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Dynamic design and management of reconfigurable manufacturing systems

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Abstract

This research proposes an approach to design and to manage Cellular Reconfigurable Manufacturing Systems (CRMSs) from a multi-product and multi-period perspective. The production environment consists of multiple cells of machines equipped with Reconfigurable Machine Tools (RMTs) made of basic and auxiliary custom modules to perform specific tasks. The approach acts into two steps; the former is the machine cell design phase, assigning machines to cells, the latter is the cell loading phase, assigning modules to each machine and cell. The goal is to guarantee the economic sustainability of the manufacturing system by exploring how to best balance the part flow among machines already equipped with the required modules and the effort to install the necessary modules on the machine on which the part is located.

Keywords: Reconfigurable manufacturing systems; Cellular manufacturing; Machine loading; Modularity; Reconfigurable machine tool; Optimization model.

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1. Introduction

Nowadays, an increasing number of factors such as short lead times, fluctuating volumes, dynamic market demand and high customized variants drives the transition towards the so-called next generation manufacturing systems [1-2]. Traditional manufacturing systems such as Dedicated Manufacturing Systems (DMSs), Cellular Manufacturing Systems (CMSs) and Flexible Manufacturing Systems (FMSs) show increasing limits in adapting themselves to the

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most recent industrial trend. DMSs are designed to produce a specific part at high volume and represent a cost-effective production system in a stable market [3]. FMSs use expensive automated numerically controlled (CNC) machines with fixed hardware and software. The ability of FMSs is their flexibility in managing resources to manufacture a large variety of parts, but the throughput rate is low. CMSs aim at achieving production efficiency and system flexibility by using the process similarities of the parts [4]. However, once machine cells are designed, the physical relocation of the facilities present in each cell in response to new production requirements becomes difficult. This rigidness prevents such systems from coping with current industrial challenges [5]. Reconfigurable Manufacturing Systems (RMSs) are an emerging manufacturing system paradigm and seem to match to the current market and technological requirements [6-7]. RMSs are characterized by Reconfigurable Machine Tools (RMTs) [8] having an adjustable and modular structure that enables machine scalability and convertibility using basic and auxiliary modules [9]. In contrast to conventional general-purpose CNC machines, RMTs are designed for a specific range of operations [10]. Suitable auxiliary custom modules are selected from a library of commercially available modules to perform specific tasks. This paper presents a two-step methodology to design and manage Cellular Reconfigurable Manufacturing Systems (CRMSs) from a multi-product and multi-period perspective, with the overall goal to guarantee the economic sustainability of the manufacturing system. In the first step, machines are assigned to cells – cell design phase – while in the second, auxiliary modules are assigned to each machine and cell – cell loading phase. The proposed model performs these two steps by exploring how to best balance the part flow among machines already equipped with the required modules and the effort to install the necessary modules on the machine on which the part is located. According to this goal, the reminder of this paper is organized as follows: the next Section 2 revises the literature on the topic. Section 3 introduces the proposed model while the model discussion and its application to a case study is in Section 4. Finally, Section 5 concludes the paper with final remarks and future research opportunities.

2. Literature review

Different approaches have been proposed over the decades for the design of CMSs [11-12]. Bortolini et al. [13] present a hybrid procedure for the cell formation problem based on cluster analysis and mathematical programming. The proposed procedure explores the possibility of duplicating a machine in one or more cells to reach the best trade-off between direct cell costs and indirect costs due to intercellular flows. Defersha and Chen [4] propose a comprehensive mathematical model for the design of CMS to minimize maintenance and overhead costs, machine procurement cost and inter-cell material handling cost. Deep and Singh [14] introduce a mathematical model for the design of robust machine cells for dynamic part production. The proposed model incorporates the machine cell configuration design problem and the machine allocation problem as well as the dynamic production problem and the part routing problem. In the last years, numerous attempts have been made to merge CMS and RMS concepts [10] to overcome the main limitations of cellular manufacturing, leading to the concept of CRMSs. They are defined as a set of Reconfigurable Machine Cells (RMCs) in which machines are logically, instead of physically, organized [15]. RMCs change during the production plan horizon since machines can be shared by different cells. In this field, methods specifically aimed at cell formation using reconfigurable machines can be found in Pattanaik et al. [5] and Pattanaik and Kumar [16]. In these studies, the Authors present a clustering-based approach to design machine cells using modular machines to achieve characteristics of reconfigurable manufacturing. Xing et al. [15] focus their effort on the design and control of a CRMS by using artificial intelligence. In particular, the focus of this research is on the formation of RMCs which derive from the dynamic and logical clustering of some manufacturing resources, driven by specific customer orders. Bai et al. [17] define an approach for the formation of virtual manufacturing cells in a reconfigurable manufacturing environment with multiple product orders. Rabbani et al. [18] explore the idea of machine modification in CRMSs through a mixed integer non-linear mathematical model. The Authors develop an Imperialist Competitive Algorithm and, then, compare the obtained results with those of a Genetic Algorithm. Eguia et al. [19] propose a new approach to simultaneously solve the cell formation and the scheduling of part families for the effective working of a CRMS. Authors define a mixed integer linear programming model to represent both problems with the overall objective of minimizing the production costs. The first attempt to integrate part grouping and loading in such systems is in Yu et al [20]. In this work, the Authors consider multiple cells, each of which has CNC machines with tool limitations. They define an optimization model to solve both problems with the objective of minimizing the maximum workload assigned to machines. Eguia et al. [8] extend the formulation of [20] by considering multiple process plans for each part type, RMTs with a library of auxiliary modules, transportation and holding costs as main objective function and balancing workloads as secondary objective.

3. Cellular reconfigurable manufacturing system design

3.1 Problem description, assumptions and notations

This study addresses the design of CRMSs. Such systems consist of multiple RMCs, each of which has RMTs, material handling and storage systems. Each RMT within a RMC has a library of basic and auxiliary modules. The basic modules are structural elements while auxiliary modules are kinematical or motion-giving (e.g. spindles, tool changers, etc.). A particular combination of both different basic and auxiliary modules gives a particular operational capability to the RMT. Figure 1 shows a schematic of a CRMS.

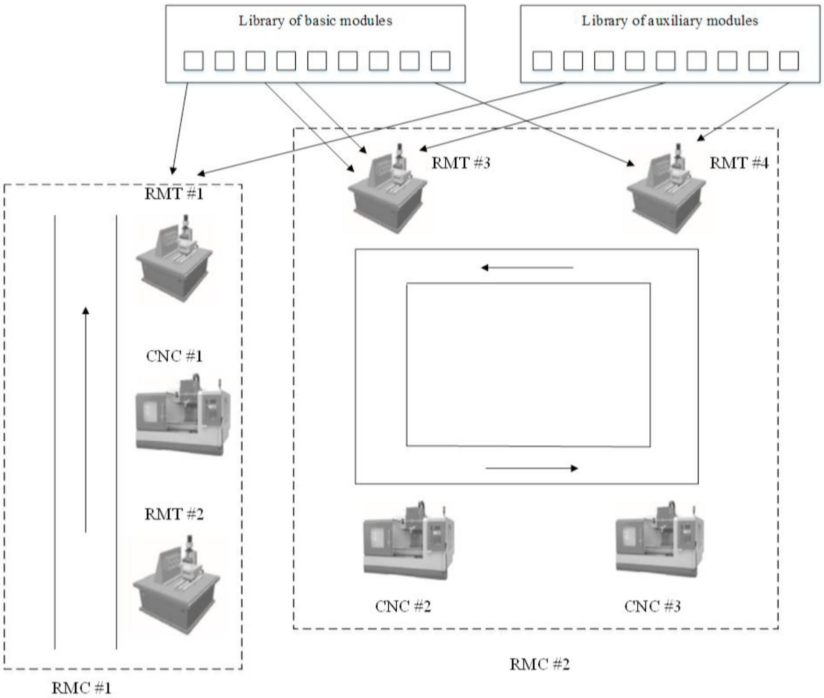

Fig. 1. Schematic description of a CRMS.

The CRMS design problem involves the grouping of RMTs in each RMC by using information about the operation sequence for each part type as well as the assignment of each auxiliary module to the RMTs. In this paper, an optimization model for the design of CRMS is proposed. The goal of the defined model is to best balance the part flow among RMTs already equipped with the required auxiliary modules and the effort to install the necessary auxiliary modules on the RMT on which the part is located with the long-term perspective of reaching the economic sustainability of the manufacturing system.

The proposed optimization model adopts the following assumptions according to the standard literature within CRMS modelling [8]-[11]:

- Operation-based process plan for the parts is known and fixed;
- Requirement of modules and machine-module compatibility information are known and unchangeable;
- Size limit for each RMC is to be given;

- Unique assignment of the machines to each cell;
- Auxiliary modules are available when needed;
- CNC machines are not considered in the optimization at this stage since they do not include elements of reconfigurability.

These assumptions are still realistic and representative of common production environments. Furthermore, the model is flexible and can be adapted to match different assumptions (e.g. mono or multi-product model, mono or multi-period model).

The following notations are used.

- Indices

i	parts $i = 1, \dots, M$
o	operations in part work cycle $o = 1, \dots, O$
m	machines $m = 1, \dots, Z$
k	auxiliary module types $k = 1, \dots, L$
j	machine cells $j = 1, \dots, N$
t	time periods $t = 1, \dots, T$

- Parameters

P_j	maximum number of machines in each cell j
G_{omk}	1 if operation o can be performed on machine m using auxiliary module type k; 0 otherwise $[binary]$
r_{it}	definition of the operation in which the part i is in period t
t_{ijj_1}	travel time for part i from cell j to cell j_1 $[min]$
λ_{mk}	assembly time of module k on machine m $[min]$
μ_{mk}	disassembly time of module k from machine m $[min]$

- Decisional variables

MAC_{mj}	1 if machine m is assigned to cell j; 0 otherwise $[binary]$
F_{ijj_1t}	1 if part i moves from cell j to cell $j1$ in period t; 0 otherwise $[binary]$
σ_{mkt}	1 if module k is on machine m in period t, 0 otherwise $[binary]$
X_{mkt}	1 if module k is assembled on machine m in period t, 0 otherwise $[binary]$
Y_{mkt}	1 if module k is disassembled from machine m in period t, 0 otherwise $[binary]$
W_{mit}	1 if part i is processed by machine m in period t; 0 otherwise $[binary]$

- Objective function

ψ Total part travel time and module installation time $[hours]$

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

$$\psi = \sum_{m=1}^{Z} \sum_{K=1}^{L} \sum_{t=1}^{W} X_{mkt} \cdot \lambda_{mk}$$

$$+\sum_{m=1}^{Z}\sum_{K=1}^{L}\sum_{t=1}^{W} Y_{mkt}\cdot\mu_{mk}$$

$$+\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{t=1}^{W} F_{ijj_1t}\cdot t_{ijj_1} \tag{1}$$

(1) minimizes the sum of three relevant terms: the time necessary to install the auxiliary module on the specific machine, the time necessary to disassemble the module from the machine and the inter-cell part travel time.

$$\sum_{j=1}^{N} MAC_{mj} = 1 \qquad \forall m \tag{2}$$

$$\sum_{m=1}^{Z} MAC_{mj} \le P_J \qquad \forall j \tag{3}$$

$$\sum_{m=1}^{Z} W_{mit} = 1 \qquad \forall t, i \tag{4}$$

$$G_{omk}\cdot W_{mit} \le \sigma_{mkt} \qquad \forall\, m, i, k, t, o\colon r_{it} = o \tag{5}$$

$$W_{mit} \le \sum_{k=1}^{L}\sum_{o:r_{it}=o} G_{omk} \qquad \forall\, m, i, t \tag{6}$$

$$X_{mkt} \ge \sigma_{mkt} - \sigma_{mkt-1} \qquad \forall\, m, k, t = 2, \dots, T \tag{7}$$

$$Y_{mkt} \ge \sigma_{mkt-1} - \sigma_{mkt} \qquad \forall\, m, k, t = 2, \dots, T \tag{8}$$

$$F_{ijj_1t} \le \sum_{m=1}^{Z}\sum_{k=1}^{L}\sum_{o:r_{it}=o} G_{omk}\cdot MAC_{mj} \qquad \forall i, j, j_1, t = 1, \dots, T-1 \tag{9}$$

$$F_{ijj_1t} \le \sum_{m=1}^{Z}\sum_{k=1}^{L}\sum_{o:r_{it+1}=o} G_{omk}\cdot MAC_{mj_1} \qquad \forall i, j, j_1, t = 1, \dots, T-1 \tag{10}$$

$$\sum_{j=1}^{N}\sum_{j_1=1}^{N} F_{ijj_1t} = 1 \qquad \forall i, t \tag{11}$$

$$\sum_{j_1=1}^{N} F_{ij_1j\,t} = \sum_{j_1=1}^{N} F_{ijj_1t+1} \qquad \forall i, j, t = 1, \dots, T-1 \tag{12}$$

$$\sigma_{mkt} \leq \sum_{i=1}^{M} \sum_{o:r_{it}=o} G_{omk} \quad \forall m,k,t \quad (13)$$

$$MAC_{mj}\ binary \quad \forall m,j \quad (14)$$

$$F_{ijj_1t}\ binary \quad \forall j,j_1,t \quad (15)$$

$$W_{imt}\ binary \quad \forall i,m,t \quad (16)$$

$$\sigma_{mkt}, X_{mkt}, Y_{mkt}\ binary \quad \forall m,k,t \quad (17)$$

(2) ensures that each RMT is assigned to only one cell, while (3) fixes the size limit of each machine cell. (4) ensures that each part, in each period, is processed by a single machine. (5)-(6) define the assignment of the auxiliary modules to RMTs while (7)-(8) set the auxiliary modules installation and disassembly process on/from RMTs. (9)-(12) define the part flow among the defined machine cells. (13) ensures that a module is on a machine only if it is installable on that machine. (14)-(17) give consistence to the decisional variables.

4. Model application

4.1 Case study description

A case study applies the proposed model, representative of a small production company. The industrial environment manufactures 5 different products characterized by a set of maximum 6 operations, choosing among 5 RMTs, i.e. machines, and 5 auxiliary modules. Finally, 3 different RMCs, i.e. machine cells, are available in the company for machines assignment. The parts working-cycles and the machine-operation-module compatibility matrix are in Table 1a and Table 1b. The set of input data, i.e. parameters, used to feed the model are available under request to the Authors and leads to 848 parameters and 16,215 decision variables. The model is coded in AMPL language and processed adopting LpSolve Optimizer© v.4.0.1.0 solver. An Intel® CoreTM i7 CPU @ 2.40GHz and 8.0GB RAM workstation is used. The global solving time is approximately of 30 seconds.

Table 1a. Parts working cycle.

Table 1b. Machine-module-operation compatibility matrix

Part *(i)*	Working cycle
1	Op2-Op3-Op1-Op2-Op4
2	Op5-Op2-Op3-Op1-Op2-Op4-Op6-Op2
3	Op1-Op2-Op3-Op4
4	Op5-Op2-Op1-Op2-Op6
5	Op1-Op4-Op6-Op2-Op3-Op5

Machines *(m)*	Operation type *(o)*	Auxiliary modules *(k)*
1	Op1	1, 3
	Op6	3, 4
2	Op2	1
	Op5	2, 5
3	Op1	1
	Op3	2, 5
4	Op4	4
	Op5	2, 5
5	Op2	1, 4
	Op4	4, 5

4.2 Results and discussion

The optimal solution of the objective function ψ is equal to 3516.34 min. As mentioned in Section 3.1, the objective function includes three relevant terms: the auxiliary modules installation time that contributes for 46% of the optimal value (1622.9 min), the auxiliary modules disassembly time that contributes for 34.2% (1203.45 min) and the inter-cells part travel time that contributes for 19.61% (690 min). The system configuration in terms of machine-cell assignment is: RMT #4 in RMC #1, RMT #2 in RMC #2 and RMT #1, RMT #3 and RMT #5 in RMC #3. The following Figure 2 shows a schematic layout of the CRMS resulting from the model optimization, showing the flow of Part 2 as reference example.

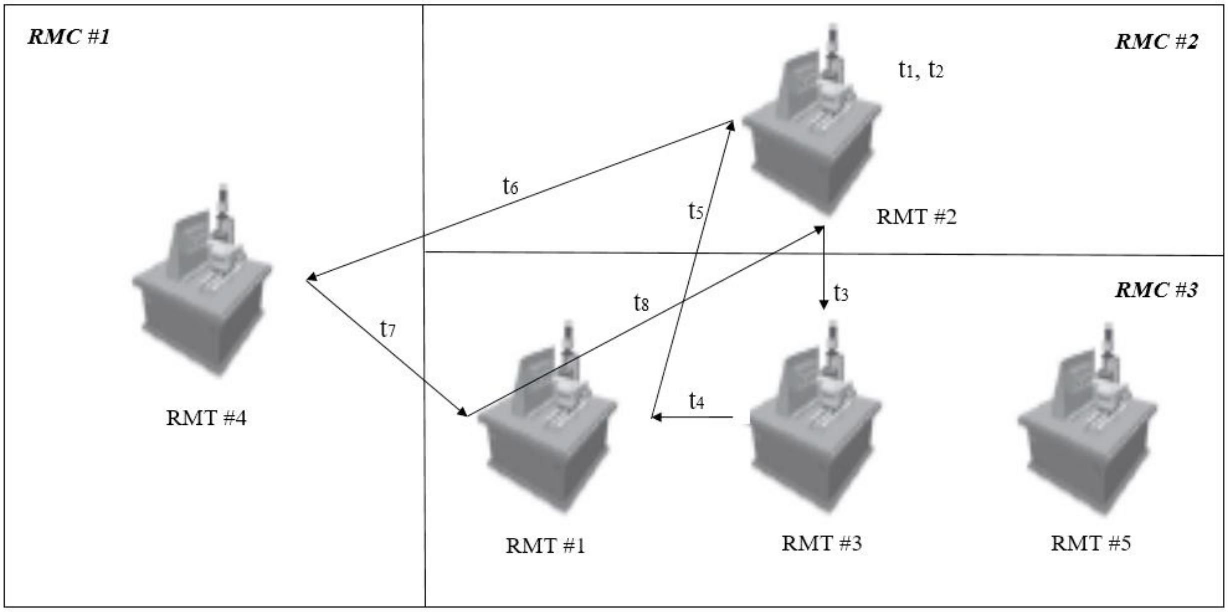

Fig. 2. CRMS layout and Part 2 flow.

Focusing on Part 2, the optimization procedure reveals that the optimal path for this product is to stay on RMT #2 in periods 1 and 2 to perform operations Op5 and Op2 – the first two operations in Part 2 working cycle – and then to move to other machines for the performance of the remaining operations.

The part scheduling indirectly comes from model resolution. The ability of this methodology is to overcome the main limitations of CMSs. In a conventional CMS, machines are grouped into cells, each of which is dedicated to the production of a particular part family in order to reduce material handling and work-in-process. However, CMSs lack of adaptability, i.e. the ability to quickly change system functionality and capacity to produce all members of the part family in a cost-effective way. Reconfigurable technologies provide a high degree of adaptability through the use of RMTs. The adjustable and modular structure of these machines allows economically changing from the production of a part to another one and thus assigning more than one part to each cell. The aim is to reach high level of flexibility without losing cost-effectiveness, looking at the economic sustainability of the manufacturing system.

5. Conclusions and future research

The research issue discussed in this paper deals with a new approach to design and manage Cellular Reconfigurable Manufacturing Systems (CRMSs) characterized by multiple Reconfigurable Machine Cells (RMCs) equipped with Reconfigurable Machine Tools (RMTs). Each RMT is made of basic and auxiliary modules to perform specific tasks. To address the CRMS design problem, assigning machines to cells and modules to each machine and cell, an optimization model is proposed based on several production parameters. The present model includes machines with the capability to perform multiple operations, as it is thought to be the key of reconfigurable manufacturing. The problem is described as minimization of the part travel time and module installation and disassembly time to best balance the part flow among RMTs already equipped with the required auxiliary modules and the effort to install these modules on the machine on which the part is located. This trade-off is new and, to the Author's knowledge, has never been explored so far by the literature. Furthermore, the present design approach can be used as a basis for cell formation to achieve reconfiguration and, due to its flexibility, it can successfully support decision-makers in selecting cell sizes and their configurations. The proposed model is applied to a case study of a small production company to prove its effectiveness. Future research deals with the extension of the model to include other relevant issues not considered at this stage i.e. production balancing, and the application of the model to larger real size instances.

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