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Dynamic layout design for scalable reconfigurable manufacturing systems

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ABSTRACT

Reconfigurable manufacturing systems (RMS) is a type of manufacturing system in which the structure and resources are changed in a fast and cost-effective way to achieve the required capacity and performance at the required time. The layout design problem in an RMS refers to the challenge of determining the optimal physical arrangement of machines, equipment, and resources within the manufacturing facility to ensure flexibility, scalability, and efficiency. The key objective is to create a layout that supports rapid reconfiguration to accommodate changes in product types, production volumes, and processes while minimising downtime, costs, and material handling. In this paper a novel approach to dynamic facility layout design within scalable RMS is proposed which focuses on reconfigurable machine tools (RMT) to accommodate varying production requirements for different products. A new mixed integer linear programming (MILP) model is proposed which enables adjustment of the facility layout to align with fluctuating production volumes and product mixes in different production periods. Hypothetical Case studies are designed to demonstrate the effectiveness of the approach, highlighting improvements in operational flexibility, system design cost, throughput, and resource utilisation. The findings contribute to the development of RMS that can adapt to changing market demands, ensuring competitive advantage in manufacturing industries.

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Reconfigurable manufacturing systems; reconfigurable machine tools; dynamic layout design; machine configuration; optimisation

1. Introduction

In today's highly competitive manufacturing landscape, the ability to rapidly respond to shifting market demands and product variations is essential for maintaining a competitive edge. To address this, scalable and reconfigurable manufacturing systems (RMS) have emerged as a viable solution, offering the flexibility and adaptability required to efficiently manage diverse part families and varying production volumes (Rezaee and Moghaddam 2025; Zhu et al. 2022).

RMSs are characterised by their ability to quickly adjust production capacity and functionality through the use of modular components. Among these, modular reconfigurable machine tools (RMTs) stand out as key enablers of this adaptability, allowing manufacturers to reconfigure production lines to meet specific requirements with minimal downtime (Huang, Huang, et al. 2024; Huang, Tan, et al. 2024; Morgan et al. 2021). However, while the reconfigurability of machinery has been extensively studied, there has been limited focus on the facility layout design within scalable RMS, particularly in the context of incorporating RMTs. The layout of a manufacturing facility plays a crucial role in determining the efficiency of the entire production process, affecting factors such as material flow, lead times, and overall throughput (Maganha, Silva, and Ferreira 2019). The static facility layout problem (SFLP) involves arranging departments within a facility, to optimise workflow and efficiency. When material flow between departments changes over time, the problem becomes dynamic, requiring a layout plan for multiple time periods. Solving the SFLP separately for each period can lead to high rearrangement costs, so the dynamic facility layout problem considers both material handling and rearrangement costs to find an optimal series of layouts for different periods (Pérez-Gosende, Mula, and Díaz-Madroñero 2021).

Approaches to solving dynamic facility layout problems generally fall into two main categories: adaptive (or flexible/agile) approaches and robust approaches. The adaptive approach is based on the premise that layouts can be adjusted over time with minimal rearrangement costs, allowing for easy relocation of machines as needed. In contrast, the robust layout approach operates under the assumption that rearrangement costs are prohibitively high, and therefore seeks to minimise total

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material handling costs across all periods by maintaining a single, optimised layout (Pourvaziri et al. 2022).

The main problem addressed in this paper is the dynamic layout design of an RMS which is capable of producing a family of parts. In this manufacturing system, Reconfigurable Machine Tools (RMTs) with modular structures are used which means it is possible to change the configuration of these machines in different production periods by changing their auxiliary modules. Therefore, it is possible to respond to changes in demand in each production period by purchasing new RMTs or changing the configuration of the existing ones.

The implemented approach in this paper is based on mathematical modelling. The presented Mixed Integer Linear Programming (MILP) model takes into account the assumptions of the problem and guarantees that the purchase, configuration change, and location selection of the RMTs are done in a way that, while responding to the fluctuations of demand in various periods of production, the sum of all incurred costs are minimised. It is noteworthy to mention that robust approach is followed in this paper for layout design since if an RMT is purchased and installed in a specific location, its location remains unchanged over different production periods and only its auxiliary modules can be added and/or removed.

The rest of the paper is organised as follows: In Section 2, a thorough literature review is provided and the existing gaps in the literature are highlighted. In Section 3 the proposed approach for dynamic robust layout design is introduced and the problem is formulated as an MILP model. To test the model, two arbitrary examples are designed and solved with the proposed mathematical formulation. Furthermore, a hypothetical case is solved in this section to demonstrate the advantages of RMT reconfiguration in facility layout design. Analysis and comparison of results and sensitivity analysis on the most important problem parameters are performed in Section 4. Finally, in Section 5, conclusions and future areas of study are presented.

2. Literature review

RMS facility layout design has always been an interesting and yet challenging problem that has helped the better realisation of the RMS concept. The literature on this subject can be mainly classified into three categories. The first group consists of papers focussing on selecting the type, number and configuration of the RMTs used to satisfy the demand in an RMS. Papers in the second group are mainly focussed on the layout design of machinery and departments in an RMS. The third group of papers concentrate on the layout design of Reconfigurable Cellular Manufacturing Systems.

2.1. Selecting the type, number and configuration of RMTs

Research on RMS emphasises optimising machine selection, configuration, and performance to meet varying production demands. A common assumption across studies is that a list of candidate RMTs is available for designing the RMS. Early works, such as that by Youssef and ElMaraghy (2007) proposed models using the universal generating function (UGF) technique to optimise RMS configuration, employing tabu search (TS) and genetic algorithms (GA) to solve the problem and determine optimal layouts and operations. Similarly, Dou, Dai, and Meng (2009) introduced a precedence graph approach to generate and evaluate configurations for single-product flow lines (SPFLs), identifying optimal and near-optimal solutions.

Several studies focussed on multi-objective optimisation to balance system costs, reconfigurability, and performance. Goyal, Jain, and Jain (2012) proposed indices for operational capacity and reconfigurability and used NSGA-II and TOPSIS to rank solutions while (Goyal, Jain, and Jain 2013) introduced a Responsiveness Index to enhance system adaptability. Bensmaine, Dahane, and Benyoucef (2013) optimised machine selection by minimising total costs and completion times using NSGA-II and Benderbal, Dahane, and Benyoucef (2015) added considerations for machine unavailability through a Robustness Index.

Flexibility and modularity were central to the work of Haddou Benderbal, Dahane, and Benyoucef (2017) and Haddou Benderbal, Dahane, and Benyoucef (2018), who introduced indices like flexibility and modularity to evaluate systems under demand uncertainty. Their models aimed to optimise system configurations, minimise costs, and address fluctuating demands by adjusting modular components. These problems were solved using advanced algorithms like Archived Multi-Objective Simulated Annealing (AMOSA).

Demand-based configuration optimisation was explored in-depth by Moghaddam, Houshmand, and Fatahi Valilai (2018); Moghaddam et al. (2020). In 2018, they proposed a two-phase approach that handled uncertainty in demand by recommending initial configurations and suggesting modifications over time. In 2020, they refined this into an integrated model that used full demand data to minimise costs for producing part families, achieving superior results compared to the earlier approach. These studies highlight a progression from foundational optimisation techniques to advanced multi-objective models, addressing key challenges in RMS design such as cost-efficiency, adaptability, and response to uncertainty.

2.2. Layout design of machinery and departments in RMSs

Research on the layout of machinery and departments in Reconfigurable Manufacturing Systems (RMSs) explores optimising configurations to improve adaptability, efficiency, and cost-effectiveness. Maganha and Silva (2017) conducted a comprehensive review of the Reconfigurable Layout Problem, defining reconfigurable layouts as systems that can frequently and easily adjust their configurations to meet changing demands. The key characteristics of such layouts include reusability, responsiveness, adaptability, dynamicity, flexibility, reliability, and modularity.

Xiaobo, Jiancai, and Zhenbi (2000) proposed a stochastic framework for RMS layout design, addressing optimal configurations under uncertain demand, part family selection, and performance measurement. The follow-up work by Xiaobo, Wang, and Luo (2000) developed probabilistic models to identify optimal configurations for manufacturing specific products, introducing two algorithms, Iterative Procedure with Simulation Approximation (IPSA) and Iterative Procedure with Exact Calculation (IPEC). Subsequent studies (Xiaobo, Wang, and Luo 2001a, 2001b) tackled part family selection and introduced a semi-Markov process to evaluate RMS performance with proposed solution approaches.

Guan, Qiu, and Yang (2012) examined layout design in RMSs using automated guided vehicles (AGVs) for material handling, proposing a mathematical model to minimise handling costs. Zheng et al. (2013) complemented this by using simulation to design layouts that reduce overall system costs, including those related to machine installation, tool management, and transportation.

Azevedo, Crispim, and de Sousa (2013) emphasised the importance of flexible and reconfigurable layouts in complex manufacturing systems, distinguishing between large-scale changes (department relocation) and small-scale adjustments (within-department reconfigurations). They proposed mixed-integer programming (MIP) models to address these challenges. Subsequent studies by Azevedo, Crispim, and de Sousa (2016, 2017) refined the approach by optimising department locations to minimise material handling and reconfiguration costs while considering interdepartment proximity and location suitability based on specific requirements.

2.3. Layout design of cellular RMS

Cellular reconfigurable manufacturing systems (CRMS) are composed of reconfigurable manufacturing cells containing RMTs, CNC machines, setup stations, automated material handling systems, and storage systems. The design of CRMS layouts focuses on grouping RMTs and CNC machines into cells to meet demand while ensuring the correct sequence of operations for part production.

Pattanaik, Jain, and Mehta (2007) introduced a multi-objective model to minimise inter-cell movements and auxiliary module changes, using the non-dominated sorting genetic algorithm (NSGA), which was later refined by Pattanaik and Kumar (2010) with the NSGA-II for enhanced optimisation.

Xing et al. (2009) employed a neural network-based method to address cell formation, grouping parts into families and using artificial neural networks (ANNs) to identify candidate reconfigurable cells and solve scheduling and layout problems. Yu et al. (2012) addressed part grouping and loading issues in CRMS by proposing an integer linear programming (ILP) model and implementing two iterative algorithms, LPT-IA and MUL-IA, to allocate parts to RMCs and assign operations and tools within cells.

Eguia et al. (2013) tackled the simultaneous problems of cell formation and part family scheduling for CRMS. They developed a MILP model to assign part families to cells and schedule operations effectively. Building on this, Eguia et al. (2017) proposed a two-phase approach for CRMS design: the first phase involved grouping machines into cells using an ILP model, while the second phase determined routeing mixes, tool allocations, and module placements using an MILP model. The summary of all reviewed papers can be seen in Table 1.

Based on the reviewed literature, there are only a few examples of systems capable of generating a layout for RMS. Few researchers have focussed on solving the layout design problem specifically for RMS and our review did not identify any significant research that simultaneously addresses both layout design and RMT reconfiguration. Hence, the main contributions of this paper can be summarised as follows:

- Introducing a new method for designing dynamic and robust facility layouts within scalable RMS by highlighting the use of RMTs to accommodate varying production requirements in a cost-effective and timely manner.
- Proposing a new MILP model for dynamic facility layout problem of RMS, considering possible RMT transformations by adding/removing auxiliary modules.

3. Overview of the proposed method

Elaborating the proposed approach, the following assumptions are made in this study regarding the production system.

3.1. Assumptions

An RMS, by definition, must be designed to manufacture all parts within a specific part family. The features of each part may necessitate specific operations such as milling, boring, drilling, tapping, and reaming. In this study, the focus is on a single part family, where the operation sequences for different parts are similar and predetermined before the system design. The RMS remains idle between production periods, and production halts during reconfiguration phases.

As previously noted, RMTs are key components of RMS. These machines consist of fixed basic modules and changeable auxiliary modules. In this study, all resources are considered to be reconfigurable, and altering the configuration of an RMT requires modifying one or more auxiliary modules at a specific cost.

The system's goal is to satisfy products' demand within the family of parts, in such a way that the total cost in all production periods is minimised. The system is considered empty and idle at the beginning of the planning horizon, that is, there are not any RMTs in the system. The possible locations to install RMTs and the entry and exit points of Work in Progress (WIP), i.e. workshop doors are predetermined. When production starts in the first period, a number of RMTs are purchased. In the following periods and with changes in the demand of each part

Table 1. Summary of the literature review.

Author(s) (year)	Objective function	Constraints	Problem type in RMS	Mathematical model	Opt. Algorithm
Xiaobo, Jiancai, and Zhenbi (2000)	Min Cost	–	Part Family Selection	Stochastic	–
Xiaobo, Wang, and Luo (2000)	Max Profit	–	Part Family Selection	Stochastic	IPEC & IPSA
Xiaobo, Wang, and Luo (2001a)	Max Profit	–	Part Family Selection	Stochastic	PRH & PMH
Xiaobo, Wang, and Luo (2001b)	Max Profit	–	Part Family Selection	Stochastic	PRH & PMH
Pattanaik, Jain, and Mehta (2007)	Min Inter-cellular Movements	Cell Size	Cellular Layout Design	MOP	NSGA
		Min Changes in Auxiliary Modules			
Youssef and ElMaraghy (2007)	Min Capital Cost	Production Stages	Configuration Selection	–	TS & GA
	Max Machine Availability	Demand Machines Operations' Precedence Capital Operations' Feasibility			
Dou, Dai, and Meng (2009)	Min Cost	Operation-Machine Allocation Space Capital Precedence	Configuration Design	ILP	CSKP
Xing et al. (2009)	–	–	Cellular Layout Design	–	–
Pattanaik and Kumar (2010)	Min Inter-cellular Movements	Cell Size	Robust Cellular Layout Design	MOP	NSGA-II
		Min Changes in Auxiliary Modules			
Goyal, Jain, and Jain (2012)	Min Cost	Machine-Station Assignment	Configuration Selection	MOP	NSGA-II & TOPSIS
	Max Operational Capacity	Demand Max Machine Reconfigurability			
Guan, Qiu, and Yang (2012)	Min Material Handling Costs	No. of Workstations	Layout Design	MIP	RELM
	Min Reconfiguration Costs	Input & Output Flow Equality			
Yu et al. (2012)	Min Max Workload	Demand Required Operations Tool Capacity No. of Available Tools Tool Life Operation-Machine Assignment	Cellular Layout Design	ILP	LPT-IA & MUL-IA
Azevedo, Crispim, and de Sousa (2013)	Min Material Handling Costs	Department Area	Layout Design	MIP	–
	Min Reconfiguration Costs Max Layout Efficiency	Capacity of each Location Machine Capacity Demand			

Table 1. Continued.

Author(s) (year)	Objective function	Constraints	Problem type in RMS	Mathematical model	Opt. Algorithm
Bensmaine, Dahane, and Benyoucef (2013)	Min Machine Usage Costs	Machine Capability	Configuration Selection	MOP	NSGA-II
	Min Tool Usage Costs	Precedence			
	Min Reconfiguration Costs	Tool Capability			
		Min Tool Change Costs			
		Min Processing Time			
		Min Tool Change Time			
		Min Reconfiguration Time			
Eguia et al. (2013)	Min Reconfiguration Costs	No. of Part Groups	Cellular Layout Design	MILP	TS
	Min Under-utilisation Costs	Production of Part Families			
Goyal, Jain, and Jain (2013)	Max Responsiveness Index	–	Configuration Selection	–	–
Zheng et al. (2013)	Min Costs	–	Layout Design	–	–
Benderbal, Dahane, and Benyoucef (2015)	Min Reconfiguration Time	Allocation of Operations	Configuration Design	MOP	NSGA-II
	Min Tool Change Time	Precedence			
	Min Processing Time	Tool Capability			
		Min Disruption			
Azevedo, Crispim, and de Sousa (2016)	Min Material Handling Costs	One Department Per Location	Layout Design	–	–
	Min Reconfiguration Costs	Area of Locations	Layout Design	–	–
	Max Departments' Proximity	Transportation Capacity	Layout Design	–	–
Azevedo, Crispim, and de Sousa (2017)	Min Material Handling Costs	One Department Per Location	Dynamic Layout Design	MIP	–
	Max Departments' Adjacency	Area of Locations			
	Min Reconfiguration Costs	Transportation Capacity			
	Min Unusable Locations	Department Location			
Eguia et al. (2017)	Min Under-utilised Machines	Machine Allocation to Cell	Cellular Layout Design	ILP & MILP	–
	Min Inter-cellular Movements	Process Allocation to Cell			
	Min Inventory Costs	Zero Inventory			
		CNC Tool, RMT Modules			
		Maximum Workload			
Haddou Benderbal, Dahane, and Benyoucef (2017)	Max Flexibility Index	Machine Unavailability	Configuration Design	MOP	NSGA-II
	Min Production Time	Operation Feasibility			
		Precedence			
Haddou Benderbal, Dahane, and Benyoucef (2018)	Max Modularity	Operation Allocation	Configuration Design	MOP	AMOSA & TOPSIS
	Min Total Time	Precedence			
	Min System Costs	Tool Capability			
Moghaddam, Houshmand, and Fatahi Valilai (2018)	Min Purchasing Costs	RMT Capacity	Configuration Design	MILP	–
	Min Reconfiguration Costs	Products' Demand			
Moghaddam et al. (2020)	Min Purchasing Costs	RMT Capacity	Configuration Design	MILP	–
	Min Reconfiguration Costs	Products' Demand			
This Paper	Min Purchasing Costs	RMT Capacity	Dynamic Layout Design	MILP	–
	Min Reconfiguration Costs	Products' Demand			
		Min Material Handling Costs			

type, the configuration of some existing machines would be changed by adding and removing auxiliary modules. Other RMTs may also be purchased at the beginning of each production period.

It should be noted that when an RMT is purchased, its location in the production system must be specified. As mentioned earlier, machines (if required) are purchased at the beginning of the production period to perform a specific operation, and their configurations may be changed in subsequent production periods. Therefore, the location of each machine is determined by considering the possible changes in its configuration to perform different operations in future production periods, as well as WIP flows. After an RMT is purchased and installed in a specific location, its location cannot be changed (for technical reasons) in future periods.

In general, three types of costs are considered in this study: the cost of purchasing new RMTs, the cost of adding and removing modules, and the cost of material handling. The proposed model aims to determine, for all production periods, the reconfigurable machines that must be purchased, their permanent positions for installation, their required reconfiguration, and the material flow in between them, in order to supply the demand of all parts within a part family by minimising total system design cost.

Every RMT has two types of material flow: *incoming* and *outgoing*. The incoming material flow of each RMT is equal to its outgoing flow. The total flow of any RMT (which is equal to the sum of its incoming or outgoing flow) never exceeds the total capacity of that machine while performing the corresponding operation. If the operation performed by one RMT (such as A) is a direct prerequisite for the operation performed by another RMT (such as B), there is a possibility of material flow between these two RMTs (from A to B). Otherwise, there will be no material flow between them.

All the examples discussed in this paper are designed using the information in Table 2. In this table, the information of available hypothetical RMTs, their different configurations, the production rate of each configuration, the cost of purchasing each RMT and the list of basic and auxiliary modules for each configuration are given.

Sets

The sets that are used in the proposed mathematical formulation are as follows:

- P: Set of all possible locations where machines can be installed.
- J: Set of all possible machine configurations.
- L: Set of all required production processes (Operations).
- T: Set of all production periods.

Indices

Based on the defined sets, the following are the indices used in the mathematical formulation:

- p: Location of a reconfigurable machine.
- j: Configuration of a reconfigurable machine.
- l: A certain operation.
- t: A certain time period.

Input Parameters

All input parameters required for the formulation are as follows:

- X_p: The x coordinate of location p.
- Y_p: The y coordinate of location p.
- C_j: Cost of purchasing an RMT with configuration j.
- d_l^t: The demand for operation l in period t.

Table 2. RMT configurations and their production rates, cost, basic and auxiliary modules used in the examples (Goyal, Jain, and Jain 2012).

M_j	mc_i^j	Operation																				Cost	Basic modules	Auxiliary modules
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			
		Production rate in parts/hour for each operation																						
M_1	mc_1^1	–	–	–	14	–	–	–	12	–	–	–	8	–	–	–	18	–	–	–	–	750	1, 5	13, 17, 21, 22
	mc_1^2	–	–	–	–	15	–	–	–	20	–	–	–	–	–	–	–	–	16	–	–	955		12, 13, 15, 20, 21
	mc_1^3	–	–	20	–	–	–	15	–	–	–	–	–	–	–	–	25	–	–	–	–	1025		11, 17, 18, 20, 21
	mc_1^4	–	–	–	–	–	–	–	–	–	15	–	–	–	–	–	–	–	–	12	–	840		15, 17, 18
M_2	mc_2^1	14	–	–	–	–	15	–	–	–	–	–	12	–	–	–	–	–	–	–	20	1215	2, 4, 8	11, 13, 16, 22, 24
	mc_2^2	–	15	–	–	–	–	–	–	–	–	–	–	14	–	15	–	–	–	–	–	910		14, 16, 19
	mc_2^3	–	–	25	–	–	–	–	18	–	–	25	–	–	–	–	–	20	–	–	–	1140		13, 19, 24
	mc_2^4	–	20	–	–	20	–	18	–	–	–	–	–	–	24	–	–	–	–	–	–	1350		11, 13, 15, 18, 24
	mc_2^5	–	–	–	18	–	–	–	–	–	–	–	–	20	–	–	–	–	14	–	15	1050		11, 14, 18
M_3	mc_3^1	–	12	–	–	–	–	–	–	15	–	–	10	–	–	–	–	10	–	–	–	780	3, 5, 7	11, 12, 14, 16, 18
	mc_3^2	30	–	–	26	–	–	–	24	–	–	24	–	–	–	20	–	35	–	15	–	1825		12, 13, 14, 17, 19, 20
M_4	mc_4^1	–	–	–	–	–	25	–	–	–	30	–	–	–	–	–	–	–	25	–	–	1350	4, 9	18, 23
	mc_4^2	25	–	–	–	–	–	–	–	–	–	–	22	–	–	–	–	30	–	–	26	1500		11, 15, 18, 20, 21
	mc_4^3	–	18	–	25	–	–	–	16	–	–	–	–	22	–	–	28	–	–	20	–	1400		13, 14, 17, 18
M_5	mc_5^1	16	–	–	–	–	–	15	–	–	–	15	–	–	18	–	–	–	18	–	–	900	3, 6, 10	20, 22
	mc_5^2	–	–	24	–	20	–	–	–	–	25	–	–	–	–	–	–	24	–	–	20	1175		16, 17, 19, 20, 25
	mc_5^3	–	–	–	24	–	–	–	–	30	–	–	–	–	–	18	–	–	–	–	–	1230		11, 12. 13, 15, 22
	mc_5^4	20	–	–	–	–	22	14	–	–	–	–	–	–	20	–	16	–	–	18	–	1175		20, 22, 24

Legend: mc_i^j = Machine i in its j^{th} configuration

MHC: The cost of moving one unit of product one unit of length.

B_{jl}: The maximum capacity of an RMT with configuration j when performing operation l.

$r_{jj'}$: Cost of changing an RMT configuration from j to j'. This is calculated as sum of the costs of adding/removing modules to/from the RMT.

$q_{ll't}$: A binary parameter which equals 1 if operation l in period t is a direct predecessor of operation l'.

$D_{pp'}$: Manhattan distance between two locations p and p' which is calculated as follows: $D_{pp'} = |X_p - X'_p| + |Y_p - Y'_p|$.

Decision Variables

The decision variables used in the formulation are as follows:

x_{pjl}: A binary decision variable which equals 1 if a machine with configuration j is purchased for operation l and installed in location p.

s_{pjlt}: A binary decision variable which shows the state of machine p. It equals 1 when the machine that is located in p and has configuration j, performs operation l in period t.

$y_{pj'jlt}$: A binary decision variable which equals 1 when at the beginning of period t the machine in location p is reconfigured from j' to j and then performs operation l.

v_{plt}: An integer decision variable which shows the total input (output) flow of the RMT in location p which performs operation l in period t.

$v'_{plp'l't}$: An integer decision variable which shows the input flow in period t from the machine in location p performing operation l to the machine in location p' performing operation l'.

3.2. Mathematical formulation

Based on the above input description, a novel MILP formulation is proposed as follows for RMS layout design and reconfiguration in different production periods. As stated in the assumptions, for technical reasons, the location of the RMTs in the production system does not change, but the configuration of each RMT and the operations it performs may change in different production periods. For this reason, in most variables, the p index is at the beginning; it is a characteristic of an RMT that does not change during production periods, and with it, the status of each RMT can be tracked in different periods.

$$\min \left\{ \sum_{p\in P}\sum_{j\in J}\sum_{l\in L} C_j x_{pjl} + \sum_{p\in P}\sum_{l\in L}\sum_{j\in J}\sum_{j'\in J}\sum_{t\in T} r_{jj'} y_{pj'jlt} + \sum_{t\in T}\sum_{p\in P}\sum_{l\in L}\sum_{p'\in P}\sum_{l'\in L} v'_{vlp'l't} D_{pp'} MHC \right\} \quad (1)$$

Subject to:

$$s_{pjlt} \le \sum_{j'\in J}\sum_{l'\in L} x_{pj'l'} \quad \forall\, p,j,l,t \quad (2)$$

$$\sum_{j\in J}\sum_{l\in L} s_{pjlt} \le 1 \quad \forall\, p,t \quad (3)$$

$$x_{pjl} \le s_{pjlt} \quad \forall\, p,j,l,t=1 \quad (4)$$

$$s_{pjlt} \le \sum_{l'\in L} s_{pjl'(t-1)} + \sum_{j'\in J} y_{pj'jlt} \quad \forall\, p,j,l,t\neq 1 \quad (5)$$

$$\sum_{j'\in J} y_{pj'jlt} \le s_{pjlt} \quad \forall\, p,j,l,t \quad (6)$$

$$y_{pj'jlt} \le \sum_{l'\in L} s_{pj'l'(t-1)} \quad \forall\, p,j',j,l,t\neq 1 \quad (7)$$

$$v_{plt} \le \sum_{j\in J} s_{pjlt} B_{jl} \quad \forall\, p,l,t \quad (8)$$

$$\sum_{p\in P} v_{plt} \ge d_l^t \quad \forall\, l,t \quad (9)$$

$$v'_{plp'l't} \le v_{plt} q_{ll't} \quad \forall\, l,p,l',p',t \quad (10)$$

$$v'_{plp'l't} \le v_{p'l't} q_{ll't} \quad \forall\, l,p,l',p',t \quad (11)$$

$$\sum_{p'\in P}\sum_{l'\in L} v'_{plp'l't} = \sum_{p'\in P}\sum_{l'\in L} v'_{p'l'plt} \quad \forall\, t, \; p\neq p_{End}, l\neq l_{End}, p\neq p_{Start}, l\neq l_{Start} \quad (12)$$

$$\sum_{p'\in P}\sum_{l'\in L} v'_{plp'l't} = \sum_{p'\in P}\sum_{l'\in L} v'_{p'l'plt} \quad \forall\, t, p\neq p_{End}, l\neq l_{End}, \quad (13)$$

$$\sum_{p'\in P}\sum_{l'\in L} v'_{p'l'plt} = v_{plt} \quad \forall\, t, p=p_{End}, l=l_{End} \quad (14)$$

$$v_{plt}, v_{plp'l't} \ge 0 \quad \forall\, p,l,p',l',t \quad (15)$$

$$x_{pjl}, s_{pjlt}, y_{pjj'lt} \in \{0,1\} \quad \forall\, j,j',p,p',l,l',t \quad (16)$$

In the above formulation, (1) is the objective function which constitutes of three types of costs: cost of purchasing a new RMT, cost of machine reconfiguration, and cost of material handling in between RMTs. The goal is to minimise the total cost. Constraint (2) indicates that the decision variable for the machine located in p is 1 if and only if that machine is purchased and installed in the corresponding position. Constraint (3) shows that an RMT that is located in p during period t can only perform one operation (l) and has only one configuration (j).

Constraint (4) indicates that for the first production period, if an RMT with configuration j is purchased to perform operation l and is installed in location p, its corresponding state variable (s_{pjlt}) equals 1 as well. Constraint (5) shows that for $t \neq 1$, s_{pjlt} equals 1 if and only if the RMT in location p had the configuration j in the previous period or has changed its configuration to j at the beginning of period t. Constraint (6) indicates that if at the beginning of period t, the configuration of the RMT located in p changes to j for performing operation l, (s_{pjlt}) would be equal to 1. Constraint (7) guarantees $y_{pj'jlt}$ equals 1, if and only if the RMT located in p has configuration j' in period $t-1$.

Constraint (8) indicates two major points: first, the value of the flow variable of the RMT located in p performing operation l is non-zero if the state variable of this RMT with one of the configurations performing l is non-zero. Second, the value of this variable will never be greater than the RMT capacity performing operation l. Constraint (9) is concerned with demand fulfilment; the sum of the flow of all RMTs performing operation l in period t must be greater than the operation's demand in that period.

Constraints (10) and (11) indicate that the flow between two RMTs is greater than zero only when these two RMTs perform two consecutive operations and the flow must be less than the total flow of the RMT with the outgoing flow and the RMT with the incoming flow. Constraint (12) guarantees the equality of the incoming and outgoing flow for each RMT.

It should be noted that since there are no machines before and after the RMTs performing the first and last operations of the production process, the equation of material flow does not hold in the normal state. For this reason, a start machine is placed before the RMTs that perform the first operation, and an end machine is placed after the RMTs that perform the last operation. These two machines are dummies and exist solely to balance the material flow of the system. For simplicity, it is assumed that the start and end machines have separate configurations (j_{Start} and j_{End}) and perform specific operations (l_{Start} and l_{End}). The production capacity of these two machines to perform l_{Start} and l_{End} is considered to be equivalent to the maximum material flow of the system in the entire production periods, and their locations are considered to be at the inbound and outbound of the RMS respectively (p_{Start} and p_{End}).

Constraint (13) shows that the total flow for an RMT is equal to the sum of all its outgoing flows. Constraint (14) indicates that since the dummy machine "End" does not have any outgoing flows, its total flow is equal to the sum of all incoming flows. Finally, constraints (15) and (16) show the feasible domains of all defined variables.

3.3. Numerical examples

In this section two different examples are created to show explicitly how the proposed formulation works. In the first example (for simplicity) a single part is considered to be manufactured. In the second example, the layout design problem is solved for a part family.

3.3.1. Example 1: RMS layout design for a single part

In this example, it is assumed that a single part is scheduled to be produced during four different production periods. Based on the information provided in Table 2, this hypothetical part requires operations 5, 1, and 17 (in that order). The demand requirements for the part in four consecutive production periods are 50, 60, 80, and 100 parts per hour respectively. The cost of adding and removing modules are 50 and 25 dollars per module. The cost of material handling for each part is 4 dollars per distance unit. Layout of the empty system is shown in Figure 1. As can be seen, 16 different locations are available. Dotted rectangles 17 and 18 are inbound and outbound doors used for l_{Start} and l_{End} respectively. The proposed model solved this problem using GAMS V.25.1.2 software on an Intel(R) Core(TM) i7-6700HQ CPU @2.60 GHz system in 11,254 s.

Figure 2(a–d) show different RMS layouts during all four production periods. As can be seen in Figure 2(a), during the first production period (where the demand rate is 50 parts/hour), 12 RMTs are purchased and are located in spots 1 to 12 respectively. In each of the white rectangles with solid lines the triple (p, j, l) shows the location of the RMT, the configuration of the RMT, and the operation performed by the RMT, during the first period. For example (1, mc_5^2, 5) shows that the RMT located in spot 1 has the configuration mc_5^2 and performs operation number 5. The dotted rectangles 13–16 in Figure 2(a) represent the empty locations where no RMT was installed. The arrows and the numbers above/below them show the exact flow between RMTs. Total cost of purchasing new equipment is \$11,025 and total material handling cost is \$1792.

In the second period, the demand rate is increased to 60 parts/hour hence some RMTs (shown by grey rectangles in Figure 2(b)) were reconfigured to perform a different operation or, in some cases, the exact same operation with a higher production rate. The white rectangles in Figure 2(b) with incoming and outgoing flows are the RMTs that remained unchanged from the previous period. The white rectangles with no incoming and outgoing flows are the RMTs that were idle during the

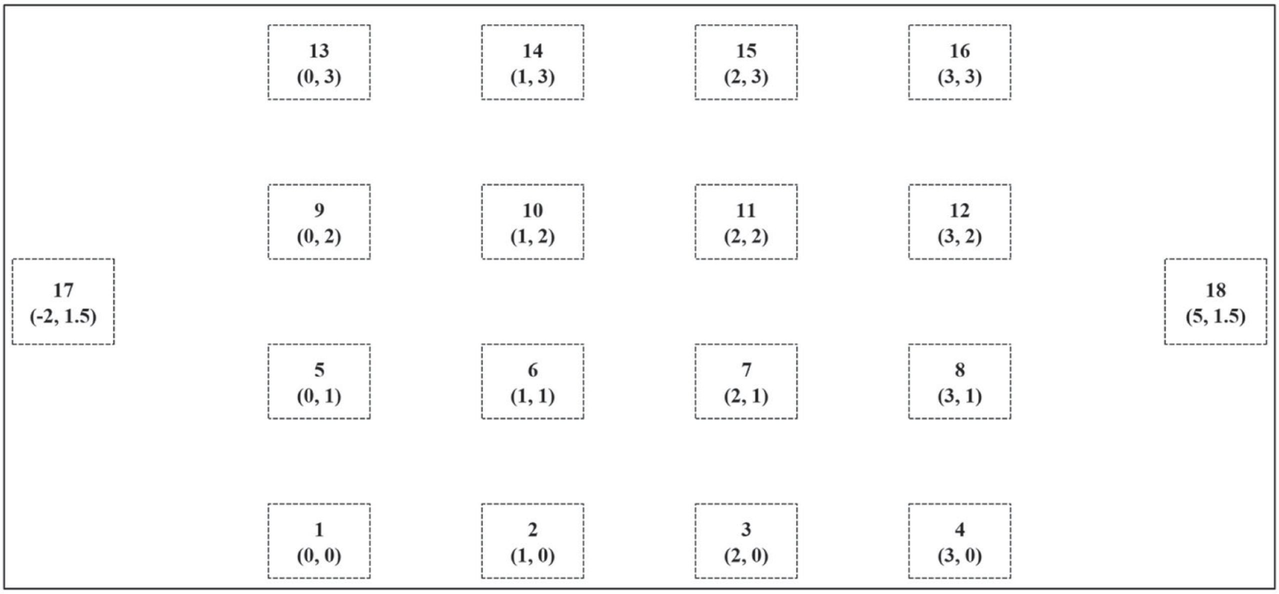


Figure 1. Layout of the empty system for the first numerical example.

second production period. Total cost of purchasing new equipment is zero in this period since no new RMTs are purchased. Total cost of RMT reconfiguration is $1100 and total material handling cost is $1960.

In the third production period where the demand rate is 80 parts/hour, only one RMT is idle and configuration of two RMTs have changed (shown in Figure 2(c)). Total cost of RMT reconfiguration is $550 and total material handling cost is $2760. In the final production period, the demand rate is 100 parts/hour, all RMTs are working and two RMTs have changed their configuration (Figure 2(d)). Total cost of RMT reconfiguration is $275 and total material handling cost is $3620.

The whole layout planning is performed in such a way that the type of RMTs purchased, the installation location of these RMTs, configuration changes in each production period, and the amount of material flow in between RMTs are optimal. The final cost of designing this system in four production periods is $23,082. It is noteworthy to mention that in all four production periods, the location of the RMTs performing the initial operation (5) is close to the entrance door (location 17). Similarly, the final operation (17) is performed on the RMTs closest to the exit door (location 18). Also, all 12 RMTs in this system are located near each other and are not scattered in the 16 available locations for installation. This shows the effect of material handling cost when permanent locations are selected by the model for RMTs. Also, in the first period, 12 RMTs are purchased to meet the demand of 50 parts/hour, until the demand is doubled (i.e. 100 parts/hour) in the final production period, the system is able to respond to the incremental increase in demand only by changing the configuration of the existing RMTs; this shows the scalability of the designed RMS.

3.3.2. Example 2: RMS layout design for a part family

In this example, RMS layout is designed for a family of products in four different production periods. Since parts that belong to a product family have similar features, they require similar operations while moving forward in a production line. The example part family consists of three different hypothetical parts (A, B, and C) with similar operation sequences and different demand rates as shown in Table 3. In this table, operation sequences are arbitrary, and each is based on the information presented in Table 2. As can be seen, operations 2, 12, are common between all three parts. Operation 11 is common between the two parts B and C and operation 8 is only performed on part C. The costs of material handling and module replacement is similar to the previous example.

Based on the information provided in Table 3, a total of 5 different operations are performed on all parts. It is noteworthy to mention that for producing a single part of the family, all required operations must be performed based on the demand/hour requirements of that part. For example, in the illustrated example of this section, demand rate of part B in the first production period is 50 parts/hour. Therefore, during the first production period, RMTs on which operations 2, 12, and 11 are performed, must be capable of operating with the rate of at least 50 parts/hour. The required production capacity for each operation and during each period is shown in Table 4.

The solution to the second example was obtained in 25,887 s on the exact same operating system used for the

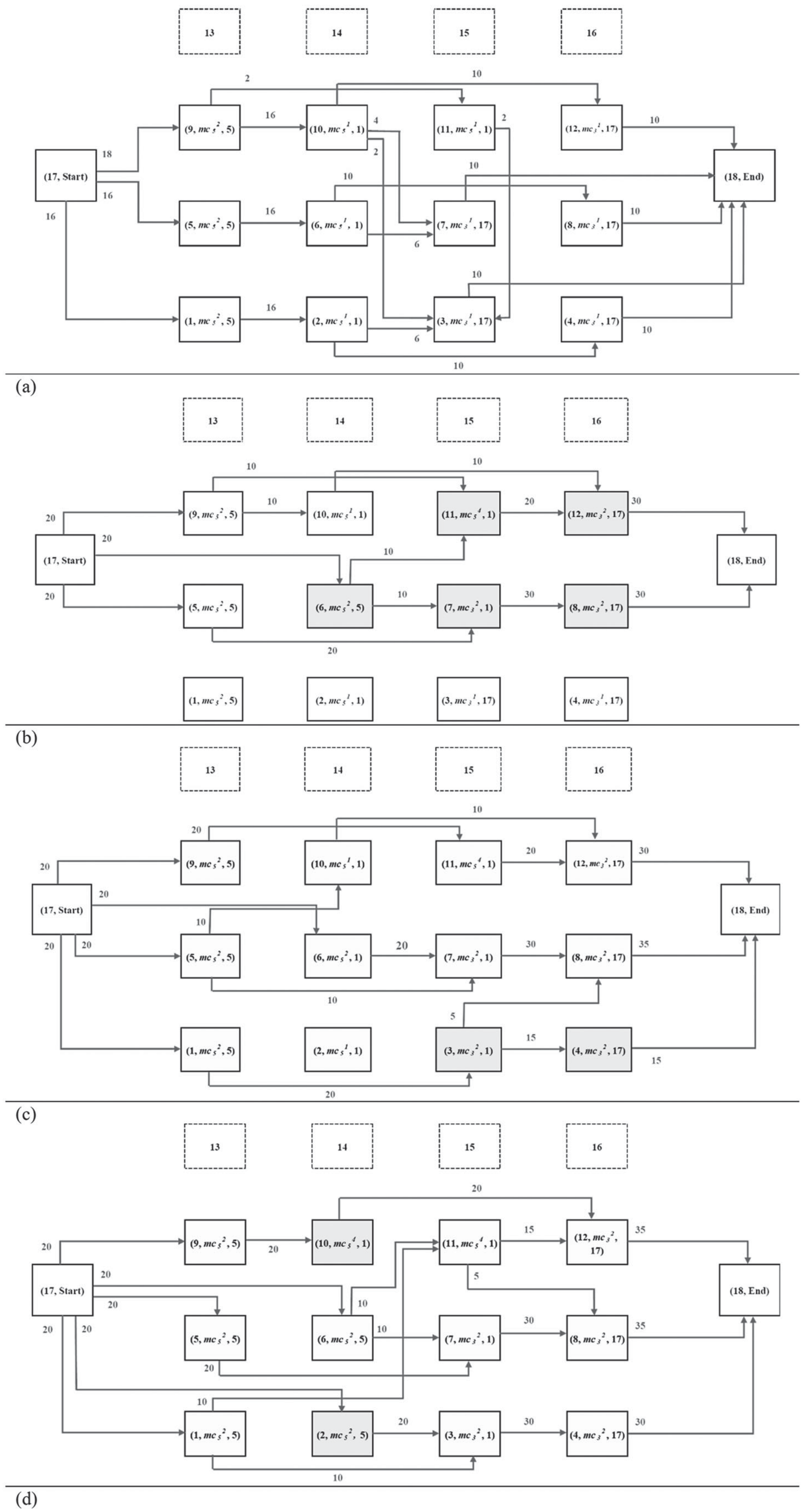


Figure 2. Layout of the RMS in the (a) first, (b) second, (c) third, and (d) final production period of the first numerical example.

Table 3. Demand rate and operation sequence of each part in each production period.

	Demand rate (parts/hour)				
Part	Period 1	Period 2	Period 3	Period 4	Operation sequence
A	20	30	15	0	2 → 12 → 17
B	50	60	45	30	2 → 12 → 11
C	0	20	40	60	2 → 12 → 11 → 8
Total	**70**	**110**	**100**	**90**	

first case. The results are shown in Figure 4(a–d). The 22 possible locations for RMT installation are shown in Figure 3. In the first production period, 16 RMTs are purchased to meet the demand of parts A and B. These RMTs are located as shown in Figure 4(a). Locations 2, 3, 5, and 17 remain empty in the first period. Locations 21 and 22 represent the entrance and exit doors for products.

Since part C is not produced in the first period, none of the RMTs perform operation 8 and only operations 2, 12, 11 and 17 are performed on different equipment. Examining the material flow of engaged RMTs in various operations shows the fulfilment of the demand for all parts in the first production period. In the first period, purchasing new RMTs and material handling costs are \$16,860 and \$2,684 respectively.

In the second period of production (shown in Figure 4(b)), with the increase in the demand for parts A and B and beginning of part C production, existing capacity is increased by purchasing new RMTs (installed in locations 3 and 17 and shown by black rectangles) and changing the configuration of existing RMTs (installed in locations 7, 10, 11, 13, 19 and 20 and shown by grey rectangles).

One interesting point to note in comparing the layouts of the RMS in the first and second periods is the configuration of the RMT installed in location 19. This RMT was purchased in the first period with configuration mc_3^1, but it was practically idle (as shown in Figure 4(a)) with no incoming or outgoing material flow. However, before the start of second period of production, the configuration of this RMT is changed to mc_3^2, and in the second period, this RMT is busy with operation 11.

There is a reason why the RMT installed at location 19 was not purchased with configuration mc_3^2 in the first place. According to the information provided in Table 2,

Table 4. Required production capacity for each operation in each production period.

		Required production capacity in each stage (parts/hour)			
Stage	Operation	Period 1	Period 2	Period 3	Period 4
1	2	**70** (*A*/20; *B*/50)	**110** (*A*/30; *B*/60; *C*/20)	**100** (*A*/15; *B*/45; *C*/40)	**90** (*B*/30; *C*/60)
2	12	70 (*A*/20; *B*/50)	**110** (*A*/30; *B*/60; *C*/20)	**100** (*A*/15; *B*/45; *C*/40)	**90** (*B*/30; *C*/60)
3	17	**20** (*A*/20)	**30** (*A*/30)	**15** (*A*/15)	**0**
4	11	**50** (*B*/50)	**80** (*B*/60; *C*/20)	**85** (*B*/45; *C*/40)	**90** (*B*/30; *C*/60)
5	8	**0**	**20** (*C*/20)	**40** (*C*/40)	**60** (*C*/60)

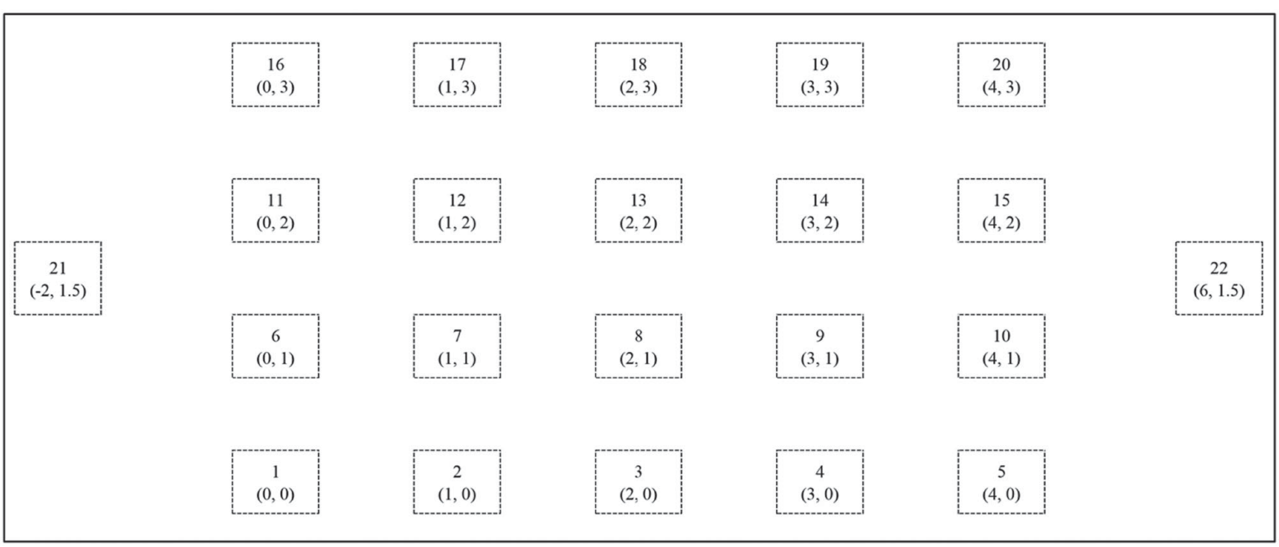


Figure 3. Layout of the empty system in the second numerical example.

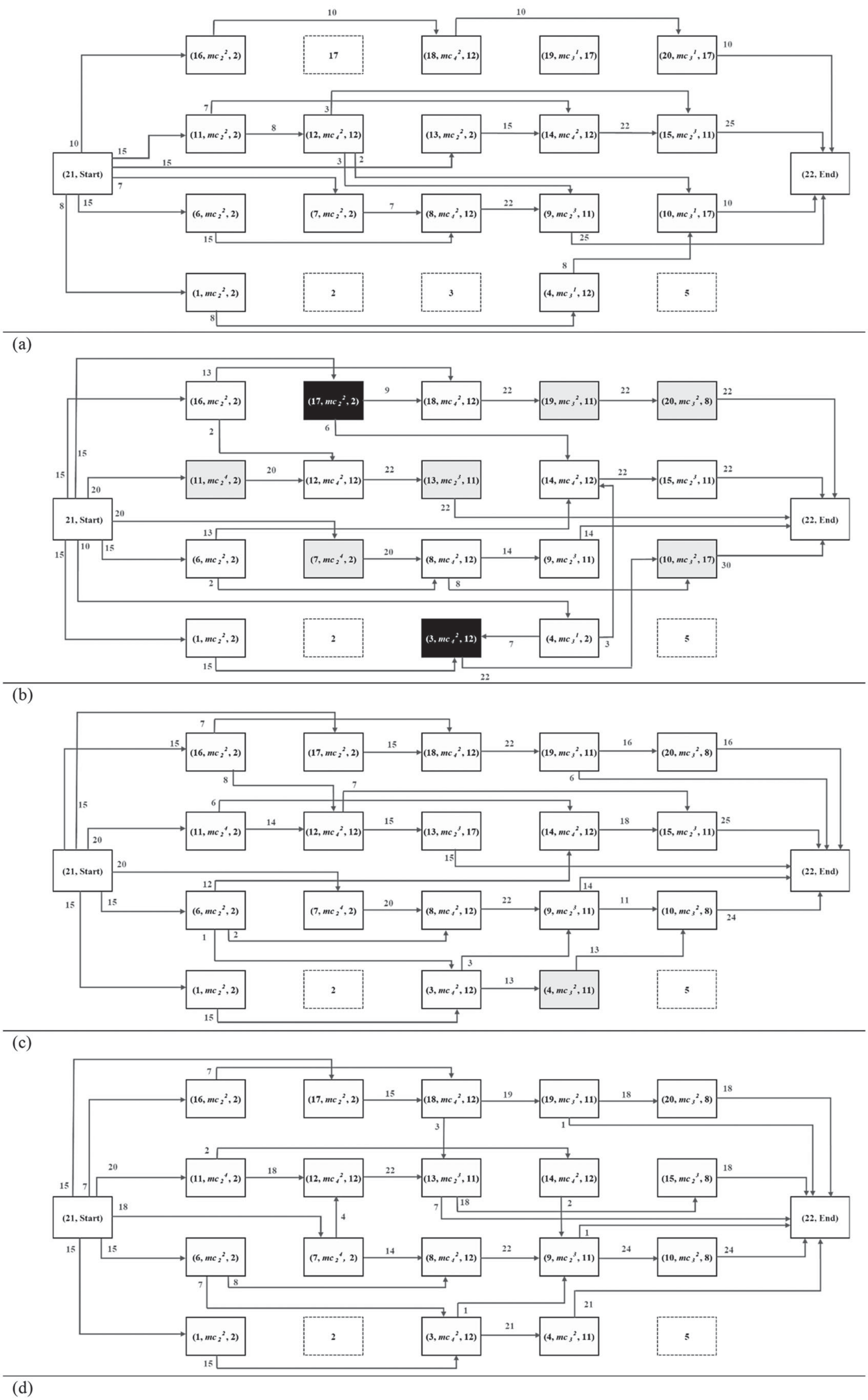


Figure 4. Layout of the RMS in the (a) first, (b) second, (c) third, and (d) final production period of the second numerical example.

the direct purchase cost of RMT mc_3^2 is \$1825, which is (based on the assumption on module replacement costs in this paper) more than the total cost of purchasing mc_3^1 and later, changing its configuration to mc_3^2 (1055 = 780 + 275). In the second production period, total cost of purchasing new RMTs is \$2410, total material handling cost is \$4520, and total reconfiguration cost is \$1625.

In the third period of production, only the configuration of one RMT is changed (with cost of \$275) and the other RMTs continue to work with the same configurations as before (Figure 4(c)). Cost of material handling in this period is \$4016. In the final period (shown in Figure 4(d)), there are not any configuration changes and all RMTs continue to operate in their previous state. The flow in between RMTs change however due to changes in different parts' demand requirements. Cost of material handling in the final period is \$3616. The total cost of RMS layout design in the second example is equal to \$36,006.

In this case, similar to the previous example, the model made effective decisions regarding installation locations, RMT purchases, and reconfigurations. As shown, RMTs responsible for the initial operation (2) are positioned on the left side of the layout near the entrance (location 21), while those handling the final operation (8) are placed on the right side, close to the exit (location 22). This demonstrates how material handling costs influence the placement of RMTs. Additionally, after the second production period, when demand reaches its peak, no further RMT purchases are necessary, and the system continues to operate by reconfiguring the existing RMTs. This efficiency is due to strategic equipment purchases made during the first two production periods.

3.4. Case study

To further demonstrate the effectiveness of the proposed method, the case study presented in Huang, Huang, et al. (2024) was solved using our mathematical formulation. In this case study, a smart manufacturing system consisting of five RMTs is studied where the reconfiguration process of five manufacturing tasks are done for four different parts within a part family. All the input parameters for this case study are shown in Table 5. To address this case, certain simplifications have been made. First, each part can only be produced following a single predefined sequence of operations, as outlined below.

Part 1: f_3, f_4, f_1, f_2
Part 2: f_1, f_3, f_5
Part 3: f_2, f_3, f_5
Part 4: f_6, f_3

Second, the configuration of the resources cannot be altered during the processing of a part. Configuration changes are only allowed in the interval between processing two parts. Finally, a batch size of 100 is assumed, meaning parts are moved and processed in batches. To obtain a solution to this problem, the mathematical model presented in Section 3.2 was modified to handle different processing costs and batch sizes. The results, visualised in Figure 5, highlight the following key points:

- In production task 1, only RMT 1 undergoes a configuration change to produce part 2. No other RMTs require reconfiguration, as the model optimises the initial machine configurations to minimise the need for changes throughout the process.
- From production task 2 onward, the utilised RMTs remain unchanged. Since RMTs' capacity is assumed to be unlimited, variations in part demand do not affect the ability of the resources to meet production requirements. Instead, these variations only influence the processing cost. Consequently, RMTs maintain their configurations across different production tasks, ensuring consistent and efficient production.

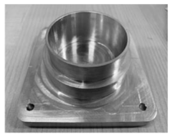
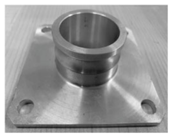
4. Results analysis and discussion

In this section, it is shown how incorporating modular RMTs can enhance the scalability of the system in a more cost-effective manner and the obtained results in Section 3.3 are compared with available results to similar examples in the literature. In addition, sensitivity analysis is conducted on key model parameters to identify those with the greatest impact on cost and runtime, particularly in the context of larger and more complex problems.

4.1. Effect of modular RMTs on system design cost

To better illustrate the impact of modular RMTs on system scalability and associated design costs, the second numerical example presented in Section 3.3.2 is solved under the assumption that equipment is selected from Table 2 without considering RMT modularity. In this scenario, once RMTs are selected, their configurations remain fixed throughout all production periods, with no option for module reconfiguration. The results of this example are presented in Figure 6(a–d) with the initial system setup similar to that shown in Figure 3. By comparing Figures 4 and 6, it is clear that two additional machines were purchased when modularity was not considered. This resulted in higher overall system design costs (\$37,546 vs \$36,006). Notably, material handling costs also increased (\$15,136 vs \$14,836) due to the

Table 5. Case study information derived from Huang, Huang, et al. (2024).

Part number	Part features	Operation sequence	Demand				
			Task 1	Task 2	Task 3	Task 4	Task 5
1		$f_3 \rightarrow f_4 \rightarrow f_1 \rightarrow f_2$ or $f_3 \rightarrow f_1 \rightarrow f_4 \rightarrow f_2$	100	60	100	0	30
2		$f_1 \rightarrow f_3 \rightarrow f_5$ or $f_1 \rightarrow f_5 \rightarrow f_3$	50	55	30	40	0
3		$f_2 \rightarrow f_3 \rightarrow f_5$ or $f_2 \rightarrow f_5 \rightarrow f_3$	75	30	66	70	50
4		$f_6 \rightarrow f_3$	40	75	77	55	100

Distance Matrix							Feature Number						
							1	2	3	4	5	6	
RMT_5	RMT_4	RMT_3	RMT_2	RMT_1	RMT_j	c_i^j	Processing Cost (per part)						Reconfiguration Cost
4	3.8	1.2	2	0	RMT_1	${c_1}^1$	$Part_1 = 0.68$	$Part_2 = 0.59$					${c_1}^1 \rightarrow {c_1}^2 = 14.7$
						${c_1}^2$		$Part_3 = 0.43$	$Part_1 = 0.33$		$Part_3 = 0.47$	$Part_2 = 0.74$	${c_1}^2 \rightarrow {c_1}^1 = 13.6$
1	3	2.1	0	2	RMT_2	${c_2}^1$						$Part_4 = 0.50$	${c_2}^1 \rightarrow {c_2}^2 = 13.7$ ${c_2}^1 \rightarrow {c_2}^3 = 13.1$
						${c_2}^2$			$Part_1 = 0.54$	$Part_2 = 0.51$ $Part_3 = 0.47$ $Part_4 = 0.44$			${c_2}^2 \rightarrow {c_2}^1 = 14.4$ ${c_2}^2 \rightarrow {c_2}^3 = 15.0$
						${c_2}^3$		$Part_3 = 0.37$	$Part_1 = 0.75$				${c_2}^3 \rightarrow {c_2}^1 = 12.6$ ${c_2}^3 \rightarrow {c_2}^2 = 13.9$

(continued).

Table 5. Continued.

Distance Matrix							Feature Number						
							1	2	3	4	5	6	
RMT$_5$	*RMT*$_4$	*RMT*$_3$	*RMT*$_2$	*RMT*$_1$	*RMT*$_j$	c_i^j	Processing Cost (per part)						Reconfiguration Cost
1.9	0.8	0	1.2	2.1	*RMT*$_3$	$c_3{}^1$	Part$_1$ = 0.63						$c_3{}^1 \rightarrow c_3{}^2 = 14.6$
								Part$_2$ = 0.68					
						$c_3{}^2$			Part$_1$ = 0.37	Part$_1$ = 0.32			$c_3{}^2 \rightarrow c_3{}^1 = 14.1$
								Part$_3$ = 0.55					
2.3	0	0.8	3	3.8	*RMT*$_4$	$c_4{}^1$			Part$_1$ = 0.60				$c_4{}^1 \rightarrow c_4{}^2 = 13.9$
										Part$_2$ = 0.33			
										Part$_3$ = 0.65			
										Part$_4$ = 0.40			
						$c_4{}^2$					Part$_2$ = 0.42		$c_4{}^2 \rightarrow c_4{}^1 = 13.2$
												Part$_3$ = 0.59	
0	2.3	1.9	1	4	*RMT*$_5$	$c_5{}^1$					Part$_1$ = 0.59		$c_5{}^1 \rightarrow c_5{}^2 = 13.4$
						$c_5{}^2$					Part$_2$ = 0.30		
												Part$_3$ = 0.55	

Legend: c_i^j = Machine *i* in its j^{th} configuration

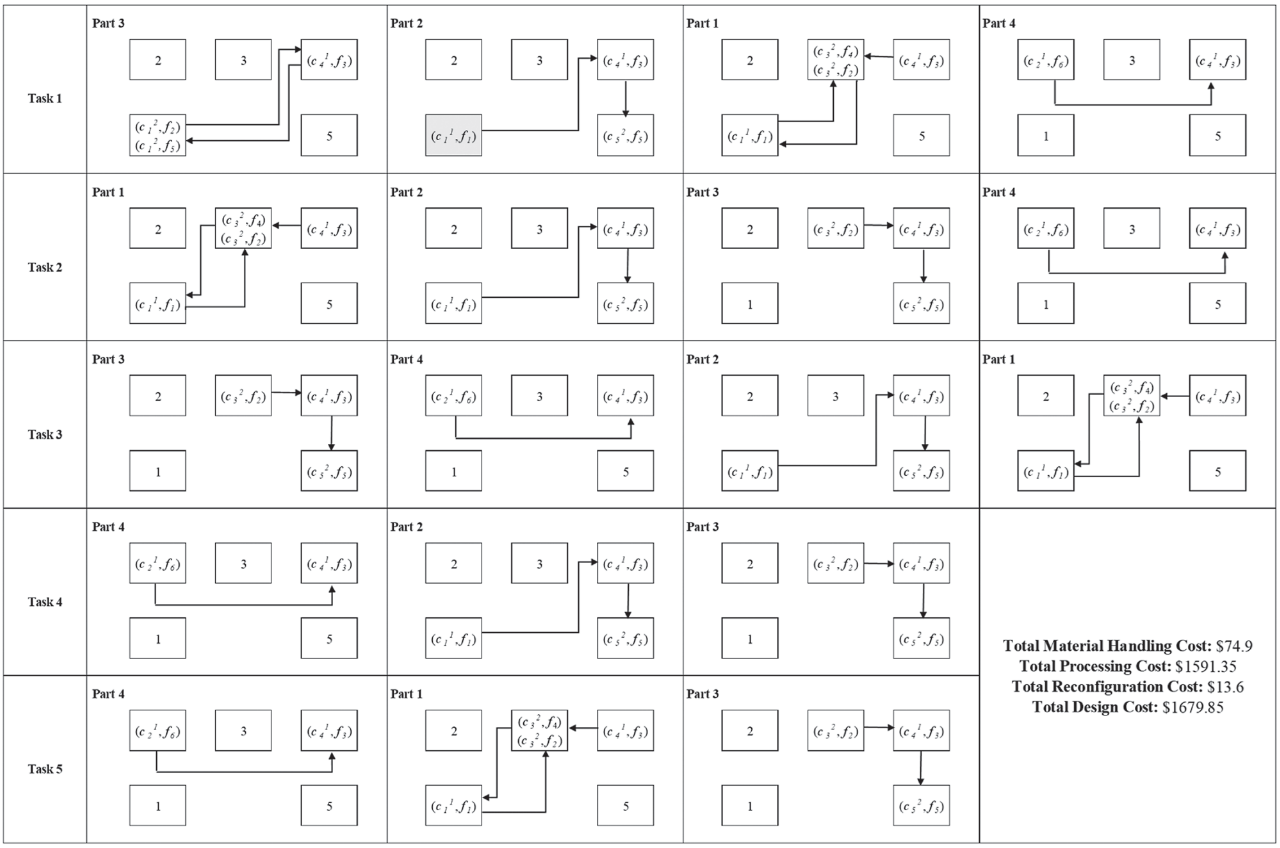


Figure 5. Proposed layout for the RMS case study based on the avialable parameters using the approach presented in this study.

greater number of machines and the associated increase in transportation requirements.

4.2. Result comparison

As stated previously, this study distinguishes itself by introducing a model for designing an RMS that incorporates machine location and material handling costs (factors not previously considered in comparable research). In this section, the proposed model is compared with those presented in Moghaddam, Houshmand, and Fatahi Valilai (2018) and Moghaddam et al. (2020), both of which also addressed RMS design but differ in scope and methodology. In Section 3.3 our model was applied to the two examples provided in these articles. Here, the obtained results are compared against these previous methods in Table 6.

As shown in Table 6 in the first example, the model achieves lower combined machine purchasing and reconfiguration costs than (Moghaddam, Houshmand, and Fatahi Valilai 2018), even though it addresses a more complex problem by incorporating constraints on machine location and material flow. This outcome underscores the superior quality of solutions generated by the proposed approach. Similarly, in the second example, the proposed model delivers results comparable to those in Moghaddam et al. (2020) in terms of machine purchasing and reconfiguration costs, despite addressing more intricate problems. The inclusion of material handling costs and machine placement optimisation demonstrates the model's capability to manage complex manufacturing challenges effectively while maintaining cost efficiency.

Further analysis of Table 6, which compares the number of machines and reconfigurations between the optimal solution from this paper and the optimal solution from Moghaddam, Houshmand, and Fatahi Valilai (2018), reveals a key insight: the RMS designed by the proposed model in this paper requires fewer machines to be purchased compared to the system in the aforementioned study. Instead, it relies on a greater number of machine reconfigurations over time. This highlights the superior flexibility and scalability of the system designed in this paper. The results obtained for similar criteria are nearly identical to those presented by Moghaddam et al. (2020) for the second example. This similarity further highlights the closeness of the solutions obtained from these two models.

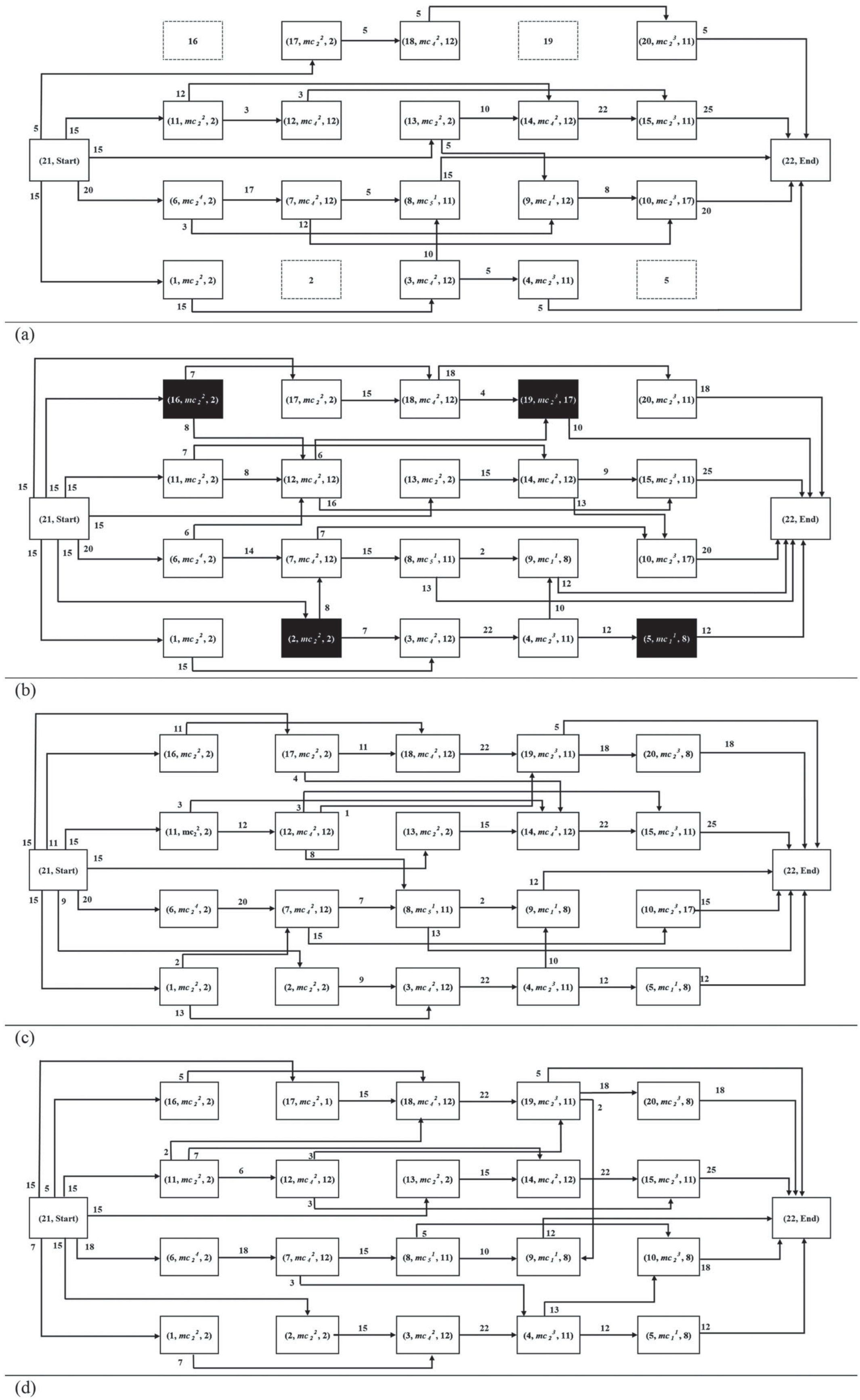


Figure 6. Layout of the production system in the (a) first, (b) second, (c) third, and (d) final production period of the second numerical example in case of non-modular machinery.

Table 6. Comparison of the obtained results vs. available results in the literature.

		Example 1		Example 2	
	Period	Moghaddam, Houshmand, and Fatahi Valilai (2018)	This Work	Moghaddam et al. (2020)	This Work
Cost of Purchase	1	\$8700	\$11, 225	\$19, 390	\$16, 860
	2	\$1500	0	0	\$2410
	3	\$3085	0	0	0
	4	\$3455	0	0	0
Cost of Reconfiguration	1	0	0	0	0
	2	\$275	\$1100	\$1475	\$1625
	3	0	\$550	\$150	\$275
	4	0	\$275	0	0
Cost of Material Handling	1	0	\$1792	0	\$2684
	2	0	\$1960	0	\$4520
	3	0	\$2760	0	\$4016
	4	0	\$3620	0	\$3616
Total Cost of Purchase		\$16, 740	\$11, 225	\$19, 390	\$19, 270
Total Cost of Reconfiguration		\$275	\$1925	\$1625	\$1900
Total Cost of Material Handling		0	\$10, 132	0	\$14, 836
Number of Purchased Machines		15	12	18	18
Number of Reconfigurations		3	9	8	7

Table 7. Required operations and demands in different production periods for each part.

		Required demand in each period			
Part	Required Operations	1	2	3	4
A	1, 2	10	8	6	4
B	1, 2, 3	10	8	6	4
C	1, 2, 3, 4	0	10	8	6
D	1, 2, 3, 4, 5	0	10	8	6

4.3. Sensitivity analysis

In this section, the behaviour of the proposed model is analysed by changing different input parameters. To this end, various scenarios have been designed. It is assumed that four hypothetical products A, B, C, and D which all belong to the same family of parts must be produced in the RMS. The operations required to produce each of these parts can be seen in Table 7. These operations are selected based on the information provided in Table 2. Information regarding required operations for each part and demand of each part in different production periods is given in Table 7.

Considered changes in the domain of each parameter can be seen as follows:

- *Products:* A, A, B, A, B, C, A, B, C, D.
- *Number of periods:* 2, 3, 4.
- *Demand:* X (As shown in Table 7), 2X (Double the amount shown in Table 7).
- *Cost of adding a module:* \$50, \$100
- *Cost of removing a module:* \$25, \$50
- *Material handling cost:* \$2, \$4

The combination of the above values results in 96 different scenarios. Each scenario was solved with the proposed MILP model, using GAMS software V.25.1.2 and on a system with similar specifications as before. For each scenario, time to obtain the solution, total cost of the RMS design, cost of purchasing RMTs, cost of RMTs reconfigurations, number of purchased RMTs, and number of reconfigurations are documented.

In Figure 7, the effect of changing the mentioned parameters can be seen on the overall costs of the system. The total cost of the system is calculated separately for each scenario. The first line of the legend represents the case where the demand parameter is X (as shown in Table 7), with material handling costs set at \$2, module removal costs at \$25 and module adding costs at \$50. This case is assigned a specific colour code, which is consistently used across all product combinations (A, A, B, A, B, C, A, B, C, D) and for all production periods considered ($t = 1$, $t = 2$, and $t = 3$). It is clear that, regardless of the number of production periods, there is a positive correlation between the number of parts being produced, demand rate, material handling costs and total layout design cost. The highest system design costs are incurred when the number of different products, their demand rates, and material handling costs are at their maximum levels. RMS layout design cost is most sensitive to the increase in the above-mentioned parameters as they significantly increase material flow in the system.

Interestingly, as shown in Figure 8, the time required to obtain the best possible solution is most sensitive to the number of production periods rather than other related parameters. As can be seen, run times for similar cases differ significantly when four periods of production are analysed.

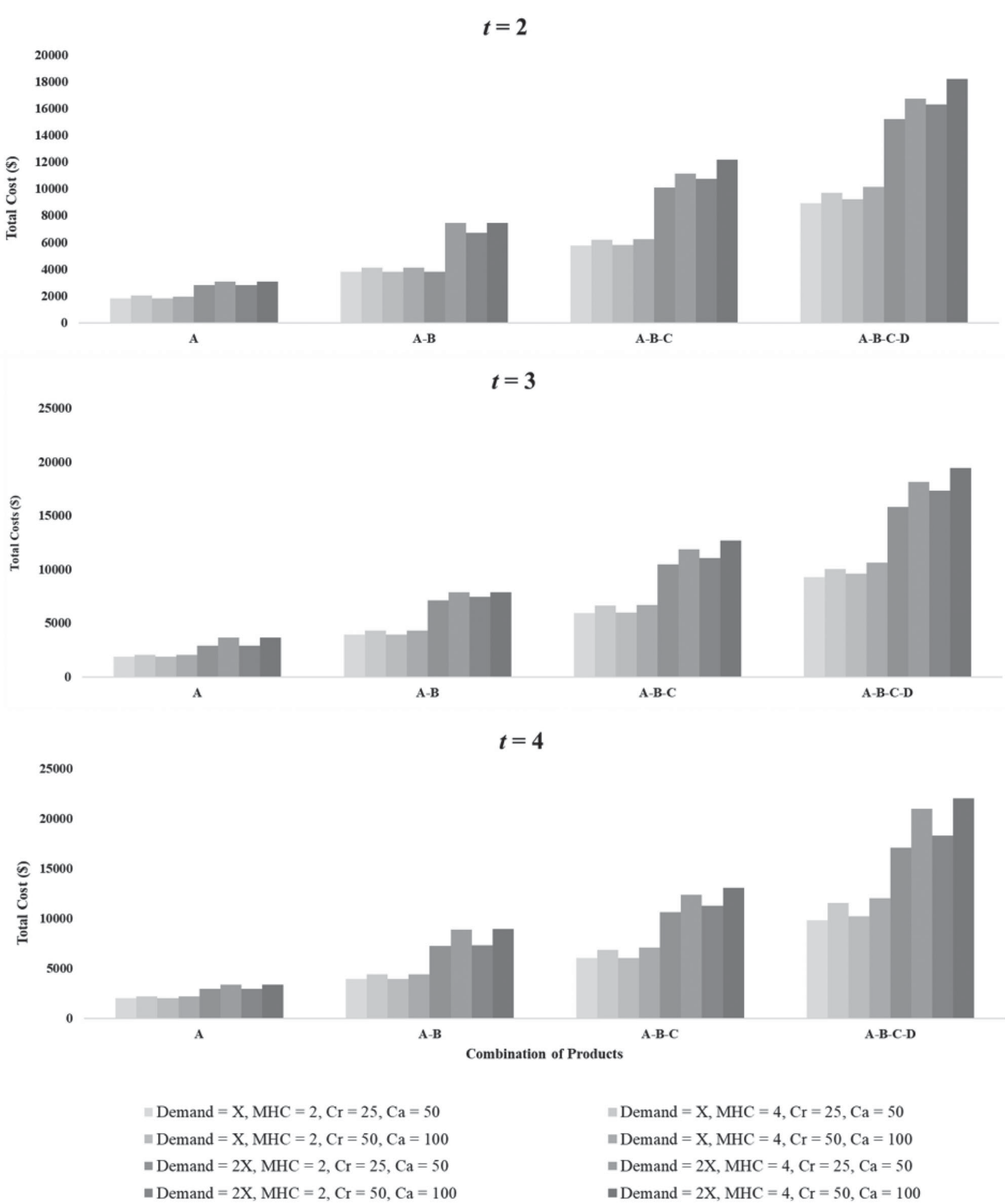


Figure 7. Effect of changing parameters on cost.

5. Conclusion and future work

This study presented a novel approach to dynamic robust facility layout design within scalable RMS, emphasising the role of RMTs in adapting to varying production demands. An MILP model was developed to allow for facility layout adjustments in response to changes in production volumes and product mixes across different periods. Hypothetical case studies were conducted to evaluate the model's effectiveness, revealing notable improvements in operational flexibility, system design

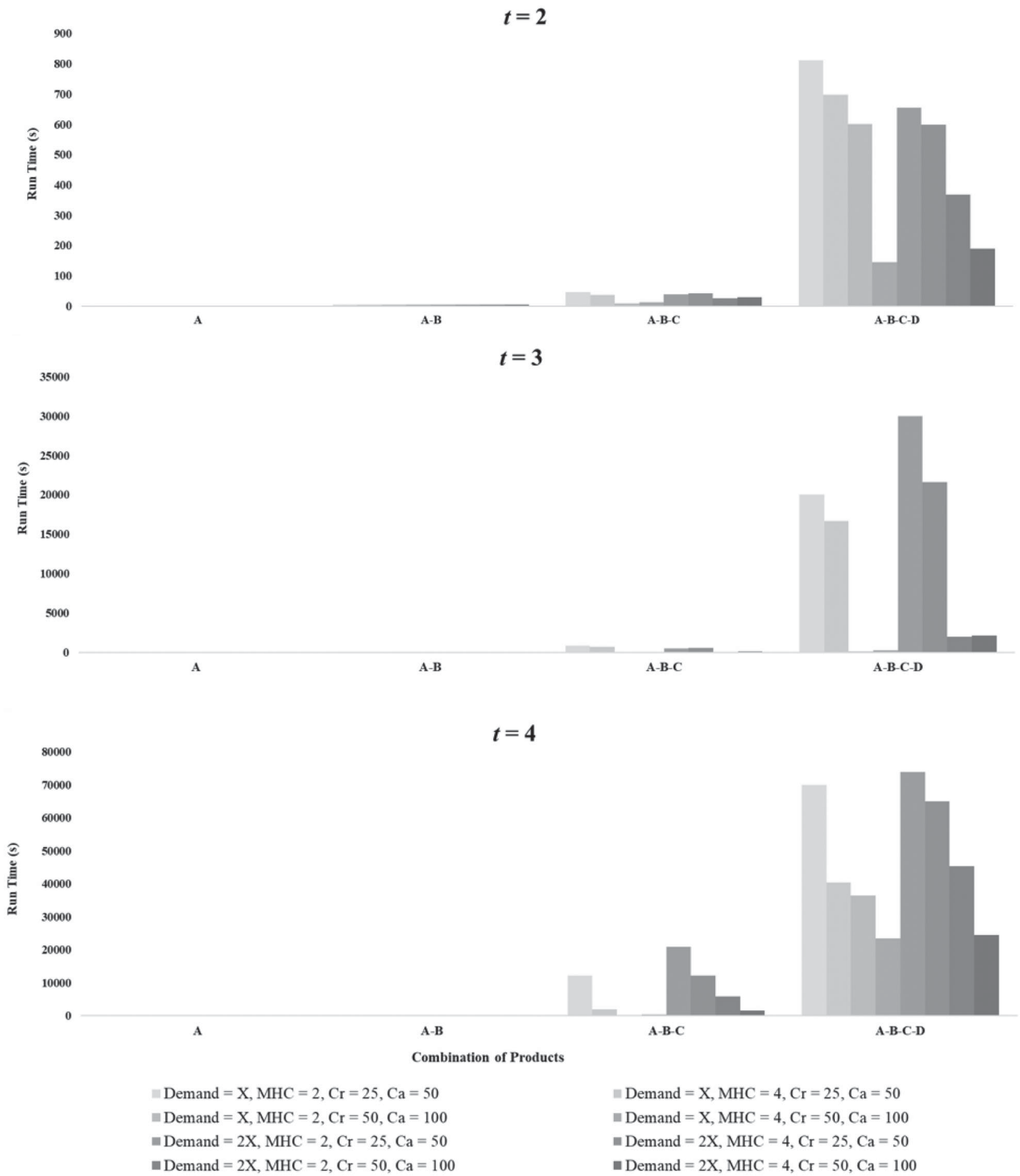


Figure 8. Effect of changing parameters on run-time.

costs, and resource utilisation. While in this paper the concept of layout design in RMS was discussed from a new perspective, there are many opportunities for further improvements.

In the proposed model, the demand of all production periods is available at the beginning of the planning horizon and the demand forecast is 100% accurate. In reality however, forecasting accuracy is seldom that high and uncertainty is always involved. Therefore, the RMS layout design problem while taking non-deterministic and/or probabilistic demand into account is a problem that can further be investigated in the future.

In this research, the amount of material flow between RMTs is determined and the path for material transportation is assumed to be the path where the shortest distance is travelled between two RMTs. This approach would cause some routes to be very crowded and in reality carrying materials may become impossible. Choosing the optimal route for material handling to prevent heavy traffic in some routes is one of the interesting topics that can be further addressed in the future.

One of the key contributions of this paper is the introduction of a linear model for RMS layout planning, which accounts for variations in product demand and product types across multiple production periods. The model allows for reconfiguration of RMTs and adjustment of the operations performed by each RMT. Similar challenges arise in the field of dynamic layout planning, where non-linear and complex models are typically used. These models are often time-consuming to solve and generally require heuristic or meta-heuristic approaches. An interesting path for future research would be exploring the application of the proposed linear model to dynamic layout problems.

It is important to acknowledge that finding industries or laboratories that have implemented RMSs in large-scale production can be challenging. Cost considerations are the major barrier, particularly for small and medium-sized enterprises, where the investment in RMS technologies may not seem immediately justifiable. Skilled personnel are required to operate and maintain RMS systems, but a lack of training or resistance to change can impede adoption. Also, industries often focus on short-term productivity goals, making it challenging to justify RMS investments that offer long-term benefits.

Applying our proposed algorithm to real-world industrial cases poses several challenges as well. For example, real-world data is often complex and unpredictable (variable demand, machine failures, and diverse product requirements) which differ significantly from the simplified assumptions in our mathematical model. Furthermore, RMS solutions often need to be tailored to specific industries, and scaling them to large-scale production can be resource-intensive. Achieving real-time adaptability to dynamic changes, such as fluctuating demand or operational disruptions, is another significant challenge, as is validating algorithms under the uncontrolled conditions of industrial environments. RMS also demands seamless integration with material handling and logistics, which adds another layer of complexity.

Finally, it it should be noted that the proposed model is well-suited for application in service industries, where various resources can provide different types of services during each time interval. Applying the model in such contexts and analysing the resulting outcomes could offer valuable insights.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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