A Systematic Review of Cellular Manufacturing System Approaches.

Ibrahim Mousad[1*], Wael Salaheddin Moughith[1], A.S. Elmesalamy[1], and Moustafa Gadalla [1]

[1] Military Technical College, Cairo, Egypt
E-mail: ibrahimmousad@mtc.edu.eg.

Abstract. Cellular Manufacturing Systems (CMS) is a key approach to improve production efficiency by integrating the principles of Group Technology (GT). In this review paper, three core aspects of CMS: Cell Formation (CF), Group Layout Design (GL), and Group Scheduling (GS) are studied to emphasise their impact on manufacturing performance. A systematic literature review was conducted, to analyse the most recent journal articles from reputable sources, focusing on optimization approaches applied to CMS. Notably, this is the first review paper that comprehensively discusses different CMS approaches, providing a comparative analysis of their optimization strategies. The findings indicate that CF represents (46%), and GS represents (36%) receive the most research attention due to their direct influence on cost reduction, throughput, and system flexibility, while GL represents (18%) which remains relatively underexplored. This study categorizes optimization techniques into exact-search methods (30%), heuristic algorithms (27%), and meta-heuristic approaches (43%), highlighting the dominance of Genetic Algorithms (GA), Simulated Annealing (SA), and Multi-Objective Programming in solving CMS-related problems. By integrating recent methodologies, this study provides valuable insights into CMS optimization trends and outlines key directions for future research.

1. Introduction

Group technology (GT) is a manufacturing philosophy that emphases on improving the resource utilization to enhance the production performance efficiency. The objective of GT is to reduce the effect of non-value added operations in the production line [1]. Cellular manufacturing (CM) is an application of GT that splits the production line into cells. each cell is designed to produce a part family. Cells are created to allow an efficient manufacturing of parts. CM provides a product-focused layout design to manufacture similar parts with low volume and high variation. The benefits of the Cellular manufacturing systems (CMS) can be summarized as follows: reduction in material handling, setup time, work-in-process inventory (WIP) ,and tooling [1,2]. In CMS, an alternative production approach is used to combine the productivity advantage offered by mass production with flexibility advantage of the workshop-style production [3]. To design and implement an effective CMS, there are three aspects must be considered as shown in Figure 1. The first one is Cell Formation (CF). It is a process of grouping parts and machines based on similarities in production to minimize the number of exceptional elements. It is concerned with Relocating parts from their designated cells to the cells containing the required machines and voids (the useless machines grouped with parts) [4]. The second aspect is Group Layout design (GL). It is focused on achieving an optimal arrangement of cells within each facility to minimize transportation costs and maximizing the space utilization [5]. the Third one is

Group Scheduling (GS). It is focused on optimizing production schedules within each cell to improve the throughput and reducing idle time [6]. Each of these aspects plays a vital role in achieving an effective cellular manufacturing system. The optimization models used requires the application of advanced computational techniques and mathematical models. Many exact search algorithms including linear programming methods, simulation-based techniques and clustering methods are used to refine the efficiency of CF, GL and GS. Thus, various heuristics and meta-heuristic approaches including genetic algorithms (GA), Simulated annealing (SA) and Particle Swarm Optimizations (PSO) are applied to solve complex CMS-related problems. The significance use of CMS extends beyond the cost minimization. by implementing an optimized CF, GL and GS, manufactures can achieve shorter cycle times, reduction in WIP, and improve the workers utilization.

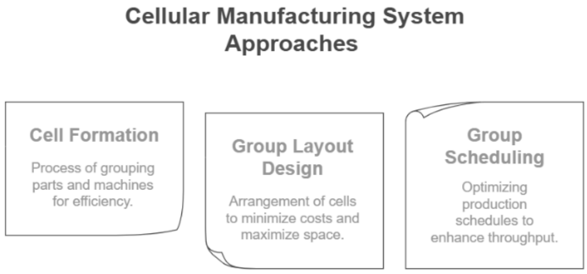

Figure 1. Approaches of CMS

Despite its advantages, the adoption of CMS poses challenges, such as initial setup costs, workforce training requirements, and the need for robust computational tools to ensure proper implementation. This paper focuses on exploring the three core aspects of CSM components, while introducing the optimization methods and objectives associated with them. By analyzing the latest strategies and methodologies used, this paper focuses on highlighting the most effective approaches used to improve the cellular manufacturing efficiency and minimizing costs. The following sections in this paper organized as follows. Section 2 shows the methodology our survey. In section 3 the literature review is discussed in detail, Section 4 analyses the survey results. Section 5 shows the conclusion of this review analysis.

2. Research Methodology

To include as many relevant contributions as possible, a systematic literature search was conducted, i.e., Elsevier, Taylor & Francis, and Springer, using the corresponding keywords. A detailed search has been done on Web of Science and SicVal, using the following keywords: Group technology, Cellular manufacturing, Cellular manufacturing systems, Integer Linear Programming, and genetic algorithms. There are a few comprehensive review papers with various objectives and viewpoints. Inclusion criteria focused on peer-reviewed studies addressing Cell Formation (CF), Group Layout Design (GL), or Group Scheduling (GS), with empirical results or mathematical models, and written in English. By retrieving papers from Elsevier, Taylor & Francis, and Springer, thereby, 148 journal articles that are related to the cellular manufacturing systems. Figure 2 shows the number of publications in this field per year since 2020. It can be noticed that there is a reduction in the number of research articles being published from 2020 till 2023. The systematic framework focuses on articles that are evaluated for relevance to CMS optimization models, methodological robustness (e.g., clarity of objectives, algorithm performance), and impact (e.g., citations, journal ranking). This study relies on open-access and publicly available journals that can be downloaded without access limitations, ensuring comprehensive and unrestricted access to relevant research materials, therefore, 50 articles are included in this study emphasize the recent advancements in CMS efficiency, balancing exact, heuristic, and meta-heuristic techniques.

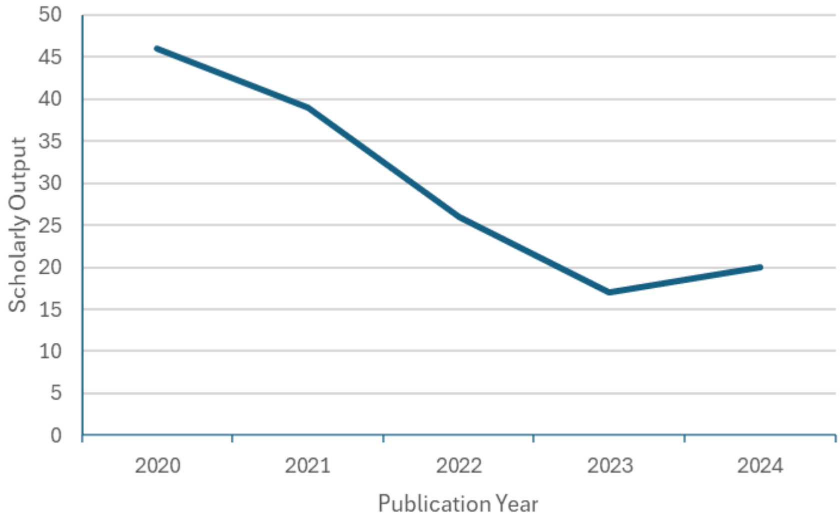

Figure 2. The number of publications in the field

3. Review of CMS Approaches

This review will focus on representation of the use of different approaches of cellular manufacturing using various methods of algorithms and search methods to meet one or more objectives. In addition to that this study integrates the use of optimization techniques needed to improve system efficiency. The study categorizes optimization techniques into exact-search methods, heuristic algorithms, and meta-heuristic approaches.

3.1 Cell Formation

Several studies have been conducted to optimize the cell formation focusing on ensuring an efficient minimization of inter-cell movements improving machine-part grouping and enhancing the workflow efficiency. CF faces challenges including sensitivity to demand fluctuations and production variability, reliance on sophisticated algorithms for complex machine-part grouping, and potential difficulties in achieving optimal results in highly dynamic environments without real-time adaptation. Meta-heuristic algorithms like Genetic Algorithm (GA), Ant Colony Optimization (ACO), and Simulated Annealing (SA) are widely used for solving large-scale complex cell formation. Meta-heuristic algorithms can handle the dynamic conditions as demand fluctuations or varying machine-part grouping by providing near-optimal solutions. Golmohammadi et al. developed a bi-objective mixed-integer non-linear programming model to explore the application of the meta-heuristics algorithms including Genetic Algorithm (GA), Keshtel Algorithm (KA), Red Deer Algorithm (RDA). They introduced a new hybrid meta-heuristic algorithm that combines the strength of these methods to optimize the cell formation while minimizing the total cost associated with parts relocation and cell reconfiguration while considering sequence-dependent intra- and inter-cell movements in a fuzzy environment to handle the uncertainties in demand and costs. The model highlights the critical role of dynamic layouts in reducing material handling costs and improving the efficiency of cellular manufacturing systems [7]. Sathish et al. studied a different hybrid heuristic algorithm with the same objectives defined by Hamza & Khalaf. both designed a multi-objective hybrid heuristic algorithm to maximize the grouping efficiency and machine utilization while minimizing the percentage of exceptional elements[8,9]. This method integrates cell formation to ensure that machines and parts are grouped to reduce the inter-cell movements and improve the workflow. Li used a heuristic-based algorithm to optimize cell formation in CMS to ensure grouping of machines and parts while focus on considering alternative operation routes and machine flexibility [11]. Won used the exact search algorithms to optimize the generalized cell formation in CMS to maximize group efficacy (GE) by optimizing the assignment of machines and parts to cells to ensure a systematic and optimal configuration of machine cells [12]. In the study provided by [13], the author employs Ant Colony Optimization (ACO)-based approach, which mimics the behavior of ants using artificial pheromone trails to define part families and remanufacturing cells. the study integrates efficiently cell formation to ensure an effective clustering of machines and products based on their similarity measures. Wu et al. used a heuristic algorithm to address the cell formation problem in CMS to minimize material intercell movements by improving similarity coefficient methods [14]. In the case study provided by [15], the authors used Genetic Algorithm (GA) combined with Simulated Annealing (SA), to efficiently solve a three-dimensional part-machine-worker assignment problem to minimize exceptional elements (EE) and voids while maximizing the part quality index. This study focuses on cell formation to ensure optimal grouping of parts, machines, and workers based on skill levels and machines capabilities. Figueroa-Torrez et al. employed a Binary Black Widow Optimization (B-BWO) algorithm to minimize total intercellular movement costs and machine breakdown costs. The author used cell formation to maximize grouping efficiency while accounting for system reliability [16]. The study introduced by the authors [17] employs the use of an Enhanced Dragonfly optimization method to minimize the manufacturing lead times and optimize the inter-cellular movements. the methodology used focuses on the cell formation to optimize outputs and reduce the production costs. Phung et al. explores the application of improved clustering algorithm to address the cell formation problem to minimize the inter-cell moves and voids within the machine cells [18]. Mansour & Ugla developed a Genetic Algorithm (GA) to optimize the formation of the manufacturing cells by minimizing the inter-cell transfer and overall processing cost[19]. Phung, Nguyen, and Truong developed a clustering algorithm to maximize group technology efficiency by minimizing actual inter-cell moves, voids, and intra-cell moves. The methodology focuses on cell formation to ensure higher compactness of machine cell and reduction in material handling costs [18].

3.2 Group Layout Design

GL focuses on improving the space utilization to ensure that groups are positioned efficiently within the facility. The effectiveness of GL is often dependent on its integration with Cell Formation (CF) or Group Scheduling (GS), or both, as it directly influences production flow, transportation costs, and overall system efficiency. Several studies have investigated different approaches to GL, utilizing optimization techniques to enhance layout efficiency while ensuring seamless workflow across the production system.

GL faces many challenges including the need for extensive reconfiguration while introducing new products or machines, reduction in flexibility during handling irregular product demand, and potential inefficiencies in fast-changing production environments without frequent adjustments. Khamlichi et al. developed a multi-objective meta-heuristic optimization algorithm to minimize the intra- and inter-cell material handling costs, holding and machine relocation costs while optimizing inventory management and lot-sizing decisions in a dynamic cellular manufacturing system. This technique integrates cell formation, group layout design and production planning to optimize resource utilization and cost efficiency [20]. Rostami et al. used a multi-objective mixed-integer linear programming model to maximize the total profit, grouping efficacy and the number of the new products developed. This methodology integrates cell formation, group layout design and group scheduling allowing for a flexible machine allocation and optimal production scheduling [21]. Rafiee & Mohamaditalab presented a mixed integer linear programming to minimize workforce-related costs, machine breakdown costs and inter-cell part movement while balancing operator skill levels and optimizing process routing. This model focuses on integrating cell formation, group layout design and group scheduling to improve production stability and enhance the workforce allocation[22]. In this study [5] presented a heuristic algorithm used to effectively group machines and products within manufacturing cells to minimize the total distance required for material handling by integrating the use of cell formation and group layout design to optimize the machine placement and reduce the unnecessary movements between workstations. Behnia et al. developed a nested Bi-level metaheuristic algorithm to minimize the voids and exceptional elements in cell formation at the upper level and maximizing worker cooperation and synergy at the lower level. this methodology combines cell formation, group layout design, and group scheduling, to ensure an optimal machine and part assignments [23]. The study introduced by Ramesh et al. used an exact search algorithm to effectively minimize the inter- and intra-cell movements, machine duplication costs and part subcontracting expenses while optimizing material flow and floor space utilization, this method uses cell formation, group layout design, and group scheduling to ensure efficient machine clustering and floor area optimization[24]. Alhawari et al. used an exact-search method to maximize the profits, the methodology used employs cell formation, group layout design and group scheduling to effectively group the product families and allocate machine resources [25]. Forghani et al. investigates the integration of cell formation, group layout design and group scheduling to minimize the material handling costs and cycle time using a Population-based Simulated Annealing (PSA) combined with linear programming [26]. Aghajani-Delavar et al. introduced a Multi-Objective Vibration Damping Optimization (MOVDO) algorithm to minimize the total costs to improve the system efficiency. The study combines cell formation, group layout design and group scheduling to ensure optimal workforce deployment and efficient tool utilization [27]. Al-Zuheri et al. used a hybrid Genetic Algorithm (GA) combined with a Desirability Function approach to minimize the intercellular movements and the overall material handling costs. The methodology integrates cell formation and group layout design to ensure high system adaptability [28]. Raja & Vignesh utilized a similarity coefficient-based heuristic method to minimize inter-cell and intra-cell movements The technique integrates cell formation, group layout, and group scheduling, ensuring optimal machine grouping and part assignment [29]. Emine Bozoklar proposed three multi-objective mathematical programming models to minimize costs associated with carbon emissions, intercellular movements, machine processing, machine replacement, worker training, and additional wages (bonuses). The methodology focuses on cell formation and group layout design to enhance system performance and reduce production costs [30]. Ramesh et al. used integer linear programming model to minimize manufacturing costs, The study integrates cell formation, group layout design, and group scheduling, considering dynamic conditions such as changes in time periods, part demand, and machine flexibility [31]. In this CMS, this paper involves the use of cell formation, group layout and group scheduling to optimize the weighted completion time, transportation cost and machine idle time using a multi-objective linear programming model solve using ϵ-constraint method and a Non-Dominated Sorting Genetic Algorithm II (NSGA-II) [32]. Razmjooei et al. used a hybrid Multi-Objective Tabu Search-Genetic Algorithm (MO-TS-GA) to maximize the makespan and reduces the intercellular translocations. The methodology used includes cell formation, group layout design and group scheduling within a three-dimensional space of machine-part-human resource allocation [33]. In the case study discussed by Naranjo et al about the Formation and Evaluation of Manufacturing Cells in a Textile Company, the authors used a Mixed-Integer Linear Programming (MILP) model to minimize the total production and material handling costs while maximizing machine utilization. The author used cell formation, group layout design, and group scheduling to ensure optimal product and machine allocation [34]. Bouaziz et al. developed a hybrid meta-heuristic and exact search algorithm to minimize material handling costs and worker movement while maximizing part quality in the CMS. the study focused on integrating cell formation, group layout design, and group scheduling to ensure an effective workforce distribution and optimal machine utilization [36].

3.3 Group Scheduling

GS is critical approach in CMS as it focuses on optimizing the production schedules within each cell using exact-search, heuristic or meta-heuristic methods. Meta-heuristic algorithms like GA, Adaptive Differential Evolution-Simulated Annealing (ADE-SA), and Multi-Objective Tabu Search-Genetic Algorithm (MO-TS-GA) adapt to dynamic task priorities to ensure a flexible scheduling and reduce idle time. GS ensures that jobs are efficiently sequenced to enhance productivity. GS is often integrated with Cell Formation (CF) or Group Layout Design (GL), or both, as the scheduling efficiency depends on well-structured machine-part groupings and optimal cell arrangements. Goli et al. used a hybrid Genetic Algorithm (GA) combined with Whale Optimization Algorithm (WOA), to minimize makespan and inter-cellular movements of parts. The methodology combines cell formation and group scheduling to optimize workforce allocation and automated material handling within CMS [37]. Mourtzis et al. focused on the small and medium enterprise (SME) manufacturing solar panel heaters. The study employs a meta-heuristic algorithm based on decision tree, integrating real time cooperation among machines, workforce and production managers. The study focused on minimizing the production latency by dynamic adjustments of schedules in response to unexpected events such as machines breakdown or new task arrivals. The methodology uses group scheduling techniques to optimize the task allocation and machine utilization within the CMS [38]. The study proposed by Kataoka et al employs a multi-period mixed integer programming model to minimize the total number of operators while meeting the required demand for the dynamic production environment. The model integrates cell formation and group scheduling to optimize cellular manufacturing and cell production systems [39]. Li used robust cluster-based approach for machine arrangement in CMS while considering spatial constraints. The objective of the proposed study is to minimize material handling costs and machine relocation while minimizing workspace utilization. This technique integrates cell formation and group layout design to minimize the unnecessary movements [40]. Costa et al. developed a parallel Self-Adaptive Genetic Algorithm to minimize makespan by optimizing job sequencing, group setup times, and machine utilization considering sequence-dependent group scheduling constraints. This study integrates group scheduling technique while considering inter-group dependencies and blocking constraints [42]. Mej developed a mixed integer nonlinear programming model to define cell formation, workload balancing, scheduling sequence to minimize operational inefficiencies and reconfiguration costs. This model combines cell formation, group layout design, and group scheduling to ensure adaptability in remanufacturing environments [43]. Ebrahimi et al. studied a hybrid meta-heuristic algorithm to efficiently schedule tasks in CSM. The study focuses on maximizing total profit by increasing revenue while minimizing energy costs and tardiness penalties. This model focuses on group scheduling problems to ensure better machine allocation and scheduling decisions [45]. Ghoushchi & Abbasi employed a heuristic algorithm, specifically a simulation-based optimization approach integrating Taguchi Design of Experiments (DOE), Discrete Event Simulation (DES), Artificial Neural Networks (ANN), and Data Envelopment Analysis (DEA) to identify the optimal workforce allocation and job sequencing strategy, such a methodology combines group scheduling to ensure that operators are optimally assigned across different cells [46]. Wu et al. used heuristic-based scheduling approach to minimize the long-run expected makespan by optimizing machine allocation, job sequencing, and synchronized order completion. This technique integrates group scheduling to ensure parallel machine utilization and order fulfillment synchronization [47]. Saraçoğlu, Süer, and Gannon employed a hybrid approach combining Mixed-Integer Linear Programming (MILP) with a Genetic Algorithm (GA) to minimize the makespan and the total flow time. The methodology used focused on cell formation, group layout design and group scheduling to ensure efficient product sequencing [3]. Cheng et al. integrates the use of the cell formation and group scheduling techniques using Q-learning-based Genetic Algorithm (Q-GA) to minimize the makespan to ensure an effective sequencing of both product families and products [48]. Yetkin & Ulutas illustrates the use of stochastic mixed integer linear programming in cell formation and group scheduling to minimize the total cost of worker employment and robot operation while considering technical and non-technical skill levels [49]. The case study provided by Cáceres-Gelvez et al about the Sewing Department of a Sportswear Manufacturing Company focused on integrating cell formation and group scheduling techniques to minimize the average flow time and setup times while maximizing throughput using simulation-based heuristic algorithm [50]. In this study, the authors used Two-Stage Adaptive Large Neighbourhood Search (ALNS) method by integrating cell formation and group scheduling to maximize workers' skill efficiency and team cohesion while minimizing total inventory levels and worker idle time variation [51]. Razmjooei et al. used a Multi-Objective Tabu Search-Genetic Algorithm (MO-TS-GA) to makespan and reduce the intercellular translocations related to bottleneck machines and workforce movement. This methodology combines cell formation and group scheduling to ensure an efficient workforce allocation and improve the machines utilization in the CMS [33]. Li developed a heuristic-based grouping approach to minimize the intercellular part movements and machine relocation and maximizing the group technology efficiency. This technique integrates the use of cell formation and group layout design to ensure efficient sequencing of operations [52]. Kataoka used an exact search algorithm to minimize the total number of operators needed. The methodology used cell formation and group scheduling to ensure optimal production efficiency in both labor-intensive and machine-intensive cells [53]. Mei et al. presented an Adaptive Differential Evolution-Simulated Annealing (ADE-SA) algorithm using cell formation and group scheduling to minimize total queuing time and move time while optimizing resource allocation and scheduling [54]. the study presented the mixed integer linear programming to optimize the two conflicting objectives: makespan and energy consumption. the methodology used focused on group scheduling to improve the system performance[55]. In this case study the authors proposed two meta-heuristic algorithms to reduce inter-cellular movements and machine idleness. The technique used in this case study focused on cell formation and group scheduling to ensure an efficient assignment of jobs in the cells [56]. All the above-mentioned articles are summarized as shown in Table 1 and 2.

Table 1. Comparison among CMS Approaches

Papers	CMS Approaches			Objective Function		Algorithms			Optimization Method
	CF	GL	GS	Single	Multi	Heuristics	Meta-Heuristics	Exact Search	
Golmohammadi et al., (2020)	+				+		+		Mixed-integer linear programming model
Mourtzis et al., (2020)			+	+			+		Decision trees
Khamlichi et al., (2020)	+	+			+		+		Hybrid Greedy Randomized Adaptive Search Procedure (GRASP) with a Path Relinking (PR) approach
Won, (2020)	+			+				+	Mixed-integer linear programming model
Kataoka, (2020)	+		+	+				+	Multi-period mixed integer programming model
Li, (2020)	+		+		+	+			Robust cluster-based approach
Rostami et al., (2020)	+	+	+		+			+	Mixed-integer linear programming model
Rafiee & Mohamaditalab, (2020)	+	+	+		+			+	Mixed-integer linear programming model
Ernawati et al., (2020)	+	+			+	+			Rank Order Clustering (ROC) method
Sathish et al., (2021)	+				+	+			heuristic-based algorithm
Hamza & Khalaf, (2020)	+				+	+			Hamming Distance method and Self-Organizing Map (SOM)
Costa et al., (2020)			+	+			+		Parallel Self-Adaptive Genetic Algorithm
Mej, (2021)	+		+	+				+	Mixed integer nonlinear programming model
Behnia et al., (2021)	+	+	+		+		+		nested bi-level genetic algorithm (NBL-GA) and nested bi-level particle swarm optimization (NBL-PSO)
Ebrahimi et al., (2021)			+	+			+		FIx-and-optimize constraint programming (CP) model
Ramesh et al., (2021)	+	+	+		+			+	Linear Programming model
Ghoushchi & Abbasi, (2021)			+		+	+			Simulation-based optimization approach
Li, (2021)	+			+		+			heuristic-based algorithm
Wu et al., (2021)			+	+		+			heuristic-based algorithm
Goli et al., (2021)	+		+		+		+		Hybrid Genetic Algorithm (GA) combined with Whale Optimization Algorithm (WOA)
Saraçoğlu, Süer, and Gannon (2021)	+		+		+		+	+	Mixed-Integer Linear Programming (MILP) with a Genetic Algorithm (GA)
Alhawari et al., (2021)	+	+	+	+				+	p-mdeian Mathematical Model
Forghani et al., (2021)	+	+	+		+		+	+	Population-based Simulated Annealing (PSA) combined with linear programming
Cheng et al., (2022)	+		+	+			+		Q-learning-based Genetic Algorithm (Q-GA)
Mejia-Moncayo et al., (2022)	+			+			+		Ant Colony Optimization (ACO)

Table 2. Comparison among CMS Approaches, cont.

Papers	CMS Approaches			Objective Function		Algorithms			Optimization Method
	CF	GL	GS	Single	Multi	Heuristics	Meta-Heuristics	Exact Search	
Yetkin & Ulutas, (2022)	+		+	+				+	Stochastic mixed integer linear programming
Aghajani-Delavar et al., (2022)	+	+	+		+		+		Vibration Damping Optimization (MOVDO) algorithm
Al-Zuheri et al., (2022)	+	+		+			+		Hybrid Genetic Algorithm (GA)
Cáceres-Gelvez et al., (2022)	+		+		+	+			heuristic-based algorithm
Pasupa & Suzuki, (2022)	+		+		+	+			Two-Stage Adaptive Large Neighbourhood Search (ALNS) method
Razmjooei et al., (2022)	+		+		+		+		Tabu Search-Genetic Algorithm (MO-TS-GA)
Wu et al., (2022)	+			+		+			heuristic-based algorithm
Razmjooei et al., (2022)	+	+	+		+		+		Tabu Search-Genetic Algorithm (MO-TS-GA)
Motahari et al., (2023)	+	+	+		+		+		ϵ-constraint method and a Non-Dominated Sorting Genetic Algorithm II (NSGA-II)
Li, (2023)	+		+	+		+			heuristic-based algorithm
Urazel & Buruk Sahin, (2023)	+				+		+		Genetic Algorithm (GA) combined with Simulated Annealing (SA)
Kataoka, (2023)	+		+	+				+	heuristic-based algorithm
Naranjo et al., (2023)	+	+	+		+			+	Mixed-Integer Linear Programming (MILP) model
Bouaziz et al., (2023)	+	+	+		+		+	+	Discrete Flower Pollination Algorithm
Figueroa-Torrez et al., (2023)	+			+			+		Binary Black Widow Optimization (B-BWO) algorithm
Mei et al., (2023)	+		+	+			+		Adaptive Differential Evolution-Simulated Annealing (ADE-SA) algorithm
Sekkal & Belkaid, (2023)			+		+			+	Mixed Integer Linear Programming
Raja & Vignesh, (2023)	+	+	+		+	+			Similarity coefficient-based heuristic method
Emine Bozoklar (2024)	+	+			+			+	goal programming model, ϵ-constraint method, and an augmented , ϵ-constraint method
Phung, Nguyen, and Truong (2024)	+				+	+			Clustering Algorithm
Sahin & Alpay, (2024)	+		+		+		+		Genetic Algorithm
Singh et al., (2024)	+				+		+		Enhanced Dragonfly optimization method
Phung et al., (2024)	+				+	+			Improved clustering algorithm
Mansour & Ugla, (2024)	+			+			+		Genetic Algorithm (GA)
Ramesh et al., (2024)	+	+	+		+			+	Mixed Integer Linear Programming Model

4. Results

This paper analyzed the reviewed literature in terms of the aspects of cellular manufacturing which are Cell Formation (CF), Group Layout Design (GL) and Group Scheduling (GS). The paper considered the solution algorithms used whether heuristic, meta-heuristic or exact search methods. The reviewed literature shows that the most research articles focus on discussing the cell formation and group scheduling. As they directly influence production efficiency, cost reduction, and system flexibility. CF ensures that machines and parts are grouped efficiently to minimize the inter-cell movement, and GS ensures that jobs and resources are optimized to reduce idle time and improve throughput. Both CF and GS involve complex operations including many factors as sequence-dependent setup time, machine-parts relationship and dynamic job arrivals. This kind of complexity requires the use of advanced optimization techniques such as Genetic Algorithms (GA), Simulated Annealing (SA), and Multi-Objective Programming to achieve near-optimal solutions. Figure 3 shows a statistical proportion of papers based on (a) CMS Approaches; (b) Objective functions; (c) Algorithms, respectively. The Traced percent of Cell formation was (46%) followed by group scheduling (36%) and then group layout (18%) as shown in Figure 3(a). Most papers studied multi-objective of CMS with 60% and single objective (40%) as shown in Figure 3(b). the analysis reflects the prioritization of immediate operational efficiencies over holistic system design. This imbalance may stem from the CF's foundational role in minimizing inter-cell movements and GS's direct impact on throughput and cost reduction, both of which align with traditional manufacturing priorities such as lean production and rapid delivery. However, the limited focus on Group Layout Design (GL) reveals a crucial gap in tackling spatial optimization and long-term adaptability, both of which are essential for modern flexible manufacturing systems (FMS) and the principles of Industry 4.0.

To optimize CMS, some algorithms are proposed. Solving algorithms are categorized into three categories: Exact methods, heuristics, and metaheuristics. Exact-Search algorithms include branch-and-bound, mixed integer linear programming, and bounded dynamic programming. The heuristics algorithms refer to Improved clustering algorithm, Robust cluster-based approach, and Rank Order Clustering (ROC) method. The meta-heuristic algorithms including Parallel Self-Adaptive Genetic Algorithm, Ant Colony Optimization (ACO), Tabu Search-Genetic Algorithm (MO-TS-GA), Enhanced Dragonfly optimization method and Binary Black Widow Optimization (B-BWO) algorithm. Figure 3(c) shows the dominance of Meta-heuristic with 43% than both Exact-Search (30%) and heuristics algorithms (27%). Meta-heuristic algorithms are a powerful tool for optimizing CMS due to their flexibility, scalability, and ability to handle complex multi-objective problems. The algorithms are effectively balance exploration and exploitation, to prevent local optima and ensure a near-optimal solutions.

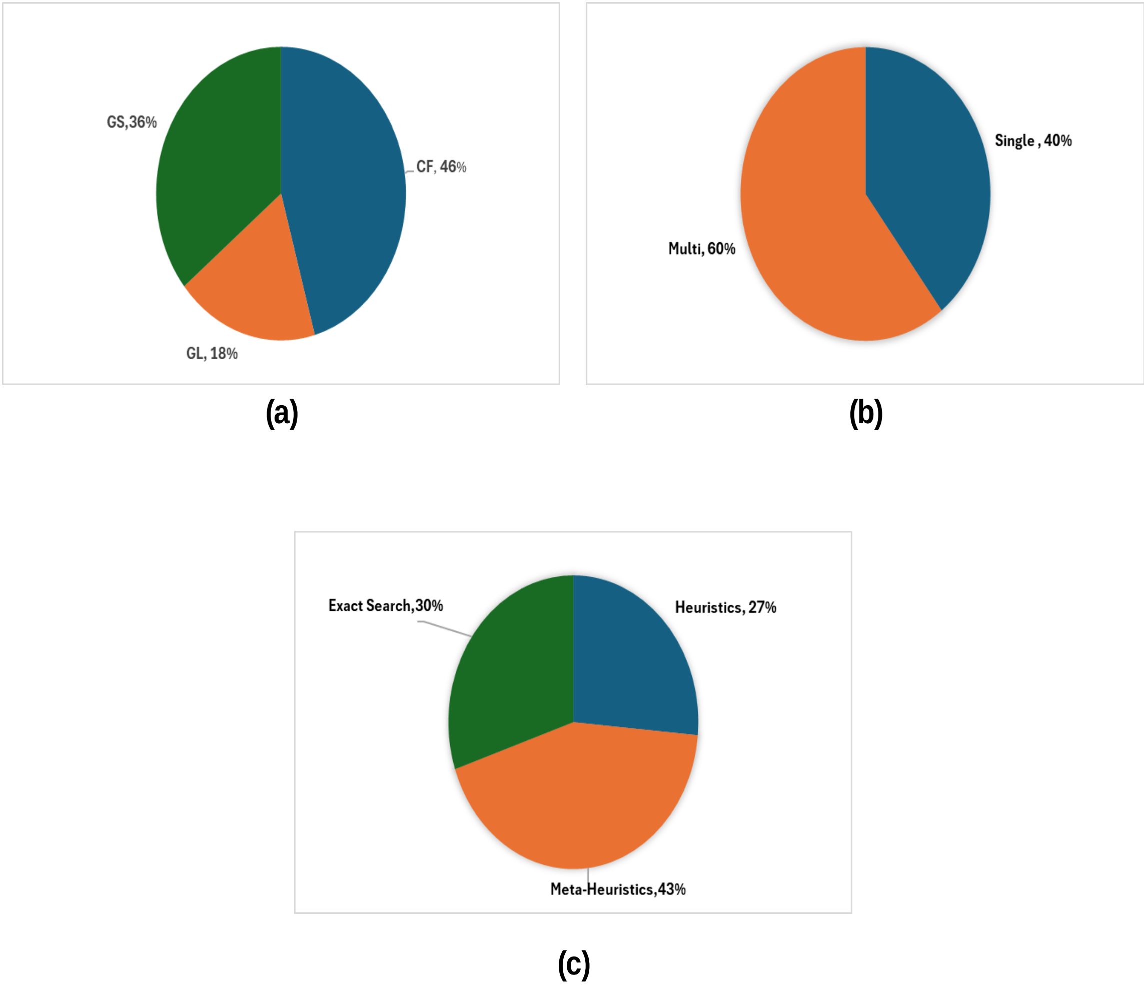

Figure 3. Statistical proportion of papers based on (a) CMS Approaches; (b) Objective functions; (c) Algorithms

5. Conclusion

This paper provides a comprehensive analysis of Cellular Manufacturing Systems (CMS) by exploring its three core aspects: Cell Formation (CF), Group Layout Design (GL), and Group Scheduling (GS). The literature review highlights that CF and GS are the most extensively studied topics, as they directly impact production efficiency, cost reduction, and system flexibility. The findings of this research shows that GL is frequently integrated with either Cell Formation (CF), Group Layout Design (GL), or both. Similarly, GS follows the same approach. The results obtained from this study shows that CF accounts for 46% and GS for 36% of research focus, as they significantly impact cost reduction, throughput, and system flexibility. In contrast, GL, representing 18%, remains relatively underexplored. This study classifies optimization techniques into exact-search methods (30%), heuristic algorithms (27%), and meta-heuristic approaches (43%), emphasizing the prevalence of Genetic Algorithms (GA), Simulated Annealing (SA), and Multi-Objective Programming in addressing CMS-related challenges. The reviewed studies indicate that addressing CMS complexity requires advanced optimization techniques. Various exact, heuristic, and meta-heuristic algorithms have been employed to improve CMS efficiency. Among them, meta-heuristic methods such as Genetic Algorithms (GA), Simulated Annealing (SA), and Multi-Objective Programming are widely used due to their capability to provide near-optimal solutions for complex optimization problems. By integrating recent aspects and optimization methods used, this study contributes to achieve a deeper understanding of CMS efficiency improvements. The findings reinforce the importance of developing intelligent, adaptive manufacturing systems that optimize productivity while minimizing costs and disruptions. Despite the advancements in optimizing CF, GL, and GS, several key research gaps remain relatively unstudied. The lower use of GL calls for more studies on its integration with technologies like Internet of Things (IoT) and Artificial Intelligence (AI) to enhance layout adaptability in real-time production environments. While GS has been studied, there is a need to investigate the real-time scheduling methods that can adapt to dynamic task arrivals and disruptions, such as machine breakdowns or unexpected changes in demand. The future research may focus on integrating the use of Industry 4.0 technologies, such as AI and IoT to enhance dynamic scheduling, workforce allocation, and system adaptability. Many implications face CMS including the need to invest in robust computational tools and workforce training to overcome the initial setup challenges and ensure smooth implementation.

References

[1] Greene T J and Sadowski R P 1984 A review of cellular manufacturing assumptions, advantages and design techniques *J. Oper. Manag.* **4** 85–97

[2] Askin R G 2013 Contributions to the design and analysis of cellular manufacturing systems *Int. J. Prod. Res.* **51** 6778–87

[3] Saraçoğlu İ, Süer G A and Gannon P 2021 Minimizing makespan and flowtime in a parallel multi-stage cellular manufacturing company *Robot. Comput. Integr. Manuf.* **72**

[4] Bouaziz H, Berghida M and Lemouari A 2020 Solving the generalized cubic cell formation problem using discrete flower pollination algorithm *Expert Syst. Appl.* **150** 113345

[5] Ernawati D, Rahmawati N, Pudji E, Sari N K and Wianto A 2020 Layout Design in Group Technology Using Cellular Manufacturing System *J. Phys. Conf. Ser.* **1569**

[6] Wu X, Chu C H, Wang Y and Yue D 2007 Genetic algorithms for integrating cell formation with machine layout and scheduling *Comput. Ind. Eng.* **53** 277–89

[7] Golmohammadi A M, Honarvar M, Hosseini-Nasab H and Tavakkoli-Moghaddam R 2020 A bi-objective Optimization Model for a Dynamic Cell Formation Integrated with Machine and Cell Layouts in a Fuzzy Environment *Fuzzy Inf. Eng.* **12** 204–22

[8] Sathish S, Lakshmanan A R, Karuppuswamy P and Bhagyanathan C 2021 An effective Sorensen-single linkage clustering hybrid algorithm for cell formation problems in cellular manufacturing industry *Concurr. Comput. Pract. Exp.* **33** 1–9

[9] Hamza S A and Khalaf A J 2020 Assessment of Hamming Distance and Self Organization Map in Solving Cell Formation Problem *IOP Conf. Ser. Mater. Sci. Eng.* **671**

[10] Li M L 2021 A novel algorithm of cell formation with alternative machines and multiple-operation-type machines *Comput. Ind. Eng.* **154** 107172

[11] Wei H, Li S, Quan H, Liu D, Rao S, Li C and Hu J 2021 Unified Multi-Objective Genetic Algorithm for Energy Efficient Job Shop Scheduling *IEEE Access* **9** 54542–57

[12] Won Y 2020 On solving large-size generalized cell formation problems via a hard computing approach using the PMP *Appl. Sci.* **10**

[13] Mejia-Moncayo C, Rojas A E, Kenne J P and Hof L A 2022 An ant approach to define product families and remanufacturing cells *IFAC-PapersOnLine* **55** 73–8

[14] Wu L, Shen Y, Niu B, Li L, Yang C and Feng Y 2022 Similarity coefficient-based cell formation method considering operation sequence with repeated operations *Eng. Optim.* **54** 989–1003

[15] Urazel B and Buruk Sahin Y 2023 Solving a Cubic Cell Formation Problem with Quality

Index Using a Hybrid Meta-Heuristic Approach *Gazi Univ. J. Sci.* **36** 752–71
[16] Figueroa-Torrez P, Durán O, Crawford B and Cisternas-Caneo F 2023 A Binary Black Widow Optimization Algorithm for Addressing the Cell Formation Problem Involving Alternative Routes and Machine Reliability *Mathematics* **11** 3475
[17] Singh A P, Shahid M, Kumari A and Karthikeyan M P 2024 Enhanced Production Through Novel Swarm-Intelligent Enabled Virtual Cell Formation: Multifaceted Approach *Proc. Eng. Sci.* **6** 353–62
[18] Phung L X, Nguyen T K and Truong S H 2024 The Enhancement of the Overall Group Technology Efficacy using Clustering Algorithm for Cell Formation *Acta Polytech. Hungarica* **21** 69–88
[19] Mansour M M and Ugla A A 2024 Employing Genetic Algorithm To Optimize Manufacturing Cells Design *Acad. J. Manuf. Eng.* **22** 53–61
[20] Khamlichi H, Oufaska K, Zouadi T and Dkiouak R 2020 A hybrid GRASP algorithm for an integrated production planning and a group layout design in a dynamic cellular manufacturing system *IEEE Access* **8** 162809–18
[21] Rostami A, Paydar M M and Asadi-Gangraj E 2020 Dynamic virtual cell formation considering new product development *Sci. Iran.* **27** 2093–107
[22] Rafiee M and Mohamaditalab A 2020 Investigation into skill leveled operators in a multi-period cellular manufacturing system with the existence of multi-functional machines *Sci. Iran.* **27** 3219–32
[23] Behnia B, Shirazi B, Mahdavi I and Paydar M M 2021 Nested Bi-level metaheuristic algorithms for cellular manufacturing systems considering workers' interest *RAIRO - Oper. Res.* **55** S167–94
[24] Ramesh S, Arunkumar N and Vijayaraj R 2021 Economic Tradeoff Optimization Model for Machine Cell Layout Design *J. Chinese Soc. Mech. Eng. Trans. Chinese Inst. Eng. Ser. C/Chung-Kuo Chi Hsueh K. Ch'eng Hsuebo Pao* **42** 331–40
[25] Alhawari O I, Süer G A and Bhutta M K S 2021 Operations performance considering demand coverage scenarios for individual products and products families in supply chains *Int. J. Prod. Econ.* **233** 108012
[26] Forghani K, Fatemi Ghomi S M T and Kia R 2021 Concurrent scheduling and layout of virtual manufacturing cells considering assembly aspects *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **235** 1036–49
[27] Aghajani-Delavar N, Mehdizadeh E, Tavakkoli-Moghaddam R and Haleh H 2022 A multi-objective vibration damping optimization algorithm for solving a cellular manufacturing system with manpower and tool allocation *Sci. Iran.* **29** 2041–68
[28] Al-Zuheri A, Ketan H S and Vlachos I 2022 Grouping technology and a hybrid genetic algorithm-desirability function approach for optimum design of cellular manufacturing systems *IET Collab. Intell. Manuf.* **4** 267–85
[29] Raja S and Vignesh K 2023 A new approach for determining optimum number of cell, cell formation and intra-machine cell layout with considering operation sequence *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.* **238** 2770–81
[30] Emine Bozoklar 2024 applied sciences Designing Sustainable Flexible Manufacturing Cells with
[31] Ramesh S, Arunkumar N, Srivastava S, Kumar V, Senthilkumaran S and Vijayaraj R 2024 Manufacturing Cell Layout Design Considering Dynamic Conditions and Inventory *Acad. J. Manuf. Eng.* **22** 80–7
[32] Motahari R, Alavifar Z, Zareh Andaryan A, Chipulu M and Saberi M 2023 A multi-objective linear programming model for scheduling part families and designing a group layout in cellular manufacturing systems *Comput. Oper. Res.* **151**
[33] Razmjooei V, Mahdavi I and Gütmen S 2022 A Hybrid Multi-Objective Algorithm to Solve a Cellular Manufacturing Scheduling Problem with Human Resource Allocation **9** 272–87

[34] Naranjo I, Porras M, Ortiz D, Tigre F, Sánchez C, Tubón E, Carrillo S, Mariño C, López J, Lema F and Rosero C 2023 Mathematical Models for the Formation and Evaluation of Manufacturing Cells in A Textile Company. A Case Study *J. Ind. Eng. Manag.* **16** 382–97
[35] Bouaziz H, Bardou D, Berghida M, Chouali S and Lemouari A 2023 A novel hybrid multi-objective algorithm to solve the generalized cubic cell formation problem *Comput. Oper. Res.* **150** 106069
[36] Bouaziz H, Bardou D, Berghida M, Chouali S and Lemouari A 2023 A novel hybrid multi-objective algorithm to solve the generalized cubic cell formation problem *Comput. Oper. Res.* **150** 106069
[37] Goli A, Tirkolaee E B and Aydin N S 2021 Fuzzy Integrated Cell Formation and Production Scheduling Considering Automated Guided Vehicles and Human Factors *IEEE Trans. Fuzzy Syst.* **29** 3686–95
[38] Mourtzis D, Siatras V, Synodinos G, Angelopoulos J and Panopoulos N 2020 A framework for adaptive scheduling in cellular manufacturing systems *Procedia CIRP* **93** 989–94
[39] Kataoka T 2020 A multi-period mixed integer programming model on reconfigurable manufacturing cells *Procedia Manuf.* **43** 231–8
[40] Li M L 2020 Arrangement of Machines under Spatial Constraint by Using a Novel Algorithm *IEEE Access* **8** 144565–74
[41] Costa A, Cappadonna F V. and Fichera S 2020 Minimizing makespan in a Flow Shop Sequence Dependent Group Scheduling problem with blocking constraint *Eng. Appl. Artif. Intell.* **89** 103413
[42] Costa A, Cappadonna F V. and Fichera S 2020 Minimizing makespan in a Flow Shop Sequence Dependent Group Scheduling problem with blocking constraint *Eng. Appl. Artif. Intell.* **89** 103413
[43] Mej C 2021 A Hybrid Architecture for a Reconfigurable Cellular Remanufacturing System 488–96duling a cellular manufacturing system based on price elasticity of demand and time-dependen
[44] Ebrahimi H, Kianfar K and Bijari M 2021 Schet energy prices *Comput. Ind. Eng.* **159** 107460
[45] Ebrahimi H, Kianfar K and Bijari M 2021 Scheduling a cellular manufacturing system based on price elasticity of demand and time-dependent energy prices *Comput. Ind. Eng.* **159** 107460
[46] Ghoushchi S J and Abbasi A 2021 An optimisation approach for simulation operator allocation and job dispatching rule in a cellular manufacturing system *Int. J. Serv. Oper. Manag.* **40** 47–67
[47] Wu L, Zhao Y, Feng Y, Niu B and Xu X 2021 Minimizing makespan of stochastic customer orders in cellular manufacturing systems with parallel machines *Comput. Oper. Res.* **125** 105101
[48] Cheng L, Tang Q, Zhang L and Yu C 2022 Scheduling flexible manufacturing cell with no-idle flow-lines and job-shop via Q-learning-based genetic algorithm *Comput. Ind. Eng.* **169** 108293
[49] Yetkin B N and Ulutas B H 2022 A Skill-Based MILP Model in Cellular Manufacturing Systems with Human-Robot Collaboration *IFAC-PapersOnLine* **55** 1728–33
[50] Cáceres-Gelvez S, Arango-Serna M D and Zapata-Cortés J A 2022 Evaluating the performance of a cellular manufacturing system proposal for the sewing department of a sportswear manufacturing company: A simulation approach *J. Appl. Res. Technol.* **20** 68–83
[51] Pasupa T and Suzuki S 2022 Two-Stage Adaptive Large Neighbourhood Search for Team Formation and Worker Assignment Problems in Cellular Manufacturing Systems *Appl. Sci.* **12**
[52] Li M L 2023 Sequencing of operations and repeatable machines in smart manufacturing *Comput. Ind. Eng.* **182** 109335
[53] Kataoka T 2023 *A Mathematical Model Considering Multi-skilled Operators and Industrial Robots on Reconfigurable Manufacturing Cells* (Springer International Publishing)

[54] Mei L, Yue L and Ge S 2023 Joint decision-making of virtual module formation and scheduling considering queuing time *Data Sci. Manag.* **6** 134–43
[55] Sekkal D N and Belkaid F 2023 A multi-objective optimization algorithm for flow shop group scheduling problem with sequence dependent setup time and worker learning *Expert Syst. Appl.* **233**
[56] Sahin Y B and Alpay S 2024 Integrated cell formation and part scheduling: A new mathematical model along with two meta-heuristics and a case study for truck industry *Sci. Iran.* **31** 888–905