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The impact of operation, equipment, and material handling flexibility on the design of matrix-structured manufacturing systems

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Abstract: Due to increasing product variety and uncertain demand for individualized products, companies need to constantly adapt their manufacturing systems to maintain an efficient production. Therefore, an increasing need for the consideration of flexibility in manufacturing system design can be observed. In this context, the concept of matrix-structured manufacturing systems (MMS) has attracted recent attention. MMS aim to achieve an efficient production by implementing a flexible material flow among stations and by deploying redundant resources for the operations, thus allowing flexible cycle times of stations and flexible material transport. This paper investigates the impact of material handling flexibility, equipment flexibility, and operation flexibility on the economic design of MMS. We conduct a numerical example to determine the impact of the flexibility types based on a mixed-integer linear program. The results demonstrate that the consideration of equipment flexibility and material handling flexibility during the design of MMS lead to economically beneficial configurations.

Keywords: Matrix-structured manufacturing system, Manufacturing flexibility, Operation flexibility, Equipment flexibility, Material handling flexibility, Manufacturing system design

1. INTRODUCTION

Manufacturing companies face different external and internal trends such as unpredictable market changes, increasing individualized customer demand, and rapid technological progress. Additionally, products are getting more complex while having even shorter life cycles (Bortolini et al., 2021). These trends ultimately result in a higher product variety and uncertain demand that manufacturing systems need to cope with to maintain an efficient production (Koren et al., 2018). Manufacturing systems therefore need to be designed to respond to changes in demand and increasing product complexity to cope with the requirements of modern industry. As conventional manufacturing systems like job shops or mixed-model assembly lines are either capable of handling a high product variety or high product volumes, they struggle to cope with both requirements simultaneously. Therefore, a transition towards so-called Next Generation Manufacturing Systems can be observed (Bortolini et al., 2021; Bortolini et al., 2018). Those manufacturing systems overcome the limitations of conventional manufacturing systems by considering the 'right' types and extent of flexibility during their design.

One concept of manufacturing systems that arose during the digitization of the manufacturing sector is the concept of matrix-structured manufacturing systems (MMS). MMS are manufacturing systems that are capable of producing a high volume of multiple products by using a flexible material flow among stations served by automated guided vehicles (AGVs) while redundant resources allow for alternative routes through the system for each product. The basic elements of MMS are standardized stations, each of which can be understood as an autonomous subsystem that may operate at an individual execution pace. By allowing an individual execution pace for every station and the flexible material flow among stations, an individual cycle time of the stations can be provided, thus avoiding an unbalanced utilization of stations. Consequently, starving or blocking of stations can be reduced (Greschke et al., 2014). Different resources, e.g., human workers or autonomous robots, are operated in the stations of MMS. Each resource is characterized by its capability to complete specific operations for certain products with a corresponding processing time. The resources are used redundantly for the execution of operations, so that several stations are capable of executing a specific operation for a product, further enabling alternative routes through the system for each individual product (Schönemann et al., 2015). As AGVs transport the products through the MMS until their assembly is completed, products can skip stations that are not required for their assembly, which leads to routing flexibility as redundant resources in different stations can be used for the processing of specific operations (Hottenrott and Grunow, 2019). MMS aim to efficiently produce a high volume of products with a high variety by combining the advantages of job shops and assembly lines (Schönemann et al., 2015).

First pioneer implementations already demonstrate the interest of manufacturing companies in the concept of MMS. The automotive company Audi AG already uses a MMS for the final assembly of the Audi R8, resulting in estimated efficiency gains of 20% in comparison with a mixed-model assembly line (Handelsblatt, 2016) and the mechanical engineering company KUKA AG advertises the concept of MMS (KUKA AG, 2016) as an example of successful application of novel technologies in manufacturing systems. MMS therefore address the need for flexibility in manufacturing system design which is specifically achieved by enabling material handling flexibility, equipment flexibility, and operation flexibility (Browne et al., 1984; Sethi and Sethi, 1990). However, the increased flexibility of MMS might result in higher production costs compared to more efficient means of production. Thus, the challenge to

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determine the beneficial types and extent of flexibility needs to be tackled during the design of MMS.

In this contribution, we investigate on the impact of operation flexibility, equipment flexibility, and material handling flexibility during the design of matrix-structured manufacturing systems. Therefore, we present a cost-oriented approach to evaluate the long-term planning problem of designing MMS, as this objective has been commonly considered in the design of other MS (Hazır et al., 2015; Yelles-Chaouche et al., 2020). We reformulate the mathematical optimization model presented in Schumacher et al. (2021) to obtain cost-efficient initial designs for MMS. To evaluate the impact of the three flexibility types, we conduct numerical examples, in which we iteratively disable the individual flexibility types.

The remainder of this contribution is structured as follows. In Section 2, we present the basic flexibilities that are enabled by the concept of MMS. The decision-making situation of designing cost-efficient initial configurations for MMS is described in detail and subsequently linked to the flexibility types in Section 3. Our numerical examples investigating on the impact of the flexibility types in the design of MMS is presented in Section 4. Finally, we conclude our contribution in Section 5.

2. BASIC FLEXIBILITES IN MATRIX-STRUCTURED MANUFACTURING SYSTEMS

During the design of manufacturing systems, decision-makers can maintain flexibility to account for necessary adaptations to cope with demand uncertainty and product variety already in the design phase of manufacturing systems. In this context, the term of manufacturing flexibility conceptualizes the available types of flexibility. This concept has received considerable attention in industrial practice and academic literature. According to Sethi and Sethi (1990), flexibility in manufacturing describes the ability to modify manufacturing resources to maintain an efficient production of different products of acceptable quality. Manufacturing flexibility is therefore considered as the property of the system elements (resources, stations, and the material handling system) that are linked to each other to adapt to various changes. As manufacturing flexibility impacts the competitive strength of companies, decisions regarding manufacturing flexibility are strategic considerations and already need to be considered during the design phase of manufacturing systems. Manufacturing flexibility can be described as a combination of various flexibility types that interact with each other and are based on three basic flexibilities, namely machine flexibility, material handling flexibility, and operation flexibility. We refer to the definition of those flexibility types as provided in the literature review of Sethi and Sethi (1990), which is commonly acknowledged as the most accepted definition of the flexibility types. In the following, those three flexibility types are described and their consideration in the concept of MMS is explained.

Machine flexibility refers to the various types of operations that the machines operated in a manufacturing system can perform without requiring effort to switch from one operation to another (Browne et al., 1984; Sethi and Sethi, 1990). The capabilities of the machines can be expressed in terms of operations they can execute, the corresponding processing times, and potentially variable processing costs. When also considering human workers, their capabilities can analogously be described. Therefore, machine flexibility can also be referred to as equipment flexibility (Pérez Pérez et al., 2016; Son and Park, 1987). In the following, this type of flexibility is referred to as equipment flexibility as we consider human workers as well as automated robots as available resources during the design of MMS.

Material handling flexibility refers to the flexibility of the material handling system and covers the processes of loading, unloading, and transportation of parts required for the manufacturing process (Browne et al., 1984). The material handling system is defined by the supported material paths. In MMS, material handling is served by AGVs that transport the products from station to station until the manufacturing process is finished.

Unless equipment flexibility and material handling flexibility, operation flexibility is not a property of the elements of MMS, but a property of the products that need to be produced. Operation flexibility describes the ability of products to be produced in different ways. Operation flexibility occurs when a product can be produced with alternative process plans, where a process plan describes a sequence of operations required to produce the specific product (Sethi and Sethi, 1990). Frequently, operation flexibility is considered by a precedence graph covering the precedence relations between the operations.

Equipment flexibility, material handling flexibility, and operation flexibility are attained by the deployment of the basic elements of MMS and jointly enable MMS to maintain flexibility for necessary adaptations. However, the 'right' amount of flexibility needs to be determined as flexible elements might result in higher costs of the overall configuration. Therefore, our problem setting sets as follows.

3. PROBLEM SETTING

We investigate on the economic design of MMS, in which a given set of products, that is characterized by a high product variety and a given demand for a certain time interval for the respective products is to be served. During this time interval, the MMS may operate for a given maximum permittable operation time. The shop floor of the MMS is represented by a set of locations, at which standardized stations can be opened. The stations are of identic size and are arranged in a grid, i.e., they can be identified by height and length coordinates. The distance between each pair of stations is determined by applying the Manhattan metric. We decide whether a station is opened at each of the available locations. While opening a station allows for the deployment of resources to this station, a certain cost rate for opening the station is induced to the system. This decision is related to General Assembly Line Balancing Problems (GALBP) of type-1 that also seek to minimize the number of opened stations during the balancing of assembly lines. For comprehensive literature reviews on GALBP, we refer to Baybars (1986) and Boysen et al. (2007).

To produce all products, a set of operations must be executed, where every product requires a known subset of those operations to be executed while complying with the known precedence relations of each operation and each product. As the precedence relations between the operations are known, operation flexibility can be exploited.

A set of resources is available and can be deployed to the stations. Due to the standardized design of the stations, every resource can be operated in every opened station, however, the maximum number of resources per station is limited. Every resource can perform specific operations subject to a corresponding processing time for the respective products. We decide, which resource is deployed to which station in the MMS. Every resource induces a cost rate to the system. Thus, equipment with higher flexibility comes at an increased cost rate for this equipment type, inducing a trade-off between flexibility and costs of the equipment. This decision is also considered in Robotic Assembly Line Balancing Problem , which investigates on the design of automated assembly lines by assigning automated robots of different capabilities to stations while mainly pursuing a minimization of used stations or minimization of capital cost for the assigned robots (Michels et al., 2018; Rubinovitz et al., 1993).

For their production, the products are transported through the shop floor by AGVs until every operation is executed by a capable deployed resource in accordance with the precedence relations of the product. The AGVs do not suffer from material path restrictions, i.e., material transport among each pair of stations is enabled. Every transport from one station to another induces a cost rate to the system depending on the distance between the stations. We, therefore, decide how many units of which product receive which operations by which deployed resources. Eventually, we seek for beneficial cost-oriented initial configurations of MMS by minimizing the sum of costs for opened stations, costs for deployed resources, and transportation costs.

We make four further assumptions which restrict our problem setting: First, we assume a linear depreciation of necessary investments and constant interest rates for stations, resources, and transportation, resulting in constant cost rates. Second, we assume that no failures occur while executing operations. Third, we assume that operations executed in the same station can be executed simultaneously, so that the scheduling of operations within the stations is neglected. Finally, we assume that processing times and the demand for each product are deterministic and known.

Only few authorships previously investigate on the concept of MMS explicitly. Greschke et al. (2014) as well as Schönemann et al. (2015) elaborate on the general concept of MMS and propose a simulation-based approach to evaluate designs of MMS. Hottenrott and Grunow (2019) propose a mixed-integer linear program and a decomposition-based solution approach for the design of a flexible segment that can be added to an assembly line. Although this contribution investigates on the design of a manufacturing system concept similar to MMS, the selection of different resources and a cost-oriented objective are not considered.

4. NUMERICAL EXAMPLE

To provide a formalized description of our problem setting, a mathematical model formulation was developed and presented in Schumacher et al. (2021). To investigate on the impact of the three basic flexibility types during the design of MMS, we present numerical examples in the following. To derive quantitative evidence, we implemented a linearized and slightly modified version of the model of Schumacher et al. (2021) (the detailed description is accessible via the supplementary data at the end of this contribution) in Python 3.9 and solved it using the Python Gurobi API (version 9.1.0). The computations were run on a standard computer with AMD Ryzen 7 PRO 3700U CPU @ 2.3 GHz and 32 GB RAM.

4.1 Generation of the numerical examples

We consider a numerical example of three different products consisting of ten operations which need to be executed complying to given precedence relations. The general precedence graph is depicted in Fig. 1. To obtain product variety, the general precedence graph is slightly modified for each product by excluding one different operation and modifying the processing times of the operations for each product.

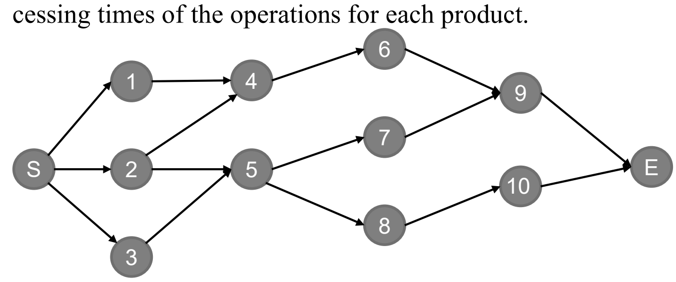

Figure 1. Precedence graph considered in the numerical example.

The demand for each product is assumed to be 35,000 units. Stations can be opened at 9 locations, which form a matrix-shaped 3x3 grid. This way, the distance between each pair of stations can be calculated by applying the Manhattan metric. A maximum of two resources can be operated in each opened station simultaneously. As the problem of designing a MMS is a long-term planning problem, we assume the life cycle of the MMS and all operated elements to be five years. The planning horizon is assumed to be five years accordingly. Thus, the aggregated demand of five years is to be produced for each of the products. Assuming 230 workdays per year and one daily eight-hour shift, the maximum time for resources to execute operations amounts to 552,000 minutes. We restrict the number of available resources to 20, consisting of ten assembly workers and ten automated assembly robots. The human assembly workers are split into two groups of five assembly workers each that are capable of executing either the first (operations 1–5) or the second half (operations 6–10) of the required operations. Due to their technical specialization, the assembly robots are only capable of executing one specific operation to accommodate their limited capabilities. To this end, one assembly robot can be deployed for each of the ten operations. We further assume that the processing times of the assembly robots are half for each operation compared to the processing times of human workers.

As we pursue a cost-oriented approach for the design of MMS, we need to state further assumptions with regard to the cost rates of the basic elements operated in the system, i.e., the costs of assembly workers, assembly robots, material transport, and opened stations. As data to estimate the investment for station opening rely on the actual assembly processes and are in general difficult to obtain, we suppose costs of 35,000 EUR per

opened station comprising for equipment and installation of the station itself as proposed in Weckenborg and Spengler (2019). Assembly robots normally have a basic price between 42,000 EUR and 67,000 EUR (RobotWorx, 2021). With additional costs for installation, we assume costs of 70,000 EUR per automated assembly robot. Further, we assume the investment in technologies to be fully depreciated during a five-year period. Costs per worker result in 327,520 EUR in the same five-year period based on hourly labor costs reported in Eurostat (2020). The cost rate for transporting one product for one distance unit, i.e., the distance between two adjacent stations, is assumed to 0.245 EUR.
In our numerical examples, initially all three types of basic flexibility are considered. To this end, we first solve the numerical example at hand without any further restrictions to derive a beneficial configuration while all flexibility types can be exploited. The resulting configuration is described in Section 4.2. These results subsequently serve as a reference for the additional examples with reduced extent of flexibility. Subsequently, we restrict our numerical example to successively disable equipment flexibility, routing flexibility, and operation flexibility. The resulting configurations are presented and discussed in Sections 4.3, 4.4, and 4.5, respectively.

4.2 All flexibility types enabled

The best found solution for this numerical example with an objective value of 1,654,710 EUR and a gap of 8.31% to optimality was found in a computational time of 26 hours and is shown in Fig. 2. While 210,000 EUR are induced by station opening, 1,355,040 EUR are induced by resource deployment and the remaining transportation costs amount to 89,760 EUR. By analyzing the depicted configuration, some beneficial design characteristics can be derived. In the found solution, a station is opened at six of the nine possible locations. The opened stations are located next to each other in a compact manner without gaps to minimize the transport distances.

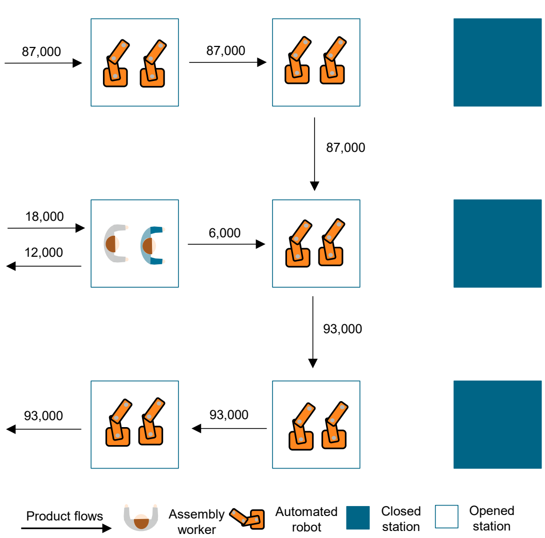

Figure 2. Solution with all flexibilities enabled

Two resources are assigned to each opened station, resulting in a maximum usage of space for resource deployment. While all ten automated assembly robots are deployed, only two of the ten available assembly workers are deployed (one of each group). Most of the products (87,000 of 105,000 units) follow the same route through the manufacturing system and are produced solely by using the automated robots. Accordingly, high utilization of those resources can be realized. Finally, it can be observed that the two assembly workers are assigned to the same station. As a tuple of workers, they are capable of executing all required operations. To this end, 12,000 units are exclusively produced in that station yielding an additional reduction of the transport distances. In the depicted solution equipment flexibility, material handling flexibility, and operation flexibility are exploited.

4.3 Equipment flexibility disabled

To compare the previous solution with an example with disabled equipment flexibility, we modified the capabilities of the resources. While in the previous example every assembly worker is able to execute five operations, in this example we restrict their capabilities to one operation each, so that each worker is exactly able to execute one different operation. Subsequently, we solved the example using the proposed model. The best found solution for this example with a gap of 3.23% to optimality was found in a computational time of 9 hours, is depicted in Fig. 3, and has an objective value of 2,053,980 EUR, consisting of 245,000 EUR for station opening, 1,682,560 EUR for resource deployment and 126,420 EUR for transportation costs.

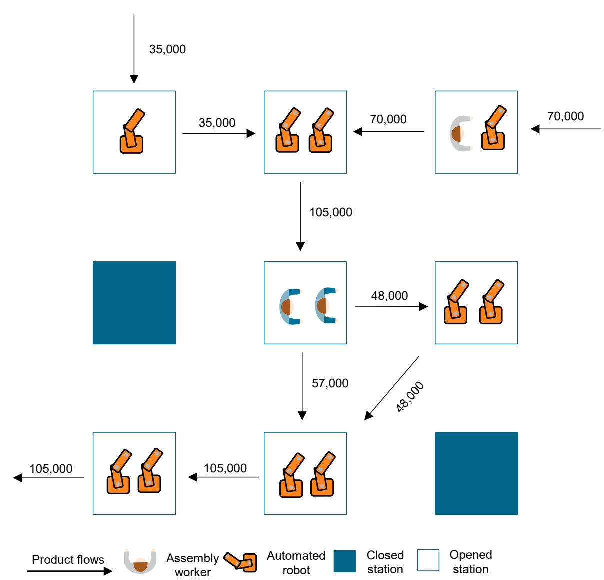

Figure 3. Solution with equipment flexibility disabled.

Compared to the previous example, some similarities can be identified: the configurations both can be described as compact to minimize transportation costs. The products still follow few routes through the manufacturing system during the production. The main difference between both configurations consists of the equipment selection. When disabling equipment flexibility, an additional assembly worker is deployed, also resulting in an additional station opening. With all flexibility types enabled, a tuple of assembly workers can be used to produce 12,000 units and therefore relieve the workload of the assembly robots. Considering the specialized assembly workers in this example, a tuple of workers cannot serve this purpose. Additionally, the transportation costs are increased by 20,335

EUR as 48,000 units cannot be transported to an adjacent station but need to be transported further and 35,000 units need to be transported starting from the additionally opened station, resulting in a longer distance to pass the shop floor.

4.4 Material handling flexibility disabled

To compare our reference solution from Section 4.2 with an example with disabled material handling flexibility, we modified the connections between stations. While in our reference example every station could be accessed from each station, we now limit the accessible stations of each station to one adjacent station. Thus, the stations can be considered serially arranged. Subsequently, we solved the example using the proposed model. The example was solved to optimality in a computational time of 33 minutes. The solution is depicted in Fig. 4 and has an objective value of 2,081,910 EUR, consisting of 245,000 EUR for station opening, 1,682,560 EUR for resource deployment and 154,350 EUR for transportation costs. When comparing this configuration with the solution of the reference example, costs for opening stations, costs for resource deployment, and transportation costs are increased: an additional station needs to be opened, an additional assembly worker needs to be deployed and the transport distance is increased. When disabling the flexible material transport among stations, products can only be transported to the next station when each previously required operation is already executed.

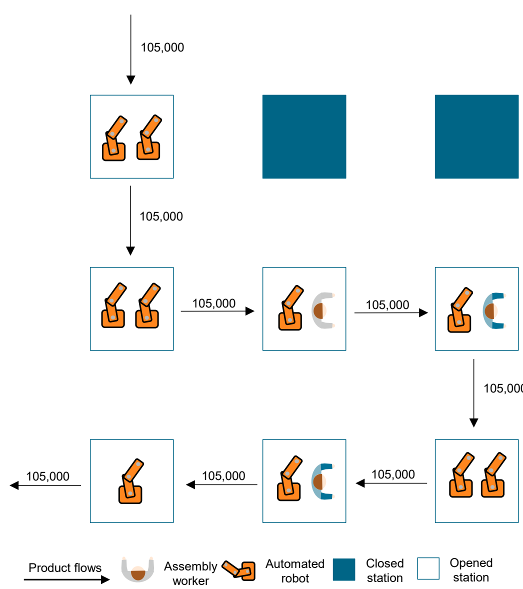

Figure 4. Solution with material handling flexibility disabled.

When a resource's capacity is fully utilized in one of the stations, another resource that is capable of executing this specific operation needs to be added to the adjacent station as no alternative routes are available. Therefore, additional resources need to be deployed and consequently additional stations need to be opened. Additionally, every product needs to pass the entire amount of serially arranged stations to receive the final operations in the last station resulting in increased transportation costs of the configuration. Finally, the existing equipment flexibility can only partially be exploited when disabling material handling flexibility.

4.5 Operation flexibility disabled

To compare the reference example with an example with disabled operation flexibility, we modified the precedence relations of the operations for each product. While in our reference example the operations needed to be fulfilled in accordance with the precedence graph depicted in Fig. 1, the precedence relations for this example are modified such that every operation has exactly one preceding and one succeeding operation, i.e., a strictly serial execution of operations in a predetermined manner is enforced for each product. The example was solved to optimality in a computational time of 23 minutes and is characterized by costs of 1,654,710 EUR. It is illustrated in Fig. 5.

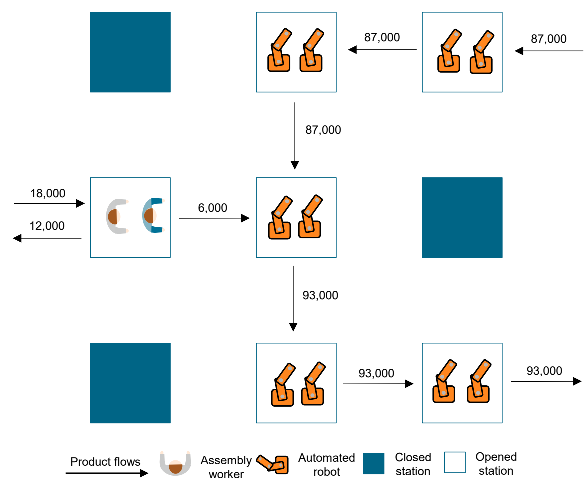

Figure 5. Solution with operation flexibility disabled.

While 210,000 EUR are induced by station opening, 1,355,040 EUR are induced by resource deployment and the remaining transportation costs amount to 89,760 EUR. The depicted configuration is similar to the solution of the reference example: the identic number of stations is opened, the same resources are deployed, and the same distances need to be passed during transport. Therefore, disabling operation flexibility has no impact in our case. This may, however, be due to the rather limited degrees of freedom in the considered precedence graph. Therefore, the impact of neglecting this flexibility type can be assumed to be limited in this example already beforehand. However, the effect of exploiting operation flexibility may be increased when considering products with higher degree of flexibility within the precedence relations.
A summarizing overview of the costs and its components for the four presented numerical examples is depicted in Table 1. Especially the total costs of the numerical examples with disabled equipment flexibility or disabled material handling flexibility are increased in comparison to the reference solution due to an additional station opening, an additional equipment deployment, and increased transport distances. The solution with equipment flexibility disabled and the solution with material handling flexibility disabled suffer from increased costs of 24.12% and 25.81% respectively in comparison to the solution with all flexibilities enabled.

Table 1. Resulting costs of the numerical examples

Costs in EUR	Station Costs	Equipment Costs	Transportation Costs	Total Costs
All flexibilities enabled	210,000	1,355,040	89,760	1,654,710
Equipment flexibility disabled	245,000	1,682,560	126,420	2,053,980
Material handling flexibility disabled	245,000	1,682,560	154,350	2,081,910
Operation flexibility disabled	210,000	1,355,040	89,760	1,654,710

5. CONCLUSION

In the contribution at hand, we investigated on the impact of equipment flexibility, material handling flexibility, and operation flexibility on the cost-oriented design of MMS by conducting numerical examples. The results indicate that especially equipment and material handling flexibility strongly affect the initial configurations of MMS and need to be exploited to derive beneficial configurations. While equipment flexibility is exploited to relieve specialized resources and tends to lead to fewer resources to be deployed, material handling flexibility allows for advantageous routing of products, thus reducing the transportation costs and enabling the further exploitation of equipment and operation flexibility.

In future work, the numerical examples need to be extended to consider larger instances from literature or industry to further validate our findings regarding the impact of the three flexibility types. To cope with high solution times, a suitable solution approach needs to be developed. Moreover, a comparison of the performance of the derived configurations of MMS to more efficient means of production, e.g., assembly lines, needs to be developed to further estimate the economic impact of flexibility on the design of manufacturing systems in general and MMS in particular.

For additional information on the modified model formulation presented in Schumacher et al. (2021) please access the supplementary information via: 10.5281/zenodo.5569292

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