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Optimal redesign of Cellular Flexible and Reconfigurable Manufacturing Systems

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Abstract

Mixed-model Flexible Manufacturing Systems (FMSs) and, more recently, Reconfigurable Manufacturing Systems (RMSs) are widely studied as diffuse solutions for complex production environments, targeting variable markets and highly dynamic production plans. Their design and management are challenging both in new plants and for plant-redesign actions. In this field, the literature suggests the adoption of cellular configurations as effective solutions. These configurations partition the FMS and RMS machines into manufacturing cells and assign the working parts to the cells to reduce the so-called intercellular flows, causing costs and inbound congestions. This paper advances the current literature presenting and applying an optimal linear programming cost model for the redesign of mixed-model FMS/RMS cellular production environments. The model goes beyond the widely studied partitioning of the FMSs among the cells and it best balances machine relocations and redundancies, the production area layout optimization and the intercellular flow reduction. The major industrial operative constraints are included in the model together with a reference case study to exemplify its advantages toward the standard approaches.

Keywords: FMS; cellular manufacturing; cell formation; layout redesign; optimization

1. Introduction

Cellular Manufacturing (CM) has been one of the most successful strategies adopted by industrial companies to cope with the challenges of modern global competitive environment [1]. Within the CM philosophy, Group Technology (GT) aims at identifying parts characterized by similar features and grouping them together in families to benefits from their similarities in manufacturing and design [2]. The fundamental idea of GT is to ease the planning and control phases of a manufacturing system decomposing it into several subsystems [3]. CM is an application of GT in which similar parts are grouped together in part families and the corresponding machines into machine cells getting significant reductions in setup times, lead times and work-in-process (WIP) [4-6]. Particularly in the last few years, the manufacturing cells are equipped with flexible and reconfigurable machines, able to perform multiple operations and tasks [7,8]. To reach the above-mentioned benefits, Cellular Manufacturing Systems (CMSs) aim at joining the advantages of both job shops and flow shops. Job shops are suitable for the manufacturing of a wide variety of products in small lot sizes. In such systems, machines performing similar functions are located in the same department so that parts requiring different machine types for the performance of their operations need to travel within the different departments. This system organization generally leads to increased amount of material handling and WIP inventories. On the opposite, flow shops are designed to produce high volumes of products at a competitive cost, but they require high investment for purchasing machines. This system performs better than the previous one in terms of material handling, WIP and setup times because of the machines are located in the

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production lines according to the product work cycles [3]. Since both job and flow shops cannot simultaneously provide efficiency and flexibility goals to the product variety, CMSs emerged to achieve these requirements. The aim of this paper is to present an original procedure based on operational research (OR) for the redesign of flexible and reconfigurable cellular production environments including both machine relocations and duplications to measure the effect of these strategies on system performances. The current literature proves that these strategies are beneficial for an effective working of CMSs but few studies still exist.
According to these goals, the reminder of this paper is organized as follows: Section 2 revises the relevant literature on the topic. Section 3 introduces the proposed mathematical model while Section 4 presents a case study, based on an instance inspired from the literature, and the results discussion. Finally, Section 5 presents conclusions and suggestions for further research.

2. Literature review

This section is organized into two parts. The former explores models and tools addressing the cell formation (CF) problem in CMSs design while the latter revises the relevant contributions considering the opportunity to relocating and/or duplicating machines in cellular manufacturing environments.

2.1. The Cell Formation problem in CMSs design

In CMSs, the CF problem is the crucial step to implement. It deals with models and tools to grouping of parts in families and machines in cells [9]. In the last decades, the literature proposed a wide set of contributions facing the CF problem with different strategies and methodologies, e.g. heuristic, metaheuristic and hybrid algorithms. Chen and Srivastava [10] proposed a programming quadratic model for the CF problem maximizing the sum of machine similarities within cells by using a simulated annealing-based algorithm. Boctor [11] defined a mathematical model to minimize the number of exceptional elements (EEs) solved with a simulated annealing algorithm. Xambre and Vilarinho [12] proposed a mathematical programming model addressing the CF problem with multiple identical machines minimizing the intercellular flow and using a simulated annealing procedure to solve it. A wide but still limited group of researchers considers the existence of alternative process routings for the production of parts. Won and Kim [13] considered the machine-part clustering problem in GT in which parts are characterized by multiple routings and developed an algorithm based on multiple clustering criteria that minimize the number of EEs. Akturk and Turkcan [14] proposed an algorithm to solving the integrated part-family and machine-cell formation problem maximizing the efficiency of both individual cells and the overall cellular systems economic performances. Jeon and Leep [15] developed a methodology to form manufacturing cells introducing a new similarity coefficient based on the number of alternative routes during demand changes within multiple time periods. Kao and Lin [16] defined a discrete particle swarm optimization (PSO) approach to face the CF problem in presence of alternative process routings, minimizing the number of exceptional parts outside the machine cells and comparing the results to those obtained by applying simulated annealing and tabu search based algorithms. Chang et al. [17] considered three relevant aspects in designing CMSs, i.e. cell formation, cell layout and intracellular machine sequence and proposed a mathematical model to integrate such issues considering alternative process routings, operation sequences, and production volumes. Mohammadi and Forghani [18] proposed an integrated approach to designing CMSs considering both inter- and intra-cell layouts. The Authors included various production factors such as alternative process routings, part demands and operation sequences in the mathematical formulation, with the overall objective to minimize the total manufacturing costs. The reviewed studies rarely proposed mathematical models and methods solved by applying heuristic and metaheuristic techniques. Among these, some researchers apply hybrid techniques to solve the CMS design problem. The main ability of these methods is to join together the strengths of different techniques. Caux et al. [19] defined an algorithm for the CF problem to minimize the inter-cell traffic. A hybrid methodology integrating simulated annealing for the CF and branch & bound for the routing selection is used for the model resolution. Goncalves and Resende [20] introduced a new hybrid approach to forming machine cells and product families based on local search and heuristic algorithms with the overall goal to maximize the grouping efficacy. Chiang and Lee [21] addressed the joint problem of manufacturing cell formation and its layout assignment, minimizing the intercell flow cost under the cell size constraint. This model is solved by combining a simulated annealing algorithm augmented with a dynamic programming. Saghafian and Akbari Jokar [22] proposed a new integrated view of manufacturing CF and both inter- and intra-cell layout problems and developed a hybrid method based on dynamic programming, simulated annealing and genetic operators to minimize the total inter- and intra-cell handling cost. Nsakanda et al. [1] integrated the CF problem, the machine allocation problem and the part routing problem in designing CMSs, defining a solution methodology based on genetic algorithm and large-scale optimization techniques.

2.2. Benefits of machines relocations/duplications in CMSs

Despite the literature focusing on the design and management of CMSs is wide, few studies explore the convenience to simultaneously relocate and/or duplicate a machine in a manufacturing cell as introduced by Selim et al. [2] and Wu [23]. They demonstrated that machine duplication significantly contributes to the reduction of intercellular flows increasing, at the same time, the interdependence among machine cells. Logendran and Ramakrishna [24] defined a model to duplicating bottleneck machines and subcontracting bottleneck parts under budgetary restrictions in CM systems. Irani and Huang [25] defined practical strategies for machine duplication in cellular manufacturing layouts. Tavakkoli-Moghaddam et al. [26] presented a fuzzy linear programming model for the design of CMSs by considering fuzzy part demands and

changeable product mix as well as alternative process plans for part type and the possibility to duplicate machines. Bortolini et al. [27] introduced a hybrid procedure based on cluster analysis and integer linear programming techniques to solving the CF problem allowing the possibility of duplicating machines. Mohammadi and Forghani (2017) proposed a bi-objective model addressing the CF problem considering alternative process routings and machine duplications. The proposed formulation aims at minimizing the total dissimilarity among the parts and the total investments needed for the acquisition of the machines.
Following this research stream, next Section 3 presents the proposed optimization model for cellular production environments redesign in which both machines relocations and duplications are allowed.

3. A model for cellular production environment redesign

According to the adopted research approach based on OR, an optimization model for cellular production environment redesign is proposed. The model belongs to the so-called improvement models because, starting from an initial configuration, it evaluates the possibility to relocate and/or duplicate machine types in other manufacturing cells. In particular, the relocation and the redundancy of a machine type in one or more cells can significantly decrease the total number of intercellular flows and consequently the total indirect costs. In contrast, in case of duplications, adding resources to the production environment makes the manufacturing system more complex and this decision generally implies an increase of investments costs. An effective trade-off is of strong interest.
In the following, an optimization model evaluates the best configuration of machine cells in the cellular manufacturing environment including machine relocations and duplications. The model is developed to avoid non-linearity and to guarantee solvability in a reasonable time.
Next Fig. 1 shows a schematic framework of the CMS structure while the model nomenclature and formulation is in the following.

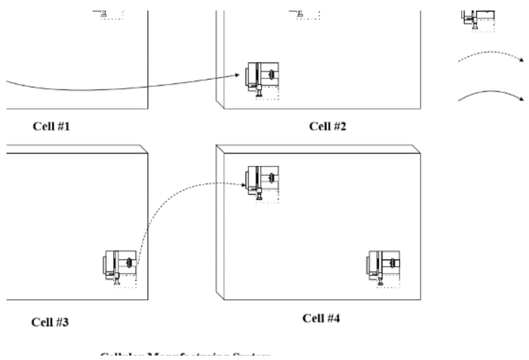

Fig. 1. Schematic framework of a CMS structure.

Nomenclature

Indices	
i	Index for parts $i = 1, \dots, M$
j, j_1, j_2	Index for cells $j, j_1, j_2 = 1, \dots, N$
k, k_1	Index for machine types $k, k_1 = 1, \dots, P$
o, o_1	Index for operations in part work cycle $o, o_1 = 1, \dots, O_i$
Parameters	
C_{kj}	Number of machines type k assigned to cell j in the initial configuration [# items]
V_{ik}^{o}	1 if part i requires machine k for operation o; 0 otherwise
q_i	Planned production volume during a predefined period of time for part i [pcs/months]
t_i^o	Processing time for operation o in part i work cycle [minutes/pc]
Z_i	Required number of trips per part i [# trips]
$€_k^{mach}$	Duplication cost of machine [€/machine]
$€_k^{reloc}$	Relocation cost of machine [€/machine]
$€_{jj_1}^{flux}$	Unit intercellular flow cost [€/machine]
τ	Available time for machines [minutes/machine]
Decision variables	
R_{kj}	Number of machines type k in cell j after relocation/duplication
RD_{kj}	Total number of relocations and duplications of machine type k in cell j
$F_{ijj_1}^{o}$	1 if part i moves from cell j to cell j_1 after operation o; 0 otherwise $o = 1, \dots, O_i - 1$

3.1. Model formulation

The analytic formulation of the proposed model is in the following.

$$\min \psi = \sum_{k=1}^{P} €_k^{reloc} \cdot \sum_{j=1}^{N} RD_{kj} + \sum_{k=1}^{P} (€_k^{mach} - €_k^{reloc}) \cdot \sum_{j=1}^{N} R_{kj} - \sum_{j=1}^{N} C_{kj} + \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{j_1=1}^{N} \sum_{o=1}^{O_i - 1} €_{jj_1}^{flux} \cdot F_{ijj_1 o} \cdot Z_i \tag{1}$$

(1) minimizes the total cost as the sum of the costs generated by relocations of machines (first term in Eq. 1), by purchasing of new machines, i.e. duplication costs (second term in Eq. 1) and by intercellular flows (third term in Eq. 1).

The model is subject to the following feasibility constraints, which reproduce real industrial contexts:

$$\sum_{j=1}^{N}\sum_{j_1=1}^{N} F_{ijj_1o} = 1 \qquad i = 1,\dots,M \quad o = 1,\dots,O_i - 1 \qquad (2)$$

$$\sum_{j_1=1}^{N} F_{ij_1jo} = \sum_{j_1=1}^{N} F_{ijj_1o+1} \qquad i = 1,\dots,M \quad j = 1,\dots,N \quad o = 1,\dots,O_i - 2 \qquad (3)$$

$$\sum_{i=1}^{M}\sum_{j_1=1}^{N}\sum_{o=1}^{O_i-1} F_{ijj_1o}\cdot V_{ik}^{o}\cdot q_i\cdot t_i^{o} + \sum_{i=1}^{M}\sum_{j_1=1}^{N} F_{ij_1jO_i-1}\cdot V_{ik}^{O_i}\cdot q_i\cdot t_i^{O_i} \le R_{kj}\cdot\tau \qquad k = 1,\dots,P \quad j = 1,\dots,N \qquad (4)$$

$$RD_{kj} \ge R_{kj} - C_{kj} \qquad \forall k,j \qquad (5)$$

$$R_{kj}, RD_{kj} \ge 0, \text{ integer} \qquad \forall k,j \qquad (6)$$

$$F_{ijj_1o} \text{ binary} \qquad \forall i,j,j_1,o \qquad (7)$$

Constraints (2) and (3) guarantee the continuity of parts flow within the manufacturing system. (4) forces the manufacturing of the part production volumes to be completed within the available machine uptime. (5) sets the auxiliary variable $\boldsymbol{RD_{kj}}$ as the difference between the number of machines k in cell j after the relocation/duplication and the number of that machines in the initial configuration. (6)-(7) give consistence to the decision variables.

4. Model application

4.1. Case study description

The proposed model is applied to a case study made of an instance of the CF problem introduced by Gupta and Seifoddini [28], characterized by a 43 x 16 matrix (number of parts x number of machines). Furthermore, a set of eight different operations is available to manufacture the parts and five machine cells are available for machine assignment. A multi-scenario analysis is performed to assess how the results change changing the relationship between duplication and intercellular flow costs. The input data with reference to the parts and their work cycles are in Appendix A. In particular, the production volumes are expressed in parts per month while the processing times in minutes. Table 1 shows the initial configuration, i.e. the machine-cell assignment and, for each machine type, the number of machines allocated to each manufacturing cell.

The model is coded in AMPL language and processed adopting Gurobi Optimizer© v.4.0.1.0 solver. An Intel® CoreTM i7 CPU @ 2.40GHz and 8.0 GB RAM workstation is used. The solving time is approximately of about 20 seconds per scenario.

Table 1. Initial cellular manufacturing configuration.

	C1	C2	C3	C4	C5
m1		1			
m2		3			
m3	2				
m4				7	
m5				7	
m6			11		
m7			1		
m8				14	
m9		5			
m10			7		
m11					10
m12					3
m13					1
m14	2				
m15				3	
m16		5			

4.2. Results and discussion

The multi-scenario analysis is carried out to test the model varying some of the key input parameters. In particular, following the above-mentioned trade-off between the number of machine duplications and the number of intercellular flows, this analysis is performed changing, in each scenario, the relationship between the duplication and the intercellular flow costs. The aim is to find a configuration solution best-balancing the investments cost generated by purchasing of new machines and indirect costs generated by intercellular flows.

According to the industrial practice, a constant parameter $\mu = €_k^{mach}/€_k^{reloc}$ equal to 2.5 and a variable parameter $\xi = €_k^{mach}/€_{jj_1}^{flux}$, ranging in [25, 3200], are introduced. The μ value specifies that the cost of machine relocation is less than half the cost of the correspondent duplication. The parameter ξ specifies that, in the model objective function, a machine duplication, i.e. $€_k^{mach}$ cost, is equivalent to ξ intercellular flows, i.e. $€_{jj_1}^{flux}$ cost. Globally, duplications become convenient if they allow to cut off more than ξ intercellular flows each.

The values of ξ parameter together with the main model results for each scenario are in Table 2 and Fig. 2.

Table 2. Key model results in each scenario.

Scenario Id.	ξ	Relocations [#]	Duplications [#]	Intercellular flows [#]	Objective function value [€]
S1	25	19	2	1	247
S2	50	19	2	1	487
S3	100	19	2	1	967
S4	200	15	2	6	1794
S5	400	15	1	9	3341
S6	800	9	1	17	5669
S7	1600	5	0	25	8145
S8	3200	0	0	55	9312

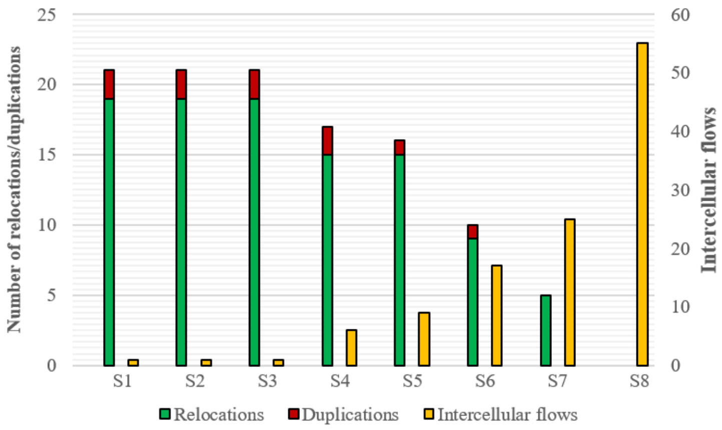

Fig. 2. Multi-scenario analysis results.

Results show that moving from S1 to S8, i.e. with the increase of parameter ξ, the number of intercellular flows increases while the number of machine relocations and duplications decreases. In particular, focusing on the first three scenarios, characterized by ξ values equal to 25, 50 and 100, respectively, the solutions present significant numbers of relocations compared to some duplications and very few intercellular flows. Such flows increase in S4 in which parameter ξ is equal to 200. Overall, in the presence of a machine purchasing cost, i.e. case of duplication, much greater than the unit intercellular flow cost, e.g. S8, the optimization process will promote the parts travelling among the machine cells. Instead, in presence of lower values of ξ parameter, the system shows the convenience of mixing the two strategies. The obtained results prove the existence of a significant trade-off between direct costs generated by machine relocations and duplications and indirect costs generated by intercellular flows, implying that the decision to relocate and/or duplicate a machine in a cellular manufacturing environment is a crucial opportunity for industrial companies to improve the economic and technical performances of their production systems.

5. Conclusions and further research

Cellular Manufacturing Systems (CMSs) represent an effective alternative in production system organization adopted by several companies to guarantee higher levels of system flexibility and reactivity. To reach such benefits, similar parts are grouped in families and the corresponding machines into cells, addressing the cell formation (CF) problem. This study presents an optimal procedure for the redesign of mixed-model cellular flexible and reconfigurable manufacturing systems. An original integer linear programming model based on operational research (OR) is defined to evaluate the opportunity to relocate and/or duplicate machine types in manufacturing cells, best managing the trade-off between the direct costs generated by machine relocations and duplications and the indirect costs generated by intercellular flows. Starting from an initial cellular manufacturing configuration, the proposed model is applied to a case study made of an instance of the CF problem inspired from the literature. The main results show a decrease of the system intercellular flows without a high increase of the machine number in all the explored scenarios, getting a convenient and significant trade-off. Future research deals with the execution of experimental analysis to test the proposed model on different industrial and literature instances to compare the results obtained by adopting different problem settings.

Appendix A

A.1. Parts input data

Part	Volume [pcs/month]	Work cycle	Processing times [minutes/pc]
p1	50	m6-m10-m7-m8-m6	3.5-5.0-10.5-23.0-3.0
p2	150	m2-m9-m6-m9-m8-m16-m14-m2	3.5-4.0-12.0-10.0-5.5-6.4-22.4-11.0
p3	500	m8-m13-m11-m8	2.5-6.7-4.8-23.0
p4	75	m9	6.8
p5	500	m4-m15-m5-m4	18.0-4.0-14.0-10.0
p6	1200	m6-m14	22.0-11.4
p7	1500	m3-m6-m16-m3	2.3-4.7-6.6-3.5
p8	750	m8-m5-m6	6.0-8.0-6.2
p9	5000	m4-m11-m5-m8-m4	7.4-9.2-4.1-10.5-2.5
p10	1300	m9-m2-m16	4.5-3.5-26.0
p11	1239	m8-m12	14.0-6.5
p12	575	m8-m6-m10-m8	3.0-5.6-9.0-14.0
p13	1239	m7-m6-m10	7.0-6.0-10.0
p14	1500	m4-m6-m5-m6	4.5-6.8-2.4-3.5
p15	14000	m5-m8	4.0-8.5
p16	39	m5	8
p17	900	m3-m14-m6-m3	3.4-5.6-2.5-12.0
p18	339	m9-m16	24.0-5.3
p19	390	m4-m6-m8-m5-m6-m15	2.0-4.8-1.4-15.0-12.0-5.0
p20	304	m8-m11	10.0-5.0
p21	405	m4-m8-m5-m15-m4	8.0-11.0-3.5-14.0-20.0
p22	1200	m5-m12	4.7-3.5
p23	5	m4-m6-m5-m8	34.0-4.5-6.9-12.0
p24	35	m8-m11-m13-m12-m8	3.5-3.6-7.5-12.5-22-0
p25	390	m7-m10	13.0-4.5
p26	750	m10	2.4
p27	39	m11-m12-m8	22.5-4.5-8.5
p28	320	m2-m9-m8	3.5-6.7-8.5
p29	1500	m4-m5	30.5-2.5
p30	11300	m11-m12	12.0-3.5
p31	310	m8-m10	4.5-15.0
p32	430	m2-m9-m6-m16-m9	22.0-4.5-6.3-9.5-12.5
p33	500	m5-m15-m6-m5	5.0-6.4-7.8-9.4
p34	275	m3-m6	4.2-5.5

p35	500	m14-m3	5.0-10.0
p36	600	m3	5
p37	1500	m1-m2-m9-m8-m6-m16-m9	4.5-3.5-7.5-8.0-32.6-21.0-5.7
p38	750	m2-m9-m8-m16-m9	4.0-9.5-7.8-2.5-3.5
p39	5000	m6-m10	6.0-20.0
p40	1300	m9-m2-m6-m9	12.0-4.0-8.9-11.0
p41	1239	m5-m8-m15	3.0-4.5-6.5
p42	575	m1-m2-m9-m6-m2-m16-m1	2.5-12.0-4.5-8.5-6.5-9.5-4.3
p43	1239	m5-m6-m8-m15-m6	3.0-5.0-8.0-15.0-6.0

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