

Article

Performance Evaluation of Reconfiguration Policy in Reconfigurable Manufacturing Systems including Multi-Spindle Machines: An Assessment by Simulation

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Abstract: Reconfigurable manufacturing systems (RMSs) are extensively studied and employed to address demand uncertainties. RMS machines are designed to be modular and adaptable to changing requirements. A recent innovation is the introduction of multi-spindle reconfigurable machines (MRMTs). This study evaluates the impact of MRMTs' introduction into an RMS, considering factors such as the number of MRMT machines and reconfiguration policies. A simulation model incorporating failures, process time variability, and part inter-arrival supports the analysis. The numerical results aid decision makers in determining the optimal RMS configuration with MRMTs. The simulation outcomes indicate that a balanced number of multi-spindle machines can significantly enhance performance compared with an unbalanced distribution.

Keywords: reconfigurable manufacturing systems; reconfiguration machines; modularity; simulation



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1. Introduction

Industry 4.0 heralds the era of 'smart factories', driving interconnected, flexible systems capable of autonomous decision making and real-time adaptation which foster global innovation and competitiveness [1]. Reconfigurable manufacturing systems (RMSs) exemplify this paradigm, designed to swiftly adapt to fluctuating market demands while ensuring sustained operations [2]. The responsiveness of RMSs is pivotal for managing product variety and accommodating variable demand. Firstly, RMS designs prioritize product variety by catering to product families rather than individual items, ensuring system flexibility. Secondly, an RMS operates as a modular system, enabling rapid reconfiguration to meet changing demand dynamics. At the heart of responsive manufacturing systems (RMSs) lies the reconfigurable machine tool (RMT), a cornerstone facilitating adaptability at the process design level [3]. This pivotal component epitomizes the agility to swiftly adapt and reconfigure its functions and capabilities, aligning with evolving production requirements and dynamic market demands. By leveraging reconfigurable machine tools (RMTs), RMSs can adeptly respond to evolving manufacturing needs, optimizing production processes and enhancing overall operational flexibility and efficiency [4]. Recent advancements in the literature, as discussed in [5], introduced modules enabling reconfigurable machines, termed multi-spindle RMTs, to perform operations simultaneously in parallel. Consequently, reconfigurable manufacturing systems (RMSs) can encompass a blend of multi-spindle machines (MRMTs) and single-spindle machines (SMRMTs), facilitating diverse operational configurations. The design intricacies of RMSs incorporating both single- and multi-spindle reconfigurable machines are explored in depth in [6]. The authors' research delved into optimizing the configuration of RMSs to capitalize on the capabilities of both single- and multi-spindle RMTs, thus enhancing overall manufacturing versatility and adaptability.

This study delves into assessing the performance of reconfigurable manufacturing systems (RMSs) incorporating reconfiguration policies, with a particular focus on the influence of multi-spindle reconfiguration machines. Simulation models are crafted to evaluate the impact of introducing one or two multi-spindle machines within an RMS under

various reconfiguration policies. The factors under scrutiny include part inter-arrival times, processing time variability, and the occurrence of failures. Through simulations, decision makers can glean insights to optimize the configuration of RMSs for enhanced performance.

The subsequent sections of this article are structured as follows. Section 2 provides a comprehensive overview of recent research on reconfigurable manufacturing systems, with a focus on the introduction of multi-spindle machines. Section 3 outlines the reference context and reconfiguration policy. Section 4 details the simulation models employed, while Section 5 delves into analysis of the numerical results. Finally, Section 6 offers conclusions and outlines potential avenues for future research.

2. Literature Review

The literature review conducted by Bortolini et al. (2018) [7] identified five key areas for future research in reconfigurable manufacturing systems (RMSs): reconfigurability level assessment, analysis of RMS features, RMS performance analysis, applied research and field applications, and reconfigurability towards Industry 4.0. They highlighted the importance of exploring the best practices to efficiently guide modern industrial companies toward adopting reconfigurable manufacturing. However, this comprehensive review does not include consideration of multi-spindle machines in RMSs. On the other hand, the authors of [8] offered a review of optimization problems related to RMSs, categorizing studies into four areas: RMS design, production planning and scheduling, layout design, and line balancing and rebalancing problems. Their review provides valuable insights into various aspects of RMS optimization, shedding light on key challenges and potential solutions in the field.

In the work proposed in [9], a sophisticated decision-making approach grounded in game theory, particularly the Gale–Shapley model, was proposed to streamline machine re-configurations effectively. Through comprehensive simulations, the authors of [10] showcased enhanced performance metrics achieved through controlled reconfigurations. Furthermore, the authors of [10] introduced the concept of focused flexible manufacturing systems (FFMSs), which integrate both general-purpose and dedicated resources to optimize system efficiency. Leveraging genetic algorithms, hybrid manufacturing systems are meticulously designed, taking into account intricate factors such as customer demand, operational requirements, and market uncertainties, which are meticulously assessed through Monte Carlo simulations. These pioneering methodologies mark significant advancements in the field, promising enhanced adaptability and performance in modern manufacturing environments.

In their groundbreaking study, the authors of [11] introduced a comprehensive multi-objective approach aimed at optimizing the design of reconfigurable manufacturing systems (RMSs). Their objectives encompass maximizing system modularity while concurrently minimizing the completion time and cost. The proposed methodology leverages a modularity-based technique employing adapted multi-objective simulated annealing (AMOSAs), complemented by a sophisticated decision-making tool based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Through an illustrative example and rigorous numerical analyses, the authors of [11] illustrated the practical applicability and effectiveness of their approach, underscoring its potential to revolutionize RMS design and performance optimization.

In their comprehensive study, the authors of [12] delved into the intricate realm of quality considerations within process planning for reconfigurable manufacturing systems (RMSs). Their analysis meticulously examined the impact of quality variations on cost-based design and modular features, elucidating the distinction between conforming and failed products. To address these challenges, the authors of [12] proposed a novel multi-objective, mixed-integer nonlinear programming model, which they applied to an industrial case study using both exact and hybrid meta-heuristic solutions. By providing valuable insights into the interplay between quality and process planning, their findings offer invaluable guidance for decision makers navigating RMS implementation.

On a related front, the authors of [13] tackled the formidable challenges of production scheduling in RMSs constrained by limited auxiliary modules (AMs). Their pioneering work introduced a sequence-based mixed-integer linear programming (MILP) model designed to minimize the total weighted tardiness (TWT). Additionally, they presented an improved genetic algorithm (IGA) tailored to addressing these scheduling challenges. Through extensive experimental validation, including real-world case studies, the authors of [13] demonstrated the remarkable effectiveness of the IGA across diverse scenarios, highlighting its potential to optimize production scheduling in RMSs with limited AMs.

In their pioneering work, the authors of [5] introduced a systematic approach to configuring reconfigurable machine tools (RMTs) through modular design principles. Their methodology entails the generation of geometry and basic structure modules which are then integrated into conceptual autonomous functional modules, ensuring adaptability to diverse manufacturing requirements. By optimizing processing plans tailored to specific part families, the authors of [5] demonstrated the efficacy of their approach in deriving RMT configurations that effectively meet process requirements. Furthermore, this study explored the feasibility and implications of incorporating multi-spindle machines into the reconfigurable manufacturing landscape. Through a comprehensive analysis, the authors of [5] illustrated the practical effectiveness of their methodology using a gearbox part family production as a case study, underscoring its potential to enhance manufacturing flexibility and efficiency in real-world applications. On a related note, the authors of [14] addressed the formidable challenge of scheduling in reconfigurable manufacturing systems (RMSs) through a formalized approach utilizing integer linear programming. Their work introduced an iterative search method aimed at optimizing scheduling solutions, revealing promising improvements in solution quality. However, the study also highlights the inherent computational complexities associated with this approach, emphasizing the need for further investigation to address these challenges and unlock the full potential of scheduling optimization in RMSs.

The authors of [15] introduced an innovative integrated approach that merges stochastic analysis with lot sequence optimization, aimed at maximizing the system service level within real industrial contexts. Their method represents a significant advancement in addressing complex scheduling challenges within manufacturing systems, offering practical insights into enhancing operational efficiency and performance.

The authors of [16] proposed a comprehensive framework for configuration selection in manufacturing flow lines (MFLs) utilizing the non-dominated sorting genetic algorithm-II (NSGA-II). Their research emphasizes the importance of considering multiple objectives in optimizing reconfigurable manufacturing systems (RMSs), contributing valuable insights into improving system performance across various operational parameters.

The authors of [17] introduced a novel nonlinear integer programming model designed to optimize both modular product and RMS configurations, making them tailored to individual customer needs. By employing a genetic algorithm approach and utilizing customizable office chairs as an illustrative example, their study underscores the critical role of integrated configuration decisions in achieving optimal process plans and minimizing associated costs. Furthermore, the authors of [18] presented an innovative nonlinear integer programming model focusing on optimizing modular product and RMS configurations to minimize the manufacturing costs for mass-customized products. Their approach, which integrates a modified brute force algorithm (MBFA) and genetic algorithm (GA), demonstrated efficient solution finding within reasonable computation time constraints, as validated through experimentation with modular smartphones. This research contributes valuable insights into the effective management of configuration decisions in reconfigurable manufacturing contexts, facilitating improved cost-effectiveness and adaptability in meeting diverse customer demands.

The authors of [19] introduced intelligent decision making for dynamic scheduling and reconfiguration using deep reinforcement learning (DRL) in a reconfigurable flow line (RFL) with dynamic job arrivals. They proposed a system architecture and mathematical model to minimize the total tardiness cost, integrating a DRL system with advantage actor critic (A2C). The results exhibited significant improvements over traditional meta-heuristics.

The authors of [20] presented a constrained nonlinear optimization problem to determine an optimal layout of reconfigurable fixtures for specific workpieces. Considering the kinematic limitations of Stewart platforms and workpiece characteristics, the experimental results confirmed that the automatically computed layouts satisfied typical production constraints effectively.

The authors of [21] introduced a digital twin-driven approach for rapid reconfiguration of automated manufacturing systems. Their method involves a semi-physical simulation integrated with an optimization component. Open-architecture machine tools (OAMTs) allow for quick module swapping, enhancing adaptability. The key techniques include twinning cyber-physical systems and bi-level programming for adaptive production. Physical implementation validates the improved system performance with minimized reconfiguration overheads. The authors of [22] proposed reconfiguration management as a holistic problem, outlining the potential goals achievable through this approach. The authors of [23] aimed to efficiently select between two types of reconfigurable machine tools (RMTs) for executing part process plans. A machine's configurational capability determines the RMT type selection, which is addressed through a genetic algorithm-based approach. An example demonstrates the method's validity for reconfigurable manufacturing system (RMS) design, with future research considerations.

The authors of [24] endeavored to optimize the set-up and process planning simultaneously, aiming to minimize the overall costs including processing, tolerance, set-up change, and tool module expenses. They introduced a hybrid genetic algorithm-based approach comprising two stages: heuristic set-up generation followed by genetic algorithm-based process plan optimization. Numerical experiments validated the approach's applicability and economic advantages.

Table 1 summarizes the main characteristics of the literature review we discussed. The main issues considered were the design of the manufacturing system (design) or the operational activities (as reconfigurations or scheduling). The main methods used to support the works were the simulation or heuristic approaches (e.g., game theory or genetic algorithms). Then, the introduction of multi-spindle machines was considered, and these cases were also studied for real industrial potential applications (case study).

Table 1. Classification of the literature review.

	Design	Reconfiguration or Scheduling	Simulation	Heuristic	Multi- Spindle	Case Study
[9]		X	X	X		
[10]	X		X			
[11]	X			X		X
[12]		X		X		
[13]		X		X		
[5]	X				X	X
[14]		X		X		
[15]		X		X		
[16]	X			X		
[17]	X			X		
[18]	X			X		
[19]		X		X		
[20]	X			X		
[21]	X			X		
[22]		X				
[23]	X			X	X	X
[24]		X		X		

From the above literature review, few works studied the introduction of multi-spindle machines in reconfigurable manufacturing systems. These works concern the design of the manufacturing system, but all works investigated the performance measures and the impact of multi-spindle machines on them, including the reconfiguration policy.

The original contribution of this work is the evaluation of the impact of multi-spindle machines in reconfigurable manufacturing systems under a reconfiguration policy. The simulation model developed allows testing the different conditions in terms of interarrival, process time variation, and the introduction of failures.

3. Reference Context

The reference context concerns a discrete manufacturing system where the process plan of the jobs can range from 1 to 6 manufacturing operations. To evaluate the impact of the multi-spindle machines, the base model is a dedicated manufacturing system. Therefore, the manufacturing system consists of six machines with different configurations discussed in Section 4. The jobs manufactured are characterized by a random operation from 1 to 6, a random sequence of the operations without a direct flow in the operation sequence, and stochastic processing times. This allows obtaining more generalized results of the numerical analysis. Finally, the jobs in the queues follow the earliest due date (EDD) rule to minimize production delays.

Machine reconfiguration times are considered negligible and can coincide with maintenance or tool change activities. Initially, the manufacturing system comprised six dedicated machines, with each tailored to a specific operation without reconfiguration capability. An alternative configuration involves six machines capable of performing one operation at a time, with reconfiguration options available for each machine to handle additional operations. Effective management of these adaptable machines necessitates a reconfiguration decision support strategy.

The notation is as follows:

$m = 1, \dots, M$ is the index of the machines;

i is the index of the part;

$k = 1, \dots, K$ is the index of the manufacturing operation;

PT_{ik} is the processing time of the part i for the operation k ;

WL_k is the direct workload of the part that requires operation k ;

WL_{av} is the average of the direct workload over all operations k ;

Th_{av} is a threshold on the WL_{av} ;

Th is a threshold $+/-$ in terms of a percentage around the WL_{av} ;

T_p is the period of time fixed to evaluate the reconfiguration of the machines.

3.1. Reconfiguration Model

The reconfiguration model serves to evaluate the status of the manufacturing system and facilitate decision making regarding reconfiguration activities, adhering to two distinct policies: periodic review and continuous review. In order to dynamically support reconfiguration, the assessment prioritizes the direct workload of jobs for each manufacturing operation, ensuring adaptability to changing demands and operational needs. When scheduling identifies the next manufacturing operation (k), its direct workload increases, considering the processing time of the operation:

$$WL_k = WL_k + PT_{ik} \quad (1)$$

Then, the average direct workload over the manufacturing operations is computed:

$$WL_{av} = \frac{\sum_{k=1}^K WL_k}{K} \quad (2)$$

The machines' reconfiguration activities can be initiated under two conditions: periodic review and continuous review.

Following the periodic review approach, at each period T_p , the reconfigurations of the machines are evaluated. First, it is determined if WL_{av} is greater than a threshold Th_{av} . If this condition is true, then the potential machines to reconfigure can be evaluated. Then, the operation k_1 with higher direct workload and the operation k_2 with lower direct workload are determined. To start the reconfiguration activities, the direct workload k_1 has to be greater than $WL_{av} \times (1 + Th)$, and k_2 has to be lower than $WL_{av} \times (1 - Th)$. If the above conditions are true, then the reconfiguration model determines the machine to reconfigure. The first machine detected that performs the operation k_2 with a lower workload compared with the average workload is reconfigured to perform operation k_1 , which is characterized by a critical level of workload.

In the case of a continuous review, the reconfiguration of the machine is evaluated after every change in workload computation. When the next operation of the job is determined, and the relative WL_k is updated (Equation (1)), if WL_k is greater than $WL_{av} \times (1 + Th)$, then it is verified if the operation k_2 with the lower workload WL_{k2} is lower than $WL_{av} \times (1 - Th)$.

If the above conditions are true, then the reconfiguration model determines the machines to reconfigure.

The first machine detected that performs the operation k_2 with a lower workload compared with the average workload is reconfigured to perform operation k_1 , characterized by a critical level for the workload.

3.2. Multi-Spindle Machines

The third manufacturing system is a reconfigurable manufacturing system equipped with one or two multi-spindle machines. These multi-spindle machines are capable of executing either a single operation or two defined operations simultaneously, provided they are compatible with the multi-spindle machine. Jobs requiring the multi-spindle machine's operations are divided into two sets: those necessitating a single operation and those capable of executing both operations together. However, these two operations must adhere to the precedence constraints outlined in the production planning. Additionally, operations that can be conducted in parallel are carefully selected to avoid any tool collisions or other interactions that might hinder their simultaneous machining. The jobs within the two sets are prioritized based on their compatibility with the multi-spindle machine; those that can be manufactured together using the multi-spindle machine are given priority over those that require the machine for a single operation. Assessing the direct workload of these two subsets and the complexity involved in evaluating the reconfiguration of one or both operations of the multi-spindle machine prompted us to focus on multi-machine configurations with fixed operations for the scheduling period under investigation. Meanwhile, the other machines in the manufacturing system can be reconfigured according to the guidelines outlined in Section 3.1.

4. Simulation Models

To evaluate the performance of the reconfigurable manufacturing system with the introduction of multi-spindle machines, several configurations have been developed. The following configurations were considered:

- A configuration with 6 machines configured, with each machine configured to perform a fixed operation (No-reconf). This was a dedicated model without reconfigurations used as a base model.
- A configuration with 6 machines with the possibility to reconfigure each machine for all 6 operations following a periodic policy (rec-p).
- A configuration with 6 machines with the possibility to reconfigure each machine for all 6 operations following a continuous policy (rec-c).
- Configurations with 5 machines and 1 multi-spindle machine, with each machine configured for performing a fixed operation (No-reconf_M1).

- A configuration with 5 machines with the possibility to reconfigure each machine for all 5 operations following a periodic policy and one multi-spindle machine (rec-p_M1).
- A configuration with 5 machines with the possibility to reconfigure each machine for all 5 operations following a continuous policy and one multi-spindle machine (rec-c_M1).
- Configurations with 4 machines and 2 multi-spindle machines, with each machine configured for performing a fixed operation (No-reconf_M2).
- A configuration with 4 machines with the possibility to reconfigure each machine for all 4 operations following a periodic policy and 2 multi-spindle machines (rec-p_M2).
- A configuration with 4 machines with the possibility to reconfigure each machine for all 4 operations following a continuous policy and 2 multi-spindle machines (rec-c_M2).

Table 2 presents the experimental conditions, where the inter-arrival times, which followed an exponential distribution (EXPO), were adjusted to achieve average machine utilization rates of approximately 80% and 90%. Two levels of processing time variations were considered, along with scenarios both without and with failures. The processing time followed a uniform distribution (UNIF), with a mean of 10 and two levels of variation: $\pm 20\%$ or 40% of the mean. The failure parameters, the mean time between failures (MTBF) and mean time to repair (MTTR), followed an exponential distribution to consider a higher variation. A total of 72 simulations were conducted, encompassing the 8 combinations of these conditions and the 9 models analyzed.

Table 2. Experimental experiments.

No.	EXPO	Processing Time	Failures
1	6	UNIF (8–12)	NO
2	5.5	UNIF (8–12)	NO
3	6	UNIF (6–14)	NO
4	5.5	UNIF (6–14)	NO
5	6	UNIF (8–12)	MTBF: EXPO(100); MTTR: EXPO(10)
6	5.5	UNIF (8–12)	MTBF: EXPO(100); MTTR: EXPO(10)
7	6	UNIF (6–14)	MTBF: EXPO(100); MTTR: EXPO(10)
8	5.5	UNIF (6–14)	MTBF: EXPO(100); MTTR: EXPO(10)

The performance measures used to test the manufacturing system configurations were the following:

- Throughput (parts/unit time): the total number of items processed over the simulation time period.
- Average throughput time (unit time): the average time in which the parts passed through the manufacturing system.
- Standard deviation of the throughput time (unit time): the stability of the manufacturing system.
- Average utilization of the machines: the utilization of the machines of the manufacturing system.
- Coefficient of variation of the average utilization of the machines: the uniformity of utilizations of the machines.
- Work in process (WIP) (parts): the average total parts in the system.
- Total delay of the parts (unit time): the customer satisfaction for the orders delivered.
- Average delay for unit of product (unit time for product): the penalty costs for the delayed order deliveries.

The simulation length was 28,800 units of time. For each experiment class, a number of replications able to assure a 5% confidence interval and 95% confidence level for each performance measure were conducted.

5. Numerical Results

This section delves into the primary simulation results to underscore the key findings. Figure 1 illustrates the throughput rate differences across the eight combinations, presented as a percentage relative to the no reconfiguration model. The results indicate minor variances, with cases 6 and 8 showcasing a 2% improvement when employing the continuous reconfiguration model with two multi-spindle machines. These cases exhibited higher average utilization and included the introduction of failures. Notably, the introduction of a single multi-spindle machine resulted in reduced performance for case 8.

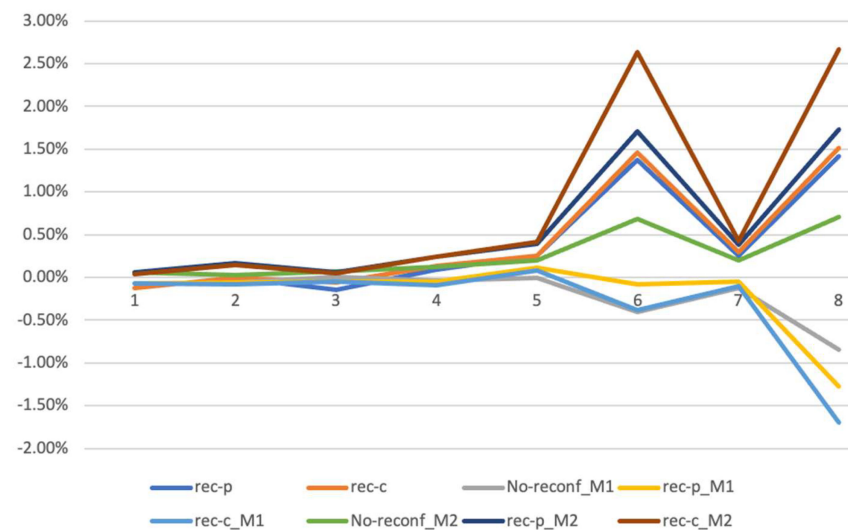


Figure 1. Throughput rate.

Figure 2 displays the average time in the system for the tested models. Reconfiguration activities showed a noticeable advantage, particularly when failures occurred within the manufacturing system (cases 5–8). Interestingly, the introduction of a single multi-spindle machine may pose challenges in management, as it did not yield improvements in the simulated cases. Conversely, introducing two balanced multi-spindle machines consistently resulted in performance enhancements, particularly when coupled with continuous reconfiguration policies in cases involving failures.

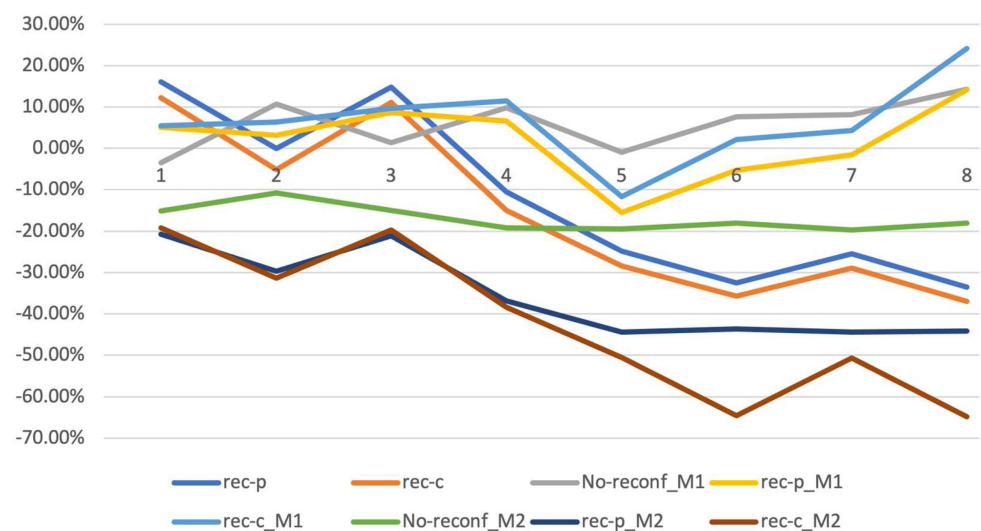


Figure 2. Average time in manufacturing system.

Figure 3 depicts the standard deviation of the average time in the system. Interestingly, introducing just one multi-spindle machine tended to increase the instability of the average time in the systems across various tested conditions. Conversely, the other models contributed to enhancing the stability of the average time in the system. Notably, the introduction of two multi-spindle machines, particularly in scenarios involving failures, substantially reduced the fluctuations by over 50%.

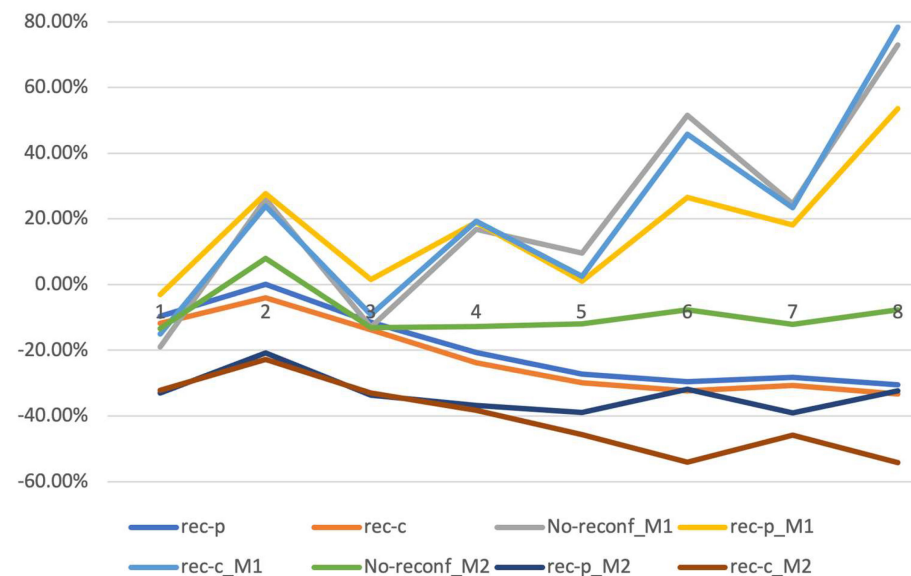


Figure 3. Standard deviation of average time in manufacturing system.

Figure 4 illustrates the average delay per part. Intriguingly, introducing only one multi-spindle machine resulted in poorer performance in this aspect. On the other hand, reconfiguration without multi-spindle machines or with two multi-spindle machines significantly enhanced this performance metric. Notably, this aspect shows the potential for greater improvement compared with other measures.

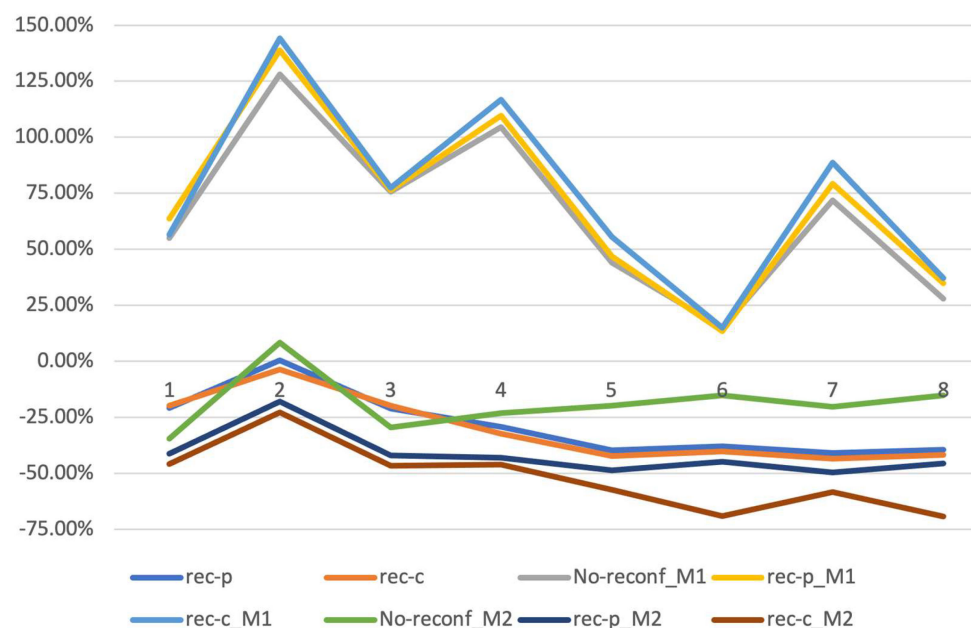


Figure 4. Average delay for unit of product.

Similar improvements were observed for the work in process, as depicted in Figure 5. However, the benefits in this regard were slightly lower compared with the average delay for a unit of product. This suggests that while reconfiguration strategies contribute to reducing the work in process, their impact may not be as pronounced as in other studied performance measures.

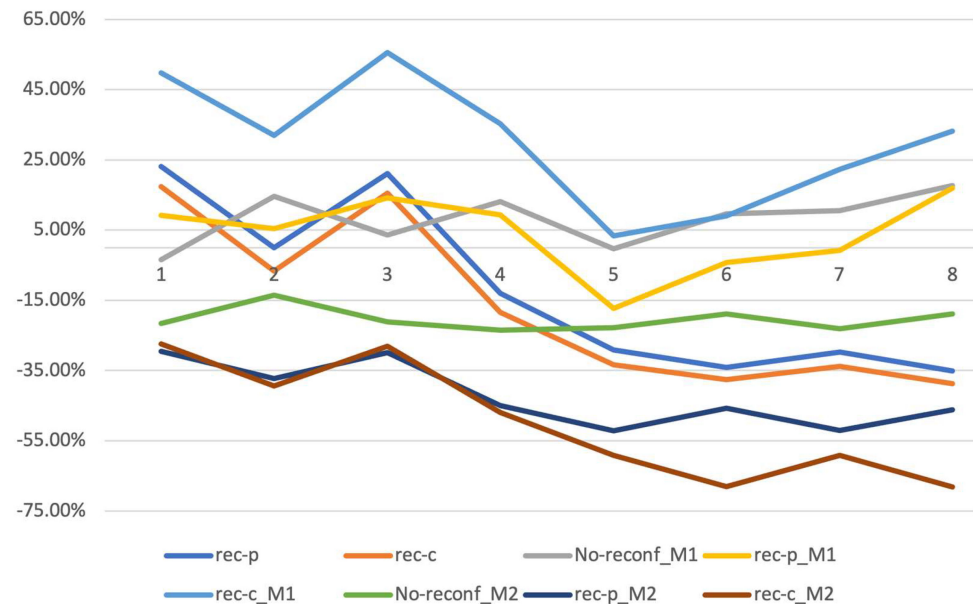


Figure 5. Work in process.

The effects of the inter-arrival time, processing time, and failures were evaluated using Design of Experiment computation to assess their impact on the performance measures. Figure 6 illustrates the main and interaction effects for each model tested. Failures emerged as the most critical factor, followed by the inter-arrival time and the interaction between the inter-arrival time and failures. Other factors exhibited comparatively lower importance. Notably, reconfiguration policies (both periodic and continuous) and the introduction of two multi-spindle machines demonstrated a robustness that mitigated the effects of these factors on the manufacturing system.

Based on the analysis of the numerical results, several key observations emerged:

- Introducing only one multi-spindle machine resulted in an unbalanced reconfiguration of manufacturing systems, complicating reconfiguration activities. Conversely, employing two multi-spindle machines yielded more substantial improvements in the performance measures, indicating a more favorable system behavior.
- The continuous reconfiguration policy demonstrated superior performance improvement compared with periodic reconfiguration.

Design of Experiment (DoE) analysis underscored the significant impact of introducing failures and exponential inter-arrival times. The reconfigurable manufacturing system exhibited greater resilience to variations in processing time.

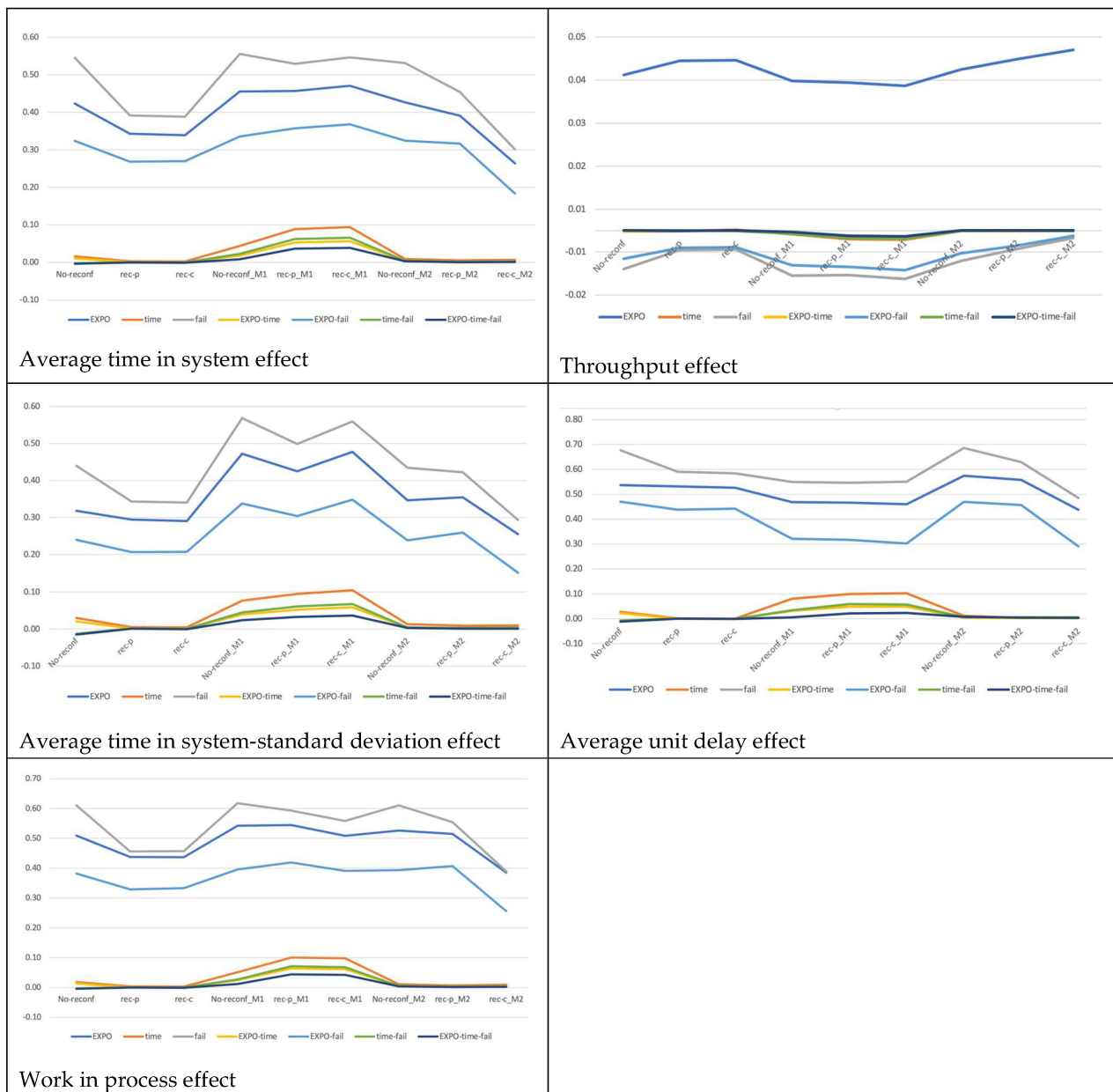


Figure 6. DoE effects on the factors.

6. Conclusions and Future Development Paths

Reconfigurable manufacturing systems (RMSs) enhanced by Industry 4.0 advancements represent a transformative approach in manufacturing. By fostering agility, cost efficiency, and heightened customer satisfaction, the RMS drives competitiveness in the manufacturing domain. The integration of new modules, particularly multi-spindle machines capable of concurrent operations, expands the versatility of reconfigurable machines. Consequently, the design of RMSs now encompasses both single-spindle and multi-spindle machines. This study aimed to assess the performance of RMSs with multi-spindle machines under varying reconfiguration policies using simulation models. The numerical analysis encompassed adjustments in the number of multi-spindle machines, inter-arrival parameters and process time variability as well as the introduction of failures.

The integration of a lone multi-spindle machine into a reconfigurable manufacturing system governed by a reconfiguration policy may disrupt system behavior, constraining performance enhancements. Conversely, the incorporation of two balanced multi-spindle

machines significantly bolsters system performance without altering the machine's reconfiguration control policy. Among the parameters, the introduction of failures emerged as the primary factor exerting the most substantial influence on the performance metrics.

The managerial implications highlight the critical role of simulation models in assessing the potential impact of introducing multi-spindle machines. Properly evaluating various configurations beforehand allows for informed decision making to optimize the performance measures effectively. This proactive approach ensures that reconfigurable manufacturing systems can adapt efficiently to changing needs and maximize their operational capabilities.

Future research directions involve refining reconfiguration policies to incorporate and optimize the utilization of multi-spindle machines within reconfigurable manufacturing systems. Additionally, there is potential for investigating module allocation management for reconfigurable machines, exploring the feasibility of exchanging modules between single- and multi-spindle machines. The economic investment in multi-spindle machines will be studied to help decision makers evaluate the financial feasibility and potential returns associated with investing in machine tools, taking into account factors such as equipment costs, expected revenue streams, depreciation, and operational expenses. These endeavors aim to enhance the adaptability and efficiency of manufacturing systems, contributing to advancements in responsive production strategies.

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