)$$

$$x_l \in \{0,1\} \qquad \forall \, l \in L \qquad (10)$$

$$y_{l,r} \in \{0,1\} \qquad \forall \, l \in L, r \in R \qquad (11)$$

$$y_{l,r,l',s} \in \{0,1\} \qquad \begin{aligned} &\forall \, l \in L, l' \in L, \\ &\quad r \in R, s \in R \end{aligned} \qquad (12)$$

$$v_{orqspn} \geq 0 \qquad \begin{aligned} &\forall \, q \in O_p, o \in O_p, o \neq q, \\ &\quad p \in P, r \in R, s \in R, n \in N_p \end{aligned} \qquad (13)$$

$$f_{pn} \geq 0 \qquad \forall \, p \in P, n \in N_p \qquad (14)$$

Objective (1) is to minimize the total costs of the initial configuration of a MMS. The total costs consist of the costs for opened stations, the costs for resources, and the transportation costs. Constraints (2) guarantee that resources can only be assigned to opened stations and that the maximum number of resources per station is complied with. Constraints (3) ensure that every resource is assigned to upmost one station. Constraints (4) link the decision variables $y_{l,r}$ to the auxiliary variables $y_{l,r,l',s}$. Constraints (5) ensure that the workload assigned to each resource is less than the maximum time for resources to execute operations. Constraints (6) assure that operations can only be assigned to resources that are deployed and capable of executing the specific operation. Constraints (7) link the variables f_{pn} and v_{orqspn}. Constraints (8) guarantee demand fulfillment for every product and Constraints (9) ensure flow balance for every resource. Constraints (10)–(14) define the domains of the decision variables. To derive quantitative evidence on the described problem, we present a numerical example in the

following section. Therefore, we implemented the model in Python 3.9 and solved it using the Python Gurobi API (version 9.0.0). The computations were run on a standard computer with AMD Ryzen 7 PRO 3700U CPU @ 2.3 GHz and 16 GB RAM.

5 Numerical Example

This study considers a numerical example consisting of $|O| = 12$ operations which need to be executed complying to given precedence relations for $|P| = 3$ different products. The demand D_p for each product is assumed to be 10.000 units. Processing times to execute the operations vary depending on the product. Common dummy start and end operations as well as dummy resources exist for every product. Stations can be opened at $|L| = 9$ locations, forming a 3x3 grid. A maximum of $K = 2$ resources can be operated in each opened station. As the problem of designing a MMS is a long-term planning problem, we assume the life cycle of the MMS and all included elements to be five years. Therefore, the aggregated demand of five years is to be produced for each of the models. Assuming 230 workdays per year and one daily eight-hour shift, the maximum time for resources to execute operations Q is 552,000 minutes. We restrict the number of available resources to $|R| = 12$, consisting of five assembly workers (resources R_1 - R_5), five automated assembly robots (resources R_6 - R_{10}), and a dummy resource for the dummy start and end operations each. While we assume human workers to be capable of executing 50% of the operations, the assembly robots are only capable of executing two out of the twelve required operations to accommodate their limited capabilities. We further assume that the processing times of the assembly robots are halved for each operation in comparison to the processing times of human workers. To derive the costs of workers, assembly robots, material transport, and opened stations we have to justify additional assumptions. Data to estimate the investment for opening a station are generally difficult to obtain as the data depend on the actual assembly processes. Therefore, we suppose costs of 35,000 EUR per opened station comprising for equipment and installation of the station itself as proposed in Weckenborg, Spengler [20]. Assembly robots normally have a basic price between 42,000 EUR and 67,000 EUR. [21] We assume costs of 70,000 EUR per automated assembly robot taking into account additional costs for installation. Further, we assume the investment in technologies to be fully depreciated during a five-year period. Costs per worker, therefore, result in 327,520 EUR in the same five-year period based on hourly labor costs reported in Eurostat [22]. The cost rate for transporting one product for one distance unit ct is assumed as 0.10 EUR.

The optimal solution for this numerical example with an objective value of 1,519,560 EUR is shown in Fig. 1. By analyzing the depicted solution, the following beneficial design characteristics can be observed: In the found solution, a station is opened at five of the nine possible locations. The opened stations are located next to each other and no gaps between opened stations occur. The resulting design can be described as compact to reduce costs for material transport. Two resources are assigned to every opened station so that the maximum space for resource deployment of opened

stations is always exploited. While all automated assembly robots (resources R_6 - R_{10}) are assigned to a station, only three assembly workers (resources R_1 - R_5) are deployed. The resources that are positioned in stations between the start resource R^S and the end resource R^E are used to execute operations for the entire maximum time Q (resources R_5, R_1, R_7 and R_{10}). Accordingly, high utilization of resources with central positioning can be assumed. Finally, it can be observed that the operations for most of the products are executed along the same routes. Only three routes were used for the production of the three products.
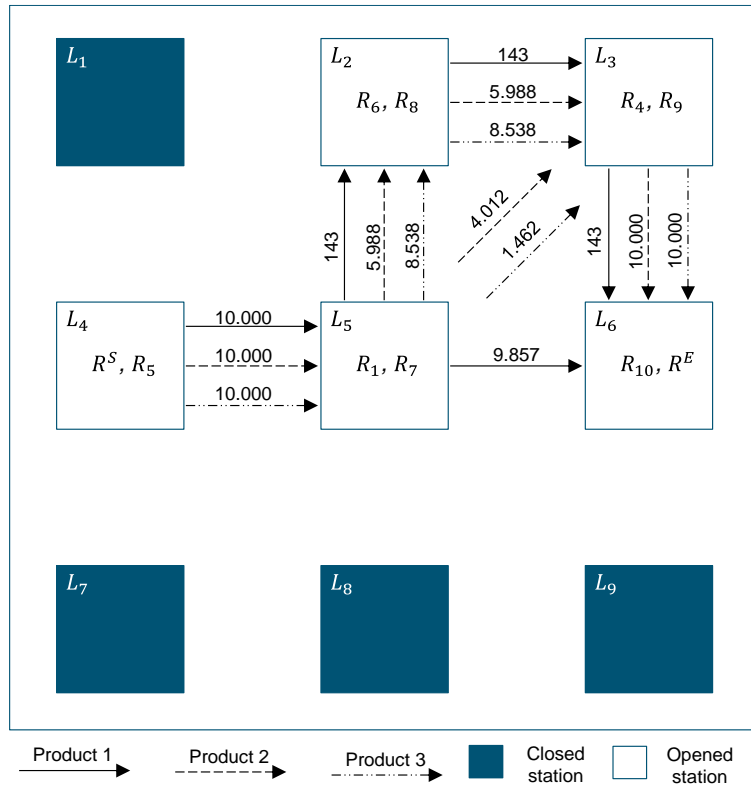
Fig. 1. Illustrative solution of the numerical example

The resulting design can be partially interpreted as serially arranged stations for every product as the model also allows a line to be the optimal design. However, the numerical example only investigates a rather small example consisting of 3 products and 9 stations, thus resulting in rather few possible designs. Nevertheless, the products are skipping not required stations, reducing short-term key figures like lead times and work in progress that would be increased if a strict serial arrangement would have been applied.

6   Conclusion

In the contribution at hand, we propose an optimization model for the economic design of MMS and illustrate our approach with a numerical example. Nevertheless, the design of MMS requires further research. In future work, the numerical example can be enhanced to examine the impact of increased product variety, available resources, the capabilities of resources, and changes in assumed cost rates on the economic design of MMS. Moreover, a comparison of the performance of derived configurations of MMS to more efficient means of production needs to be developed.

As we assumed the initial design of MMS to be a long-term planning problem, we decided to focus on a static and deterministic environment in the contribution at hand. However, as the stations of MMS are standardized and resources can be operated in every station, the configuration of MMS can easily be reconfigured. By considering dynamic demands and changing requirements for the MMS, the reconfigurability of MMS will also be the subject of our future research.

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