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Review

Review of Responsiveness and Sustainable Concepts in Cellular Manufacturing Systems

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Abstract: Cellular manufacturing systems are widely used due to their advantageous capability of combining the flexibility of the job-shop and the productivity of the flow-shop. In recent years, the reduction of the product life cycle, variation in demand products, and introduction of new technologies, have driven the manufacturing companies to improve responsiveness, thus reducing the cellular manufacturing life cycle with a focus on re-designing the cells. Another issue concerns the sustainability of the manufacturing systems due to the introduction of energy costs in the design model of cellular manufacturing systems. This study is an overview of the more recent works on design approaches to improve the responsiveness and the models to support the sustainability of cellular manufacturing systems. The analysis of the literature review highlights the main findings and suggests future development paths considering the open problems in this field.

Keywords: cellular manufacturing system; reconfigurable machines; sustainable manufacturing; energy consumption

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1. Introduction

The digitalization of manufacturing systems due to industry 4.0, the internet of things (IoT), big data, and cloud computing, has provided information that has enhanced the possibility of reacting to internal and external changes. Models and algorithms have become more important in using this opportunity to improve manufacturing efficiency, thus making production systems more competitive.

The opportunity provided by digitalization has highlighted how the classical manufacturing systems, such as dedicated manufacturing systems (DMSs), flexible manufacturing systems (FMSs), and cellular manufacturing systems (CMSs), have some limitations in their ability to adjust to the latest industrial and market tendencies [1].

Group technology is a method to form a family of parts that have similarities in design and manufacturing. Cellular manufacturing systems (CMSs) are an application of group technology in which machines, equipment, and human resources are grouped together to form a cell that produce one or more family of parts. The manufacturing cell is organized to arrange equipment and machines to optimize the production process to follow the main benefits of the flow lines.

Figure 1 shows the main characteristics of CMSs compared to dedicated and flexible systems. An example of flexible manufacturing systems are job-shops, which are production systems where machines of the same type are grouped into functional sections to manufacture a wider range of products. The dedicated systems, which work as flow-shops, are designed to produce a specific product. Machines and equipment are organized following the tasks' sequence of the product in a linear system that assures a direct flow with reduced movements. Figure 1 considers four main issues, which are flexibility, production efficiency, production volume, and production mix variations. CMSs are a trade-off between the two extreme characteristics of dedicated and flexible systems.

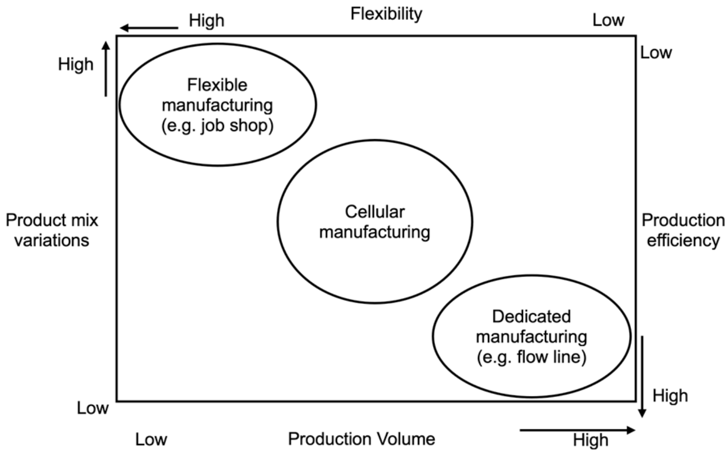

Figure 1. Comparison of cellular manufacturing systems with dedicated and flexible systems.

As argued by Nsakanda et al. [2], companies, to meet global competitive challenges, have effectively used cellular manufacturing; indeed, some benefits of cellular manufacturing systems include increased throughput and reduced costs, also in terms of material handling. The authors state that reductions in cycle, downtime, setup, and material handling times can be achieved, as well as further improvements in process work, inventory level, factory layout size, and defect rates. Cellular manufacturing systems (CMSs) integrate the flexibility of the FMSs and the benefits of mass production systems, such as DMSs. CMSs consist of manufacturing cells designed to work on part families, thus improving productivity, reducing set-up times, and work in process [3–5].

In recent years, the reduction of energy consumption and greenhouse gas emissions has become a very important issue in manufacturing systems. One of the targets of the Europe Union for 2030 is to reduce energy consumption by 32.5% [6]. As reported in [7], more than 80% of emissions savings could be achieved through energy efficiency and renewable energy sources, to limit the increase of the global average temperature. Furthermore, sustainability is included in the 17 goals for building a better world, as reported in the 2030 UN Agenda for Sustainable Development [8]. For these reasons, researchers are focused on implementing energy efficiency, and finding strategies and policies for saving energy in manufacturing systems. Production systems must be able to react to continuous changes that may arise from external sources (such as demand) or internal sources (machine degradation and human resource management). Recently, the ability to adapt to the supply of energy sources and to improve the efficiency of the use of energy resources has become increasingly important.

The development of industry 4.0 and IoT encourages manufacturing systems to be more innovative and resilient, and to improve their responsiveness to dynamic changes. In recent years, one of the crucial factors is the energy management of manufacturing systems; therefore, the responsiveness includes their capacity to react to energy changes. Consequently, the improvements of resilience and responsiveness due to the industry 4.0 concept have to include not only market changes, but also energy management adaptations [9].

This paper is an overview of the literature focused on the more recent trends in production systems. The goal of this review article is twofold: i) the first goal concerns the description of the approaches proposed to improve the responsiveness of CMSs to continuous changes, via a comprehensive review of the recent works to support modern CMSs, which includes dynamic designs, virtual manufacturing cell models, the use of reconfigurable machines, and robust design approaches; ii) the second goal is to provide information about the sustainability of the CMSs in terms of efficiency and the reduction of energy use connected to the responsiveness of CMSs. In this area, the works concern the reduction of energy consumption in terms of manufacturing and material handling movements, energy price, and peak power.

The paper is organized as follows: the research methodology and the bibliometric analysis are presented in Section 2; Section 3 discusses the solutions proposed to improve the responsiveness of CMSs; Section 4 examines the recent works on the energy issue in CMSs; Section 5 provides some suggestions for future research.

2. Research Methodology

This study used online databases to recognize journal papers, conference proceedings, and book chapters that include the keywords “dynamic cellular manufacturing”, “virtual cellular manufacturing”, “cellular reconfigurable manufacturing”, “sustainable cellular manufacturing”, “energy efficiency in cellular manufacturing”, and “energy efficiency in cellular manufacturing”. The research focused on the academic databases of Scopus, Web of Science (ISI Database), and Google Scholar. The works analyzed were published between 2015 and 2022, focusing on the more recent years to consider the more recent models and solutions proposed. The works studied are selected from 2015 to relate the analysis of the digital transformation to industry 4.0. Some of the works studied stem from government projects, some of which ran until 2015, others began in 2015; e.g. [10]: the United States proposed actions and recommendations titled “Advanced Manufacturing Partnership” around 2011; the German government supported the action plan “High-Tech Strategy 2020” from 2012; in 2013, the French government initiated a strategic plan “La Nouvelle France Industrielle” and the United Kingdom government proposed the policy called the “Future of Manufacturing”; in 2014 the European Commission started the programme “Factories of the Future (FoF)” and the South Korea government announced the “Innovation in Manufacturing 3.0”; in 2015 the Chinese Government launched the strategy “Made in China 2025” and the Japanese government adopted the “5th Science and Technology Basic Plan”. The objective of this database search was not to provide a complete overview on cellular manufacturing systems, but to begin the discussion on the more recent works that support the more recent changes in the competitive manufacturing production systems environment. Figure 2 shows the shows the time trend of the articles analyzed. The main models discussed concerns the years 2019, 2020, and 2021.

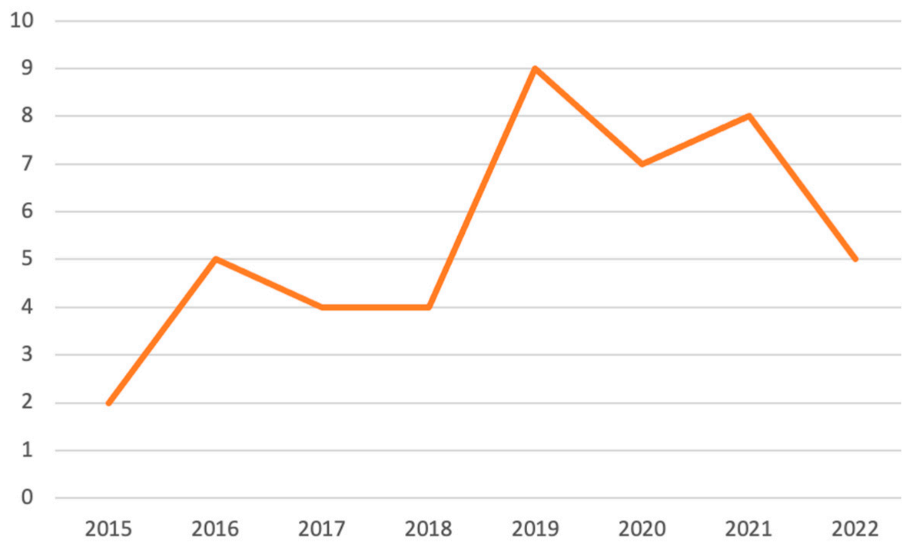

Figure 2. Distribution of articles discussed.

Figure 3 highlights the main different types of documents discussed; this review focused on journals’ documents.

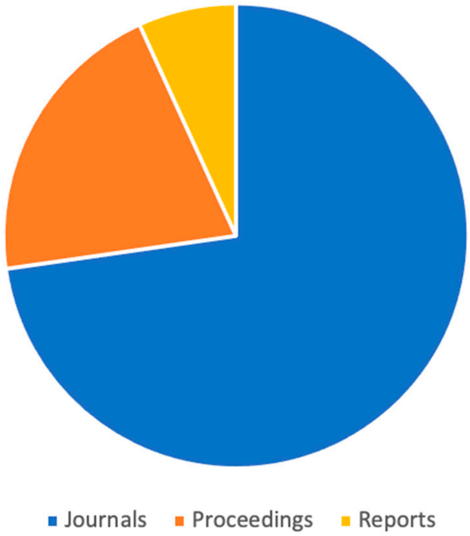

Figure 3. Type of articles discussed.

3. Review of the Responsiveness Approaches

The current competitive context requires production systems to be able to react and adapt to continuous changes. The design of cellular manufacturing systems needs to be revised when the conditions change. The main solutions proposed in the literature and discussed in this section are the following: dynamic design models that support the re-design of cellular manufacturing systems when conditions change, thus maintaining a high level of efficiency; a method that reduces the complexity of the redesign models is the introduction of virtual cellular manufacturing that does not physically move the machines, but instead reconfigures the machines to create a distributed cell in the plant area; the development of reconfigurable machines that supports the reconfiguration of the cells by considering the characteristics of these machines; and finally, robust cell design models that are able to handle uncertainty without further reconfiguration.

3.1. Dynamic Design

The dynamic reconfiguration of the cells enables them to react to unforeseen events and dynamic changes, thus avoiding the degradation of the performance of the manufacturing system. The dynamic reconfiguration of the cells can depend on the layout designed. Some of the most common layouts are U-shaped, O-shaped, and T-shaped. U-shaped is characterized by the arrangement of the machines in the shape of letter U. This layout is more compact, saving space, with the workers much closer to each other, enabling them to help in case of difficult. O-shaped is similar to the U-shaped but the machines are arranged roughly in a circle. In this layout, the cells can be managed by lower number of high-skilled workers. T-shaped is adaptation to a scenario when the raw items come from different sources and converge in a flow of the materials. Fatemi-Anaraki et al. [11] studied the dynamic scheduling problem in a U-shaped cell with multiple robot arms in a dynamic environment using mixed-integer linear programming (MILP) and constraint programming approaches. They related the dynamic scheduling problem to the layout of the cells; the U-shaped layout cell enabled the possibility to place the robotic arms in the middle of the cell to perform the material handling process.

The introduction of reconfigurable machines can support the reconfiguration of the cells more rapidly and efficiently. Among the recent works proposed on this theme, Renna and Ambrico [12] proposed the use of reconfigurable machines to support the design, reconfiguration, and scheduling of cellular manufacturing systems in dynamic conditions. The originality of this work concerns the connection of three linked mathematical models that work on different planning periods; the medium (planning), medium-short (reconfiguration), and short (scheduling). The linked mathematical models allowed for the reduction of the computational complexity and proved effective in the design, reconfiguration, and scheduling when considering several dynamic conditions. Bayram and Şahin [13] proposed a hybrid approach combining combinatorial particle swarm optimization and linear programming to determine the optimal allocation of machines, parts and workers. The approach proposed is suitable when the cellular manufacturing systems are characterized by the labor rate of the relevant workers.

Delgoshaei et al. [14] proposed a genetic algorithm for scheduling in cellular manufacturing systems to adjust the load of the cells using the outsourcing allocation to obtain the best trade-off between in-house manufacturing and outsourcing. The approach proposed showed efficacy when the load variation was under a limited value.

Delgoshaei and Gomesa [15] studied the cell-load variation in cellular manufacturing systems. They proposed a scheduling approach using artificial neural networks in the presence of bottlenecks and parallel machines. The aim was to find the trade-off values between in-house manufacturing and using outsource services.

Kia [16] proposed a genetic algorithm to design cellular manufacturing systems under dynamic conditions. The approach proposed re-designing the cellular manufacturing system considering the aggregate planning decisions.

Xue and Offodile [17] proposed a mixed integer programming model to reconfigure the cells considering the hierarchical production planning. The decisions about the cellular manufacturing concern the stock of products, the costs due to the inter- and intra-cell movements of materials, the costs due to the backlog, and the trade-off between internal and outsourcing production.

Alimian et al. [18] proposed a mixed integer programming model that integrates the dynamic cell formation, scheduling and preventive maintenance. The result highlighted how preventive maintenance improved the availability of the cells, leading to greater efficacy of the dynamic cells reconfiguration.

Salimpour et al. [19] studied the problem of cell formation and cell layout in cellular manufacturing systems. The approach proposed was able to react to changes of product mix and demand. The complexity of the mathematical model lead to the use of a modified non-dominated sorting genetic algorithm (MNSGA-II) to obtain Pareto-optimal solutions.

The recent works on dynamic design proposed heuristic algorithms, such as genetic algorithms, and neural networks, but these approaches can be limited in real industrial cases when the problems become larger. The combination of deep learning and reinforcement learning proposed for dynamic scheduling in job-shops [20] could be a promising approach for the dynamic reconfiguration of cells.

3.2. Virtual Cellular Manufacturing

A different approach to handling dynamic conditions is the virtual cellular manufacturing system (VCMS). This approach forms cells including machines that are not physically moved. This type of cell leads to increased movements costs because the machines cannot move closer to the materials. Moreover, the costs related to the reallocation of the machines to support the reconfiguration of the cells are minimized, and the reconfiguration of virtual cells are faster and easier.

Liang and Fung [21] proposed a multi-agent system to control virtual cellular manufacturing cells in real-time. This coordination mechanism to support scheduling problems reacts to the changing market dynamics, reducing the processing and holding costs.

Baykasoglu and Gorkemli [22] developed a multi-agent system to support the family part formation, virtual cell formation, and scheduling, considering dynamic demand arrivals. The numerical results showed that the proposed model was the most promising in dynamic conditions for the manufacturing system. These approaches proposed can use a multi-agent system to distribute the computational complexity of the problem.

Aalaei et al. [23] proposed a stochastic model to assign parts and machine workers to multi-dynamic virtual cells. The approach proposed minimizes the costs of holding, outsourcing, inter-cell material handling, and external transportation, and fixed the costs for producing each part. The complexity of the mathematical model obtained needs a genetic algorithm to solve the problem.

Forghani and Ghomi [24] studied the problems of cell formation, cell scheduling, and group layout in the case of virtual cellular manufacturing and classical cellular manufacturing systems. To solve the problem, metaheuristic algorithms were proposed to minimize the cycle time and total handling costs. The numerical results from their experiments demonstrated that virtual cell configurations lead to better solutions than classical cell configurations.

Virtual cellular systems are a promising approach when combined with multi-agent systems to obtain more robust cellular manufacturing systems.

3.3. Reconfigurable Machines

Flexed machines can be used to improve the responsiveness of production systems. This solution leads to purchasing in advance a degree of flexibility that is expected to be used in the future, often leading to an initial outlay greater than is actually needed.

The reconfigurable machines can be a valid alternative to the flexible machines. A reconfigurable machine includes a basic process module of both hardware and software that has the capability to quickly add, remove, or modify the module to react to the changing market demands or technologies. The objective is to reconfigure the machine to provide new functionalities and capacities when needed [25].

Brahimi et al. [26] in their paper provided an overview of the literature considering the optimization problem of reconfigurable manufacturing systems (RMS). The discussion of the literature is divided in two main parts: the first part discusses the optimization problems for the RMSs addressed in the literature; the second part studied the solutions proposed to solve the optimization problems for the RMSs. This work aims to support researchers to evaluate the main areas and to focus future research paths for optimization in RMSs.

Eguia et al. [27] studied the design and loading of cellular manufacturing systems that consist of reconfigurable machines. The first problem studied was the design of the cells, and the second problem was the loading of the cells developed by mixed integer linear programming. The input of the mathematical model was the demands of each part type, and the objective was the minimization of holding and movement costs. This objective balances the workloads among the cells in each period and during the production planning period.

Bortolini et al. [28] studied a cellular manufacturing system where the cells consist of reconfigurable machines. There were several auxiliary modules available to change or add operations that the machine can manufacture. The model proposed allocated the auxiliary modules to the reconfigurable machines to improve the workload balance among the cells. The numerical results showed relevant benefits in terms of global time saving, which highlights the fact that reconfigurable machines are an opportunity for the cellular manufacturing systems to face dynamic market changes.

Bortolini et al. [29] proposed an optimal linear programming cost model for the dynamic design of cellular manufacturing systems that include flexible and reconfigurable machines. The numerical results showed a decrease of the system intercellular flows without a high increase of the machine number, but the higher costs due to the flexible machines were not considered.

Moghaddam et al. [30] studied the design problem of RMSs that are able to adapt to different product types. The models proposed support a scalable manufacturing system that can change the configuration in the different production planning periods. The approaches proposed considered the possibility of adding and removing modules in the reconfigurable machines to adjust the capacity of the system, minimizing the total costs.

Guo et al. [31] developed a mixed integer nonlinear programming model to cell formation, and to optimize the equipment configuration of reconfigurable machines and mixed product plan. The objective was to maximize the profit reacting to the dynamic changes of market demands.

Renna [32], in an attempt to overcome the limits of the computational algorithm reducing the problems that can be solved, proposed the use of game theory to reconfigure the reconfigurable machines. The reconfiguration of the reconfigurable machines allowed for the improvement of the performance when new production was introduced or mixed with dynamic demand changes. This approach works in the same way that a single reconfigurable machine can work as a single cell.

Arista et al. [33] presented a literature review on the use of reconfigurable machines in the aeronautical industries where cellular manufacturing systems are widely used. The review of the literature highlighted how the potentiality of the reconfigurable machines was insufficiently considered in the aeronautical industries to improve the responsiveness of this industrial sector.

Hao et al. [34] proposed a single model that included the reconfiguration of machines, workforce adjustment, transfer batch sizes and costs for intracellular and intercellular travel, production planning in terms of inventory holding, and internal production and backorder costs, where each period has varied demands. To solve this complex model, a genetic algorithm was proposed, and the simulation was used to validate the proposed model.

Ashraf and Hasan [35] argued that the selection of the configuration of RMSs is crucial for the efficiency of these manufacturing systems. The problem to select the configurations of the machines has multiple objectives, and it is important to search the best trade-off among the different objectives. They proposed a framework to support the selection of the manufacturing configurations, and used a genetic algorithm to solve the mathematical problem.

Bortolini et al. [36] proposed an optimization linear programming model for the dynamic management of reconfigurable machines considering the availability of the auxiliary modules. The proposed model allows for reactions to the dynamic market changes.

3.4. Robust Design

Robust design approaches attempt to design cellular manufacturing systems that are able to handle dynamic changes, by taking these changing conditions into account in the model's design.

Bagheri et al. [37] in their paper highlighted how the efficient execution of a dynamic manufacturing system depends on various factors. They introduced human errors in the design of the cells as a factor. The proposed approach for cells in a dynamic environment for several consecutive periods included three objectives: maximizing the grouping effectiveness, minimizing the total costs, and minimizing total non-interest workers.

Salimpour et al. [19] addressed the problem of cell formation and how the design of the layout of the cell formed. They proposed a semi-robust cellular approach, which is able to cope with the continuous change of product mix and demand. The layout of the facility does not change from one period to another, but rather the locations of the cell pick-up/drop-off points change. The mathematical model developed to support the proposed approach is a multi-objective mathematical programming model. A genetic algorithm is necessary to solve the complex mathematical model obtained.

Shafiee-Gol et al. [38] studied the design of cellular manufacturing systems distributed in multiple plants in dynamic conditions developing a mixed-integer nonlinear programming model. The mathematical model included different objectives: the sale revenue and total costs of machine operation, machine overhead, inter-cell material handling, inventory holding, outsourcing, machine installation/uninstallation, products transportation, dispersing machines, establishing plants, and forming cells. The model obtained is NP-hard, therefore, genetic algorithm and grey wolf optimization were proposed to solve the problem.

Mejia-Moncayo et al. [39] studied an ant-based algorithm that addresses the formation of product/part families and remanufacturing cells. The numerical results highlighted the best performance of an ant-based algorithm compared to a genetic algorithm and a bacterial foraging optimization algorithm, improving the possibility introduce remanufacturing cells in classical cellular manufacturing systems.

Table 1 summarizes the main issues highlighted by the works analyzed on the responsiveness approaches.

Table 1. Comparison among responsiveness approaches.

	Responsiveness Approaches													
	Dynamic Scheduling	**MILP**	**Reconfiguration of the Cells**	**Particle Swarm**	**Cell Configuration**	**Genetic Algorithm**	**Outsourcing**	**Neural Networks**	**Reinforcement Learning**	**Virtual Cells**	**Multi Agent Systems**	**Reconfigurable Machines**	**Game Theory**	**Human Issue**
[11]	X	X												
[12]		X	X											
[13]		X		X	X									
[14]	X					X	X							
[15]	X						X	X						
[16]			X			X								
[17]		X	X				X							
[18]		X	X											
[19]					X	X								
[20]	X								X					
[21]	X									X	X			
[22]	X		X							X	X			
[23]					X	X				X				
[24]										X				
[25]												X		
[26]												X		
[27]		X		X								X		
[28]			X									X		
[29]		X										X		
[30]		X			X							X		
[31]		X			X							X		
[32]			X									X	X	
[33]												X		
[34]					X	X						X		
[35]						X						X		
[36]		X	X									X		
[37]					X									X
[38]					X	X								
[39]					X						X			

The analysis of the responsiveness works proposed in the literature highlights the following issues. The mathematical models proposed to support the dynamic reconfiguration of the cellular manufacturing systems are characterized by relevant computational complexities that limit their potential application in real industrial cases where the number of machines, jobs, and equipment are significant. This reason leads to the proposal of alternative methods, such as the genetic algorithm, that can be relevant in terms of solution time. The introduction of reconfigurable machines allows the cellular manufacturing systems to be scalable, reducing time and costs to reconfigure and adapt the cells to the dynamic changes of demand. Some works proposed hybrid cells that include dedicated, flexible, and reconfigurable machines. This allows for the minimization of the costs of the reconfiguration. Virtual cells can be a promising approach, but the literature did not explore their potential in recent years with the development of industry 4.0.

4. Energy Consumption

The goal of reducing CO_2 emissions and energy costs drives the production systems to improve their energy efficiency and to adopt renewable energy sources. Therefore, it is necessary to adopt new models and approaches in manufacturing systems to include the energy issues.

The energy efficiency in manufacturing systems has been deeply analyzed in a recent work by Renna and Materi [40]. In their work, the authors proposed a review of the literature on energy efficiency and sustainability deepening the different typologies of manufacturing systems. They focused also on cellular manufacturing; the most significant works analyzed by the authors are reported herein.

The layout designs of cellular manufacturing systems has been studied by Niakan et al. [41,42]; in their first work, they presented a mathematical model considering as objective functions the total cost and the total energy loss minimization; in the second work proposed, the authors considered the minimization of total production waste as a second objective, which included several typologies of waste, such as chemical, energy, raw material, and greenhouse gas emission.

In the context of cellular manufacturing systems, the energy issue has been considered also in [43]. Indeed, the authors evaluated the machines and the material handling electricity costs, and assumed it as value adding cost to the work in process. The cell formation has been obtained, in order to minimize the value-added work in process, using a genetic algorithm and discrete event simulation.

Iqbal and Al-Ghamdi [44] proposed a nonlinear mathematical model to minimize the energy consumed in the operation of the machines and the energy for the transportation of the parts in cellular manufacturing systems. An algorithm based on a simulated annealing metaheuristic algorithm was developed for the solution of the mathematical model.

Wang and Liu [45] studied a virtual cellular manufacturing system integrated with the energy consumption levels. The model proposed allowed the managers to choose the consumption energy level considering the back orders of the manufacturing system. Then, the trade-off between energy and backorder cost is pursued.

Saddikuti and Pesaru [46] proposed a NSGA based algorithm for minimizing the makespan and flowtime, as well as energy, for cellular manufacturing systems. The numerical results highlighted that there is a significant potential for improving the schedule of operations by considering energy consumption and reducing the idle time of the machines.

Liu et al. [47] developed a model to support virtual reconfiguration in cellular manufacturing systems that includes the group workstations, scheduling virtual cells, and selecting energy consumption levels. The complexity of the mathematical model developed needed a metaheuristics algorithm to solve this problem.

A mathematical model that minimizes the costs linked to material handling and machine rearrangement and minimizes electricity consumption of the automated guided vehicles has been provided by Lamba et al. [48]. A cellular manufacturing layout, that allows the reduction of material handling cost and energy consumption, has been provided, solving the proposed mathematical model with a simulated annealing-based solution methodology. Forghani et al. [49] developed a mixed-integer program to design cellular manufacturing systems considering energy consumption. The machines are assumed to be capable of processing operations with different energy consumption rates and processing times. To solve the mathematical problem, they proposed the combination of a genetic algorithm and a simulated annealing algorithm.

Ebrahimi et al. [50] studied the scheduling problem in cellular manufacturing systems to maximize the profit, considering the revenues earned from sales, as well as energy consumption costs and order tardiness penalties. The mathematical model developed includes the time-dependency of energy prices, price elasticity of demand, and speed-based power consumption of machines.

Jafarzadeh et al. [51] studied the cellular manufacturing systems from the point of view of sustainability in terms of economic, environmental, and social responsibility. They proposed a mathematical model function of minimizing costs, minimizing CO_2 emissions, and minimizing product shortages.

Table 2 summarizes the main issues highlighted by the works analyzed on the energy consumption approaches.

Table 2. Comparison among energy consumption approaches.

Energy Consumption in Cellular Manufacturing Systems								
	Sustainable Review in Manufacturing Systems	**MILP**	**Energy Reduction**	**Genetic Algorithm**	**Simulated Annealing**	**Backorder Costs**	**Speed Control of the Machines**	**CO_2 Emission**
[40]	X							
[41]		X	X					
[42]		X	X					
[43]			X	X				
[44]			X		X			
[45]			X			X		
[46]			X	X				
[47]			X	X				
[48]			X		X			
[49]			X	X				
[50]			X				X	
[51]								X

The main focus of the research on the sustainability issue concerns the introduction of energy consumption in the mathematical model, in order to minimize costs and energy consumption. The main limits of the works in this literature review concerns the lack of studies on the active policies implemented to reduce the consumption of energy, and the introduction of renewable energy sources is not investigated.

5. Conclusions and Future Research Paths

Cellular manufacturing systems are widely used nowadays in production systems. This paper presents an overview of the responsiveness models and sustainability issues in recent works between 2015 and 2022. The focus of this paper is to provide the more recent works on the above themes, and is not a complete overview on cellular manufacturing systems. The review focused on the main issues relevant for recent developments in industry, such as industry 4.0, big data, digital twins, and energy use. Cellular manufacturing systems will be able to use the additional information provided by the integration of industry 4.0, digital twins, and big data to improve their responsiveness and their reconfiguration to continuously adapt to the industrial changes. The continuous increase in the production of energy from renewable sources forces companies to use new energy management models, not only to reduce energy consumption, but also to integrate the various energy sources.

Future Research directions for Cellular Manufacturing Systems

This section discusses the potential future research issues starting from the analysis of the literature overview. The industrial revolution, referred as industry 4.0, improves the intelligence level and the amount of information available in the manufacturing systems; in these conditions, it is important to use the advanced decision models to support the rapid reconfiguration of cellular manufacturing systems.

The collection of the data in real time from the manufacturing system (big data) and the reduction of the time to make decisions limits the industrial applications of the greater part of the mathematical/heuristic approaches proposed in the literature.

In this context, a future research path will be the use of multi-agent architectures that are able to adapt to solve complex problems in a dynamic environment. The multi-agent architectures adopting digital twins can build intelligent algorithms for managing the computational complexity and improving the performance of the manufacturing systems. The intelligent algorithms that support manufacturing systems can be learning models based on neural networks and fuzzy systems, which learn from the data provided by the manufacturing systems' sensors. This can develop the future research path of self-optimization, and self-configuration in industry 4.0 context. The effectiveness of multi-agent systems heavily depends on negotiation and coordination strategies. This area of research was not investigated for the cellular manufacturing context; for example, the use of cooperation strategies based on game theory can support the multi-agent architectures with limited computational complexity. Therefore, two main research issues can be developed: the multi-agent architecture to support cellular manufacturing systems, and the coordination strategies with reduced computational complexity to allow for their introduction in real industrial cases.

The main models proposed in the literature optimize economic issues or manufacturing performance, while the sustainability issues are not investigated.

One of the future research paths in this context is the development models that improve the energy efficiency in cellular manufacturing systems. Some models that are proposed as switch-off policies for flow lines for other manufacturing systems can be studied also for cellular manufacturing systems. These switch-off policies proposed reduce energy consumed by starting and stopping the flow lines as required without changing the design of the manufacturing operation.

Another important issue is the efficient use of renewable energy, enabling the reduction of greenhouse gas emission. Models that support the efficient use of renewable energy integrated with the electricity grid can improve the energy efficiency and reduce the energy costs. In this case, it is relevant to use models that change machines' parameters to improve the use of renewable sources following the generation state.

Moreover, the introduction of the energy accumulators can improve these models to handle the uncertainty of the manufacturing systems and the renewable energy sources.

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References

1. Bortolini, M.; Galizia, F.G.; Mora, C. Reconfigurable manufacturing systems: Literature review and research trend. *J. Manuf. Syst.* **2018**, *49*, 93–106. [CrossRef]
2. Nsakanda, A.L.; Diaby, M.; Price, W.L. Hybrid genetic approach for solving large-scale capacitated cell formation problems with multiple routings. *Eur. J. Oper. Res.* **2006**, *171*, 1051–1070. [CrossRef]
3. Singh, N. Design of cellular manufacturing systems: An invited review. *Eur. J. Oper. Res.* **1993**, *69*, 284–291. [CrossRef]
4. Wemmerlov, U.; Johnson, D.J. Cellular manufacturing at 46 user plants: Implementation experiences and performance improvements. *Int. J. Prod. Res.* **1997**, *35*, 29–49. [CrossRef]
5. Defersha, F.; Chen, M. A comprehensive mathematical model for the design of cellular manufacturing systems. *Int. J. Prod. Econ.* **2006**, *103*, 767–783. [CrossRef]
6. Tsemekidi, T.S.; Bertoldi, P.; Paci, D.; Castellazzi, L.; Ribeiro, S.T.; Economidou, M.; Zangheri, P. Energy Con-Sumption and Energy Efficiency Trends in the EU-28, 2000–2018. Publications Office of the European Union. 2020. Available online: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/energy-consumption-and-energy-efficiency-trends-eu-28-2000-2018 (accessed on 21 December 2022).
7. IRENA. Reaching Zero with Renewables: Eliminating CO2 Emissions from Industry and Transport in Line with the 1.5 °C Climate Goal. 2020. Available online: https://www.irena.org/publications/2020/Sep/Reaching-Zero-with-Renewables (accessed on 16 December 2022).
8. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981 (accessed on 16 December 2022).
9. El Maraghy, H.; Monostori, L.; Schuh, G.; El Maraghy, W. Evolution and future of manufacturing systems. *CIRP Ann.* **2021**, *70*, 635–658. [CrossRef]
10. Liao, Y.; Deschamps, F.; Loures, E.; Ramos, L.F.P. Past, present and future of Industry 4.0—A systematic literature review and research agenda proposal. *Int. J. Prod. Res.* **2017**, *55*, 3609–3629. [CrossRef]
11. Fatemi-Anaraki, S.; Tavakkoli-Moghaddam, R.; Foumani, M.; Vahedi-Nouri, B. Scheduling of Multi-Robot Job Shop Systems in Dynamic Environments: Mixed-Integer Linear Programming and Constraint Programming Approaches. *Omega* **2023**, *115*, 102770. [CrossRef]
12. Renna, P.; Ambrico, M. Design and reconfiguration models for dynamic cellular manufacturing to handle market changes. *Int. J. Comput. Integr. Manuf.* **2015**, *28*, 170–186. [CrossRef]
13. Bayram, H.; Şahin, R. A comprehensive mathematical model for dynamic cellular manufacturing system design and Linear Programming embedded hybrid solution techniques. *Comput. Ind. Eng.* **2016**, *91*, 10–29. [CrossRef]
14. Delgoshaei, A.; Ariffin, M.K.M.; Bin Baharudin, B.H.T.; Leman, Z. A new method for decreasing cell-load variation in dynamic cellular manufacturing systems. *Int. J. Ind. Eng. Comput.* **2016**, *7*, 83–110. [CrossRef]
15. Delgoshaei, A.; Gomesa, C. A new method for minimizing cell underutilization in the process of dynamic cell forming and scheduling using artificial neural networks. *J. Adv. Mech. Des. Syst. Manuf.* **2019**, *13*, JAMDSM0021. [CrossRef]
16. Kia, R. A genetic algorithm to integrate a comprehensive dynamic cellular manufacturing system with aggregate planning decisions. *Int. J. Manag. Sci. Eng. Manag.* **2020**, *15*, 138–154. [CrossRef]
17. Xue, G.; Offodile, O.F. Integrated optimization of dynamic cell formation and hierarchical production planning problems. *Comput. Ind. Eng.* **2020**, *139*, 106155. [CrossRef]
18. Alimian, M.; Ghezavati, V.; Tavakkoli-Moghaddam, R. New integration of preventive maintenance and production planning with cell formation and group scheduling for dynamic cellular manufacturing systems. *J. Manuf. Syst.* **2020**, *56*, 341–358. [CrossRef]
19. Salimpour, S.; Pourvaziri, H.; Azab, A. Semi-robust layout design for cellular manufacturing in a dynamic environment. *Comput. Oper. Res.* **2021**, *133*, 105367. [CrossRef]
20. Zhang, M.; Lu, Y.; Hu, Y.; Amaitik, N.; Xu, Y. Dynamic Scheduling Method for Job-Shop Manufacturing Systems by Deep Reinforcement Learning with Proximal Policy Optimization. *Sustainability* **2022**, *14*, 5177. [CrossRef]
21. Liang, F.; Fung, R.Y. Coordination mechanism in real-time scheduling of Virtual Cellular Manufacturing Systems. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2016**, *230*, 534–547. [CrossRef]
22. Baykasoglu, A.; Gorkemli, L. Dynamic virtual cellular manufacturing through agent-based modelling. *Int. J. Comput. Integr. Manuf.* **2017**, *30*, 564–579. [CrossRef]
23. Aalaei, A.; Kayvanfar, V.; Davoudpour, H. Integrating multi-dynamic virtual cellular manufacturing systems into multi-market allocation and production planning. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2019**, *233*, 643–664. [CrossRef]
24. Forghani, K.; Ghomi, S.F. Joint cell formation, cell scheduling, and group layout problem in virtual and classical cellular manufacturing systems. *Appl. Soft Comput.* **2020**, *97*, 106719. [CrossRef]
25. Mehrabi, M.G.; Ulsoy, A.G.; Koren, Y. Reconfigurable manufacturing systems: Key to future manufacturing. *J. Intell. Manuf.* **2000**, *11*, 403–419. [CrossRef]
26. Brahimi, N.; Dolgui, A.; Gurevsky, E.; Abdelkrim, R.; Chaouche, Y. A literature review of optimization problems for reconfigurable manufacturing system. *IFAC Pap.* **2019**, *52*, 433–438. [CrossRef]
27. Eguia, J.C.; Molina, S.; Lozano, S.; Racero, J. Cell design and multi-period machine loading in cellular reconfigurable manufacturing systems with alternative routing. *Int. J. Prod. Res.* **2016**, *55*, 2775–2790. [CrossRef]

28. Bortolini, M.; Galizia, F.G.; Mora, C.; Pilati, F. Reconfigurability in cellular manufacturing systems: A design model and mul-ti-scenario analysis. *Int. J. Adv. Manuf. Technol.* **2019**, *104*, 4387–4397. [CrossRef]
29. Bortolini, M.; Ferrari, E.; Galizia, F.G.; Mora, C.; Pilati, F. Optimal redesign of Cellular Flexible and Reconfigurable Manufac-turing Systems. *Procedia CIRP* **2019**, *81*, 1435–1440. [CrossRef]
30. Moghaddam, S.K.; Houshmand, M.; Saitou, K.; Valilai, O.F. Configuration design of scalable reconfigurable manufacturing systems for part family. *Int. J. Prod. Res.* **2019**, *58*, 2974–2996. [CrossRef]
31. Guo, S.; Cui, F.; Geng, N.; Jiang, Z. Cell Formation for Cellular Reconfigurable Manufacturing Systems with Alternative Routing. In Proceedings of the IEEE 17th International Conference on Automation Science and Engineering (CASE), Lyon, France, 23–27 August 2021; pp. 292–297. [CrossRef]
32. Renna, P. Decision-making method of reconfigurable manufacturing systems' reconfiguration by a Gale-Shapley model. *J. Manuf. Syst.* **2017**, *45*, 149–158. [CrossRef]
33. Arista, R.; Fernando, M.; Domingo, M.; Carpoforo, V. Industrial Resources in the design of Reconfigu-rable Manufacturing Systems for aerospace: A systematic literature review. *Comput. Ind.* **2022**, *142*, 103719. [CrossRef]
34. Hao, C.; Luan, S.; Kong, J. Simulation analysis of an integrated model for dynamic cellular manufacturing system. In Proceedings of the AIP Conference Proceedings, Tokyo, Japan, 1–2 November 2017; p. 020162. [CrossRef]
35. Ashraf, M.; Hasan, F. Configuration selection for a reconfigurable manufacturing flow line involving part production with operation constraints. *Int. J. Adv. Manuf. Technol.* **2018**, *98*, 2137–2156. [CrossRef]
36. Bortolini, M.; Ferrari, E.; Galizia, F.G.; Regattieri, A. An optimisation model for the dynamic management of cellular reconfigurable manufacturing systems under auxiliary module availability constraints. *J. Manuf. Syst.* **2021**, *58*, 442–451. [CrossRef]
37. Bagheri, F.; Safaei, A.S.; Kermanshahi, M.; Paydar, M.M. Robust Design of Dynamic Cell Formation Problem Considering the Workers Interest. *Int. J. Eng.* **2019**, *32*, 1790–1797. [CrossRef]
38. Shafiee-Gol, S.; Kia, R.; Kazemi, M.; Tavakkoli-Moghaddam, R.; Darmian, S.M. A mathematical model to design dynamic cellular manufacturing systems in multiple plants with production planning and location–allocation decisions. *Soft Comput.* **2021**, *25*, 3931–3954. [CrossRef]
39. Mejia-Moncayo, C.; Rojas, A.E.; Kenne, J.P.; Hof, L.A. An ant approach to define product families and reman-ufacturing cells. *IFAC-Pap. OnLine* **2022**, *55*, 73–78. [CrossRef]
40. Renna, P.; Materi, S. A Literature Review of Energy Efficiency and Sustainability in Manufacturing Systems. *Appl. Sci.* **2021**, *11*, 7366. [CrossRef]
41. Niakan, F.; Baboli, A.; Moyaux, T.; Botta-Genoulaz, V. A new bi-objective mathematical model for sustainable dynamic cellular manufacturing systems. In Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management, Selangor Darul Ehsan, Malaysia, 9–12 December 2014; pp. 938–942. [CrossRef]
42. Niakan, F.; Baboli, A.; Moyaux, T.; Botta-Genoulaz, V. A bi-objective model in sustainable dynamic cell formation problem with skill-based worker assignment. *J. Manuf. Syst.* **2016**, *38*, 46–62. [CrossRef]
43. Imran, M.; Kang, C.; Lee, Y.H.; Jahanzaib, M.; Aziz, H. Cell formation in a cellular manufacturing system using simulation integrated hybrid genetic algorithm. *Comput. Ind. Eng.* **2017**, *105*, 123–135. [CrossRef]
44. Iqbal, A.; Al-Ghamdi, K.A. Energy-efficient Cellular Manufacturing System: Eco-Friendly Revamping of Machine Shop Configuration. *Energy* **2018**, *163*, 863–872. [CrossRef]
45. Wang, J.; Liu, C. A priority rule based heuristic for virtual cellular manufacturing system with energy consumption. In Proceedings of the EEE 15th International Conference on Networking 2018, Sensing and Control (ICNSC), Zhuhai, China, 27–29 March 2018; pp. 1–5. [CrossRef]
46. Saddikuti, V.; Pesaru, V. NSGA Based Algorithm for Energy Efficient Scheduling in Cellular Manufacturing. *Procedia. Manuf.* **2019**, *39*, 1002–1009. [CrossRef]
47. Liu, C.; Wang, J.; Zhou, M. Reconfiguration of Virtual Cellular Manufacturing Systems via Improved Imperialist Competitive Approach. *IEEE Trans. Autom. Sci. Eng.* **2018**, *16*, 1301–1314. [CrossRef]
48. Lamba, K.; Kumar, R.; Mishra, S.; Rajput, S. Sustainable dynamic cellular facility layout: A solution approach using simulated annealing-based meta-heuristic. *Ann. Oper. Res.* **2020**, *290*, 5–26. [CrossRef]
49. Forghani, K.; Fatemi, S.M.T.; Kia, R. Group layout design of manufacturing cells incorporating assembly and energy aspects. *Eng. Optim.* **2021**, *54*, 770–785. [CrossRef]
50. Ebrahimi, H.; Kianfar, K.; Bijari, M. Scheduling a cellular manufacturing system based on price elasticity of demand and time-dependent energy prices. *Comput. Ind. Eng.* **2021**, *159*, 107460. [CrossRef]
51. Jafarzadeh, J.; Khalili, H.A.; Shoja, N. A Multiobjective Optimization Model for a Dynamic and Sustainable Cellular Manufacturing System under Uncertainty. *Comput. Intell. Neurosci.* **2022**, *2022*, 1334081. [CrossRef] [PubMed]