Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 59-10 (2025) 1095–1100

Dynamic Layout Design in Reconfigurable Manufacturing Systems: Optimization and Simulation-Based Validation

Shokraneh K. Moghaddam * **Fatemeh Saffar** **

* *School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield, AL10 9AB, UK (e-mail: s.khashkhashimoghadam@herts.ac.uk).*
** *Department of Industrial Engineering, Sharif University of Technology, Tehran, 11155-9466, Iran (e-mail: f.saffar78@gmail.com).*

Abstract: This paper presents a novel approach to layout design for Reconfigurable Manufacturing Systems, focusing on optimizing the physical arrangement of machines and resources to enable rapid, cost-effective adjustments for varying production needs. Using a new Mixed Integer Linear Programming Model, the approach targets Reconfigurable Machine Tools to enhance flexibility in response to fluctuating product types and volumes. A case study is developed and analyzed using the proposed model, followed by validation through a simulation approach. Simulation results provide insights into model behavior and enable solution refinement, particularly in optimizing resource utilization and average waiting time of products in the system.

Keywords: Reconfigurable Manufacturing Systems, Reconfigurable Machine Tools, Dynamic Layout Design, Optimization, Simulation.

1. INTRODUCTION

In today's competitive manufacturing environment, reconfigurable manufacturing systems (RMS) have become essential for adapting to fluctuating market demands and varying product types. RMS provides the flexibility to manage diverse parts and changing production volumes by using modular, reconfigurable machine tools (RMTs), which allow manufacturers to rapidly adjust production lines with minimal downtime (Rezaee and Moghaddam (2025)). While substantial research has focused on the adaptability of reconfigurable machinery (Zhu et al. (2022); Huang et al. (2024b,a)), less attention has been given to facility layout design within scalable RMS, especially concerning RMT integration. Effective facility layout design is critical to optimizing material flow, lead times, and overall throughput, and becomes increasingly complex when it must account for changes over time. The dynamic facility layout problem considers both material handling and rearrangement costs over multiple production periods, through adaptive layouts - where regular rearrangement is allowed - or robust layouts - where rearrangements are minimized to save costs (McKendall Jr et al. (2006)).

This paper addresses the dynamic layout design for an RMS producing a family of parts, employing RMTs with modular structures that can be reconfigured by adjusting auxiliary modules. This capability allows for flexibility in responding to demand changes across production periods by reconfiguring or adding new RMTs as needed. A Mixed Integer Linear Programming (MILP) model is proposed to optimize the purchase, reconfiguration, and placement of RMTs while minimizing total costs. The proposed approach adopts a robust layout strategy, wherein each RMT remains in a fixed location over time, though its auxiliary modules may be modified to meet production requirements. By maintaining stable machine locations, this robust design approach seeks to reduce rearrangement costs while allowing sufficient adaptability in equipment configuration to efficiently handle varying production demands. This paper's contributions include:

- A novel method for designing dynamic layouts in scalable RMS using RMTs to meet diverse production needs efficiently;
- A new MILP model for the dynamic layout problem in RMSs, accounting for RMT adaptability through auxiliary module adjustments;
- Validating the model by designing and solving a hypothetical case study using exact and simulation-based approaches.

The rest of the paper is organized as follows: In Section 2, a comprehensive literature review is provided, identifying existing research gaps. In Section 3, the proposed mathematical formulation for dynamic and robust layout design is presented. In Section 4, the proposed approach is presented by demonstrating an example to showcase the benefits of RMT reconfiguration in facility layout design. Finally, Section 5 concludes the paper by validating the model through simulation and suggesting directions for future research.

2. RELATED WORK

The literature on RMS facility layout design primarily addresses three areas: selecting optimal types and configurations of RMTs, designing layouts for RMS machinery and departments, and developing layouts for Reconfigurable

10.1016/j.ifacol.2025.09.185

Cellular Manufacturing Systems. Studies in the first area use various optimization techniques, including metaheuristic algorithms like Tabu Search and Genetic Algorithms, to balance machine adaptability, operational capacity, and cost-effectiveness (Goyal et al. (2013); Bensmaine et al. (2013); Haddou Benderbal et al. (2017, 2018)). Recent approaches emphasize scalability by allowing RMS layouts to evolve with production needs to integrate flexibility and modularity indices that respond to fluctuating demand. For instance, Moghaddam et al. (2018) and Moghaddam et al. (2020) introduced an RMS configuration model that optimizes machine purchases and configurations over time as demand data updates, offering a comprehensive, cost-efficient solution for RMS adaptability.

Research on RMS facility layout focuses on optimizing the arrangement of machinery and departments to enhance adaptability and minimize reconfiguration efforts in response to changing demands. Maganha and Silva (2017)'s review highlights the essential attributes of reconfigurable layouts, such as re-usability, flexibility, and modularity. Xiaobo et al. (2001) developed stochastic and probabilistic models to optimize layout configurations, part family selection, and system performance under uncertain demand. Guan et al. (2012) addressed material handling in RMS layouts using automated guided vehicles (AGVs), proposing a model to reduce material handling costs. Simulation frameworks by Zheng et al. (2013) minimized system costs through optimized machine placement and material flow adjustments. Azevedo et al. (2013) research on flexible layouts supports both large-scale relocation and smaller adjustments within departments, using mixed-integer programming to minimize material handling and reconfiguration costs, ensuring close departmental proximity for efficient workflows.

A Cellular Reconfigurable Manufacturing System (CRMS) groups reconfigurable manufacturing cells containing tools like RMTs, CNC machines, and material handling systems to efficiently meet demand and ensure proper operation sequences. CRMS layout design focuses on minimizing inter-cell movements and module changes, as shown in Pattanaik et al. (2007) where multi-objective models are solved by NSGA algorithms. Xing et al. (2009) introduced an ANN-based method to tackle cell formation, part grouping, and scheduling. Yu et al. (2012) proposed integer linear programming for part grouping and operation loading within cells. Eguia et al. (2017, 2013) advanced CRMS design by combining cell formation and part family scheduling with an MILP model which was further refined in a two-phase approach for machine grouping and resource allocation to optimize workflow within cells.

The literature reveals limited focus on layout generation specifically tailored for RMS, with few studies addressing the combined challenges of layout design and RMT reconfiguration. Hence our paper is novel in its approach for designing dynamic and resilient facility layouts within scalable RMS and emphasizing the role of RMTs in efficiently adapting to changing production demands while minimizing costs and delays.

3. PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION

In this study an RMS is designed to produce parts within a single family, with similar and determined operational sequences across different parts. Production is halted during reconfiguration phases in which the system is idle. The RMS uses RMTs with fixed basic modules and adjustable auxiliary modules that allow various machine configurations to accommodate changing demands. RMTs are purchased at the beginning of each period, and some may undergo configuration changes or be added in later periods.

Costs considered include purchasing RMTs, module adjustments, and material handling. The model aims to optimize RMT purchases, locations, configurations, and material flow to meet production demands while minimizing total costs. Once purchased, each RMT's location is fixed, and installation locations are strategically chosen based on future operational needs and Work in Progress (WIP) flows. The model also ensures that material flows align with machine capacities and operational requirements, allowing flow between RMTs only when their operations are directly sequential.

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

P: Set of all possible installation locations.
J: Set of all possible machine configurations.
L: Set of all required 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 an RMT.
j: Configuration of an RMT.
l: A certain operation.
t: A certain time period.

Input Parameters: All input parameters required for the formulation are as follows:

MHC: The cost of moving one unit of product one unit of distance.
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.
B_{jl}: The maximum capacity of an RMT with configuration j while 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' ($D_{pp'} = |X_p - X_p'| + |Y_p - Y_p'|$).

Decision Variables: The decision variables used in the formulation are as follows:

x_{pjl}: Equals 1 if an RMT with configuration j is purchased for operation l and is installed in location p.

s_{pjlt}: Equals 1 when the RMT that is located in p and has configuration j, performs operation l in period t.

$y_{pj'jlt}$: Equals 1 when at the beginning of period t the RMT in location p is reconfigured from j' to j and then performs operation l.

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

$v'_{plp'l't}$: Shows the input flow in period t from the RMT in location p performing operation l to the RMT in location p' performing operation l'.

Based on the above input description, a novel MILP formulation is proposed for RMS layout design and reconfiguration across different production periods.

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

Subject to:

$$s_{pjlt}\leq\sum_{j'\in J}\sum_{l'\in L}x_{pj'l'} \qquad \forall p,j,l,t \tag{2}$$

$$\sum_{j\in J}\sum_{l\in L}s_{pjlt}\leq 1 \qquad \forall p,t \tag{3}$$

$$x_{pjl}\leq s_{pjlt} \qquad \forall p,j,l,t=1 \tag{4}$$

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

$$\sum_{j'\in J}y_{pj'jlt}\leq s_{pjlt} \qquad \forall p,j,l,t \tag{6}$$

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

$$v_{plt}\leq\sum_{j\in J}s_{pjlt}B_{jl} \qquad \forall p,l,t \tag{8}$$

$$\sum_{p\in P}v_{plt}\geq d_l^t \qquad \forall l,t \tag{9}$$

$$v'_{plp'l't}\leq v_{plt}q_{ll't} \qquad \forall l,p,l',p',t \tag{10}$$

$$v'_{plp'l't}\leq v_{p'l't}q_{ll't} \qquad \forall l,p,l',p',t \tag{11}$$

$$\sum_{p'\in P}\sum_{l'\in L}v'_{plp'l't}=\sum_{p'}\sum_{l'}v'_{p'l'plt}$$
$$\forall t,p\neq p_e,l\neq l_e,p\neq p_s,l\neq l_s \tag{12}$$

$$\sum_{p'\in P}\sum_{l'\in L}v'_{plp'l't}=v_{plt} \qquad \forall t,p\neq p_e,l\neq l_e \tag{13}$$

$$\sum_{p'\in P}\sum_{l'\in L}v'_{p'l'plt}=v_{plt} \qquad \forall t,p=p_e,l=l_e \tag{14}$$

$$v_{plt},v_{plp'l't}\geq 0 \qquad \forall p,l,p',l',t \tag{15}$$

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

In the above formulation, (1) is the objective function which minimizes cost of purchasing a new RMT, cost of machine reconfiguration, and cost of material handling in between RMTs. Constraint (2) indicates that the decision variable associated with the RMT located in p equalls 1 if and only if that RMT is purchased and installed in the corresponding location. Constraint (3) shows that the RMT located in p during period t can only perform one operation (l) and has only one configuration (j). Constraint (4) specifies that in the first production period, if an RMT with configuration j is purchased for operation l at location p, the state variable s_{pjlt} is set to 1. Constraint (5) indicates that for $t\neq 1$, s_{pjlt} equals 1 only if the RMT at location p had configuration j in the previous period or changed to configuration j at the beginning of period t. Constraint (6) indicates that (s_{pjlt}) equals 1, if at the beginning of period t, the configuration of the RMT located in p changes to j for performing operation l.

Constraint (7) guarantees $y_{pj'jlt}$ equals 1, only if the RMT located in p has configuration j' in period $t-1$. Constraint (8) specifies two points: (1) the flow variable of the RMT at location p performing operation l is non-zero only if its state variable for one of the configurations performing l is non-zero, and (2) this flow variable cannot exceed the RMT's capacity for operation l. Constraint (9) is concerned with demand fulfillment; 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) state that flow between two RMTs exists only when they perform consecutive operations, and this flow must be less than the total flow capacity of the RMT with outgoing flow and the RMT with incoming flow. Constraint (12) guarantees the equality of the incoming and outgoing flow for each RMT.

Since no machines precede or follow the RMTs handling the first and last operations, normal material flow equations don't apply. To balance flow, a "Start" machine is placed before the first operation, and an "End" machine after the last. These dummy machines, with configurations j_s and j_e for operations l_s and l_e, match the system's maximum flow capacity and are positioned at the RMS's inbound and outbound points, p_s and p_e. 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.

4. PROPOSED APPROACH

This section provides a detailed explanation of the proposed approach through a hypothetical example. In this example, a single part is scheduled for production across four periods, requiring operations *5*, *1*, and *17* in sequence. Demand per period is 50, 60, 80, and 100 parts per hour. Module addition and removal costs are \$50 and \$25 per module, with a material handling cost of \$4 per unit of distance. Information related to the available RMTs and their cost of purchase, production rates, basic and auxiliary modules, and different configurations can be found in Table 1.

Table 1. Information related to RMTs.

M_j	mc_i^j	Operation # 1	5	17	Cost	Basic Modules	Auxiliary Modules
		Production rate (parts/hour)					
M_1	mc_1^2	-	15	-	955	{1, 5}	{12, 13, 15, 20, 21}
M_2	mc_2^1	14	-	-	1215	{2, 4, 8}	{11, 13, 16, 22, 24}
	mc_2^3	-	-	20	1140		{13, 19, 24}
	mc_2^4	-	20	-	1350		{11, 13, 15, 18, 24}
M_3	mc_3^1	-	-	10	780	{3, 5, 7}	{11, 12, 14, 16, 18}
	mc_3^2	30	-	35	1825		{12, 13, 14, 17, 19, 20}
M_4	mc_4^2	25	-	30	1500	{4, 9}	{11, 15, 18, 20, 21}
M_5	mc_5^1	16	-	-	900	{3, 6, 10}	{20, 22}
	mc_5^2	-	20	24	1175		{16, 17, 19, 20, 25}
	mc_5^4	20	-	-	1175		{20, 22, 24}

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

Figure 1 shows the layout with 16 available locations, and locations 17 and 18 serve as inbound and outbound doors for l_s and l_e. The model was solved using GAMS V.25.1.2 on an Intel Core i7-6700HQ CPU in 11,254 seconds.

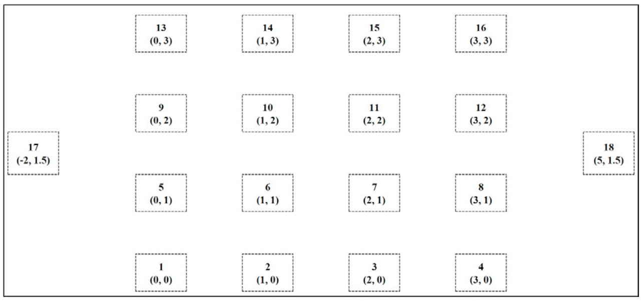

Fig. 1. Layout of the empty system for the numerical example.

Throughout the four production periods (shown in Figure 2), RMS layout adapt to meet increasing demand rates. In the first period (50 parts/hour), 12 RMTs are installed across locations 1-12, with empty locations shown as dotted rectangles; the setup cost totals $11,025, and material handling costs $1,792 (Fig. 2(a)). In the second period (60 parts/hour), several RMTs are reconfigured to increase output, while others remain idle, resulting in no additional purchase costs, reconfiguration costs of $1,100, and material handling costs of $1,960 (Fig. 2(b)). In the third period (80 parts/hour), two RMTs are reconfigured and only one is idle, incurring reconfiguration and material handling costs of $550 and $2,760, respectively (Fig. 2(c)). In the final period (100 parts/hour), all RMTs are active, with two reconfigurations costing $275 and material handling costs reaching $3,620 (Fig. 2(d)).

The layout planning ensures optimal selection of RMT types, installation locations, reconfigurations across production periods, and material flows, with a total system design cost of $23,082. The RMTs performing initial and final operations are strategically located near the entrance and exit doors, minimizing material handling costs. The location of all 12 RMTs remain unchanged, reflecting the model's efficiency in minimizing expenses by optimizing fixed RMT locations. Initially, 12 RMTs are sufficient to meet a demand of 50 parts/hour, and as demand doubles to 100 parts/hour by the final period, the system accommodates the increase solely through RMT reconfigurations, showcasing its scalability.

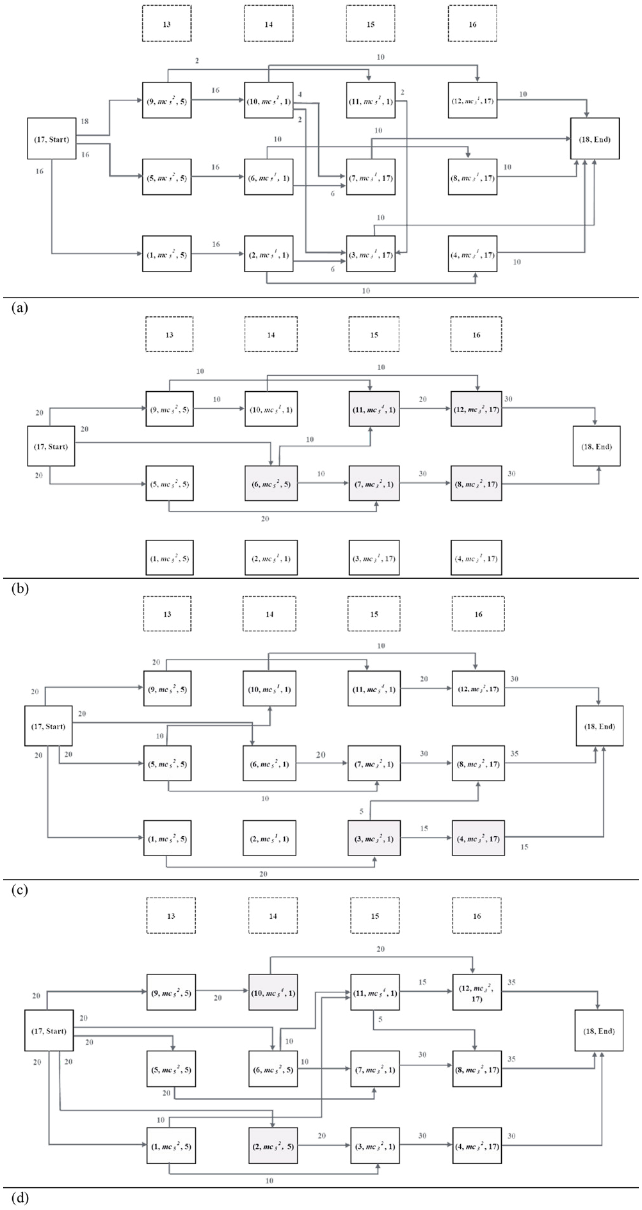

Fig. 2. Layout of the RMS in the (a) first, (b) second, (c) third, and (d) final production period of the numerical example.

5. RESULTS ANALYSIS AND DISCUSSION

To validate our model, we utilized Arena simulation software (version 14). The optimal solution derived from the mathematical model was replicated within the Arena environment, simulating four distinct production periods with corresponding demand rates. For simplicity, each period was assumed to represent a day with 24 machine hours available. Post-simulation, two metrics not included in the mathematical model—resource utilization and average waiting time per machine and across the system—were analyzed.

Results, as shown in Fig. 3 indicated imbalanced resource utilization, with over %50 of RMTs operating above %90 capacity, which is suboptimal. Some resources, such as the RMT2 (RMT which is located in position 2), remained

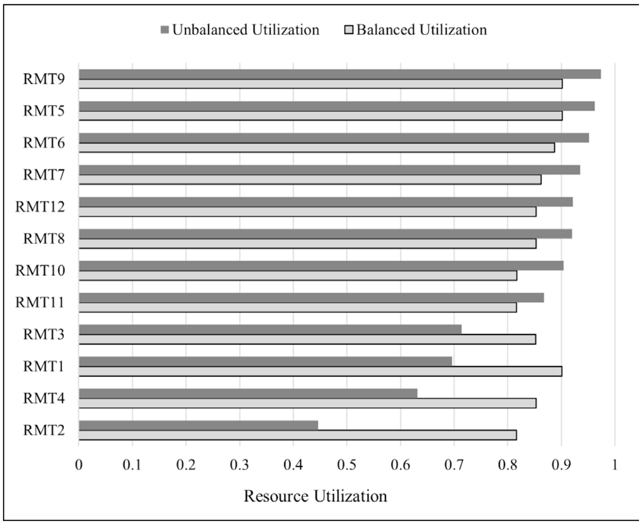

Fig. 3. Resource utilization when **not** all RMTs are used in all periods vs. when all RMTs are used in all periods.

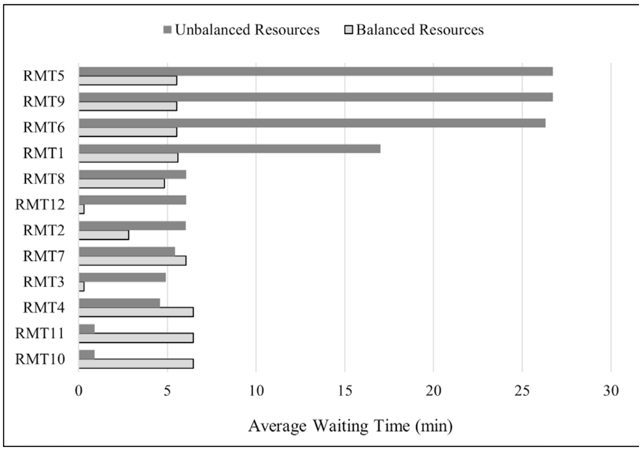

Fig. 4. RMTs average waiting time before and after line balancing.

idle for over half of the available time. Additionally, the average system wait time per part was 33.2 minutes, an unexpectedly high figure that may lead to long WIP queues, which are undesirable in any layout (Fig. 4).

Further analysis of the simulation model reveals that unbalanced resource utilization results primarily from idle RMTs during periods 2 and 3; specifically, four RMTs remain unused in period 2. This imbalance stems from the mathematical model's objective to minimize material handling costs, leading it to prioritize workload allocation among adjacent RMTs. Moreover, the mathematical model does not account for costs associated with waiting times or unbalanced production lines.

In a modified simulation model where all RMTs are active across all periods, resource utilization improved significantly, with utilization rates between %80 and %90 and a reduced average waiting time of 11.29 minutes per part—nearly one-third of the initial figure (as shown in Fig. 3 and Fig. 4).

In this specific case, when material handling costs are minimal compared to other system design costs, the obtained solution from (1) could be improved further by incorporating waiting time and RMT utilization considerations into the simulation model. While modeling the stochastic behaviors of system entities can be challenging mathematically, simulation modeling offers valuable insights into critical performance metrics, enabling informed trade-offs where necessary.

6. CONCLUSION

This study proposes a novel approach to robust facility layout design for scalable RMS, focusing on the flexibility of RMTs to adapt to fluctuating production demands. An MILP model was developed to adjust facility layouts according to shifts in production volume and product types across various time periods. A hypothetical case study showed that the model enhances operational flexibility and reduces system design costs. It was discussed that the solution obtained by the model can be further improved through simulation to consider resource utilization and average waiting time of products in the RMS. This study also highlights future research opportunities, such as considering non-deterministic demand forecasts, optimizing material transport routes to prevent congestion, and exploring applications in dynamic layout problems and service industries. Despite challenges in finding large-scale RMS applications, the model's potential adaptability to service industries is noted as an area for further exploration.

REFERENCES

Azevedo, M.M., Crispim, J.A., and de Sousa, J.P. (2013). Flexible and reconfigurable layouts in complex manufacturing systems. In *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services: IFIP WG 5.7 International Conference, APMS 2012, Rhodes, Greece, September 24-26, 2012, Revised Selected Papers, Part I*, 484–493. Springer.

Bensmaine, A., Dahane, M., and Benyoucef, L. (2013). A non-dominated sorting genetic algorithm based approach for optimal machines selection in reconfigurable manufacturing environment. *Computers & Industrial Engineering*, 66(3), 519–524.

Eguia, I., Molina, J.C., Lozano, S., and Racero, J. (2017). Cell design and multi-period machine loading in cellular reconfigurable manufacturing systems with alternative routing. *International Journal of Production Research*, 55(10), 2775–2790.

Eguia, I., Racero, J., Guerrero, F., and Lozano, S. (2013). Cell formation and scheduling of part families for reconfigurable cellular manufacturing systems using tabu search. *Simulation*, 89(9), 1056–1072.

Goyal, K.K., Jain, P.K., and Jain, M. (2013). A novel methodology to measure the responsiveness of rmts in reconfigurable manufacturing system. *Journal of Manufacturing Systems*, 32(4), 724–730.

Guan, X., Qiu, B., and Yang, H. (2012). Integrated rms layout and flow path design: Modelling and a heuristic method. In *Computer, Informatics, Cybernetics and Applications: Proceedings of the CICA 2011*, 403–411. Springer.

Haddou Benderbal, H., Dahane, M., and Benyoucef, L. (2017). Flexibility-based multi-objective approach for machines selection in reconfigurable manufacturing system (rms) design under unavailability constraints. *International Journal of Production Research*, 55(20), 6033–6051.

Haddou Benderbal, H., Dahane, M., and Benyoucef, L. (2018). Modularity assessment in reconfigurable manufacturing system (rms) design: an archived multi-objective simulated annealing-based approach. *The International Journal of Advanced Manufacturing Technology*, 94, 729–749.

Huang, J., Huang, S., Moghaddam, S.K., Lu, Y., Wang, G., Yan, Y., and Shi, X. (2024a). Deep reinforcement learning-based dynamic reconfiguration planning for digital twin-driven smart manufacturing systems with reconfigurable machine tools. *IEEE Transactions on Industrial Informatics*.

Huang, S., Tan, J., Lu, Y., Moghaddam, S.K., Wang, G., and Yan, Y. (2024b). A multi-objective joint optimisation method for simultaneous part family formation and configuration design in delayed reconfigurable manufacturing system (d-rms). *International Journal of Production Research*, 62(1-2), 92–109.

Maganha, I. and Silva, C. (2017). A theoretical background for the reconfigurable layout problem. *Procedia Manufacturing*, 11, 2025–2033.

McKendall Jr, A.R., Shang, J., and Kuppusamy, S. (2006). Simulated annealing heuristics for the dynamic facility layout problem. *Computers & operations research*, 33(8), 2431–2444.

Moghaddam, S.K., Houshmand, M., and Fatahi Valilai, O. (2018). Configuration design in scalable reconfigurable manufacturing systems (rms); a case of single-product flow line (spfl). *International Journal of Production Research*, 56(11), 3932–3954.

Moghaddam, S.K., Houshmand, M., Saitou, K., and Fatahi Valilai, O. (2020). Configuration design of scalable reconfigurable manufacturing systems for part family. *International Journal of Production Research*, 58(10), 2974–2996.

Pattanaik, L.N., Jain, P.K., and Mehta, N. (2007). Solving multi-objective cell design problem: an evolutionary genetic algorithm approach. *International journal of manufacturing technology and management*, 11(2), 251–273.

Rezaee, P. and Moghaddam, S.K. (2025). Assessment of design approaches for reconfigurable manufacturing systems based on forecasted demand data. *Computers & Industrial Engineering*, 110878.

Xiaobo, Z., Wang, J., and Luo, Z. (2001). A stochastic model of a reconfigurable manufacturing system-part 4: Performance measure. *International Journal of Production Research*, 39(6), 1113–1126.

Xing, B., Nelwamondo, F.V., Battle, K., Gao, W., and Marwala, T. (2009). Application of artificial intelligence (ai) methods for designing and analysis of reconfigurable cellular manufacturing system (rcms). In *2009 2nd International Conference on Adaptive Science & Technology (ICAST)*, 402–409. IEEE.

Yu, J., Doh, H.H., Kim, H., Kim, J., Lee, D., and Nam, S. (2012). Iterative algorithms for part grouping and loading in cellular reconfigurable manufacturing systems. *Journal of the Operational Research Society*, 63(12), 1635–1644.

Zheng, L., Zhu, L., Wang, B., and Bai, L. (2013). A simulation analysis of facility layout problems in reconfigurable manufacturing systems. In *2013 international conference on computer sciences and applications*, 423–427. IEEE.

Zhu, Q., Huang, S., Wang, G., Moghaddam, S.K., Lu, Y., and Yan, Y. (2022). Dynamic reconfiguration optimization of intelligent manufacturing system with human-robot collaboration based on digital twin. *Journal of Manufacturing Systems*, 65, 330–338.