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An optimisation model for the dynamic management of cellular reconfigurable manufacturing systems under auxiliary module availability constraints

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Abstract

In the last decade, traditional industrial and market features were replaced by emerging factors, such as the variable market demand, the need for flexibility, the shorter product life cycles and the mass personalisation, which drastically modified the production environment, pressing industrial companies to embrace and implement new types of production paradigms. Reconfigurable Manufacturing Systems (RMSs) rose as effective systems able to meet the current challenges rapidly changing their hardware, i.e. physical, and software, i.e. logical, structures to address changes in market needs. The manufacturing environment is usually characterised by dynamic cells, i.e. Reconfigurable Machine Cells (RMCs), including intelligent machines called Reconfigurable Machine Tools (RMTs). Such machines consist of fixed parts, i.e. basic modules, and dynamic parts, i.e. auxiliary modules, which allow performing different tasks, i.e. operations. This paper aims at proposing an optimisation linear programming model for the dynamic management of RMSs best balancing the RMTs reconfiguration, considering the auxiliary modules availability, i.e. the efforts to install and disassemble the auxiliary modules on/from the machines, and the part flows among the RMTs. The application to an operative case study widens the model discussion and a multi-scenario analysis concludes the study analysing how the overall system performances change varying the available auxiliary modules. Globally, results show the joint presence of multiple parts on the same RMT in each period allow concluding about the key role of the auxiliary modules to create useful and flexible structures suitable for multiple part processing.

Keywords: reconfigurable manufacturing systems; reconfigurability; modularity; optimisation; Industry 4.0

1. Introduction

In the recent years, the growing competition, the pressure of globalisation, the presence of complex manufacturing systems and products characterised by short life cycles are leading industrial companies to redesign their production practices [1-3]. In particular, modern manufacturing context is experiencing a shift from traditional systems, e.g. dedicated lines, flexible manufacturing systems and cellular manufacturing systems, to changeable manufacturing systems at both physical and logical levels [4, 5]. Reconfigurability is one of the most relevant attribute to enable changeability and, from the Industry 4.0 perspective, it is essential to adapt production to the increasing complexity of the modern industrial and market scenarios [6-9]. Reconfigurable Manufacturing Systems (RMSs) rose in 1999 as systems '*designed at the outset for rapid change in structure, as well as in hardware and software components to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements*' [10, 11]. These systems are arranged in a cellular production pattern called Cellular Reconfigurable Manufacturing System (CRMSs) [12] including a set of dynamic cells, called reconfigurable machine cells (RMCs), in which machines are organised in a logical, instead of physical, way. RMCs include reconfigurable machine tools (RMTs) characterised by a modular structure through a set of basic and auxiliary modules, which increase the number of feasible tasks to perform [12-14]. In detail, such machines are composed by fixed parts, i.e. the basic modules, which represent structural entities, and by dynamic and kinematical entities, i.e. the auxiliary modules, that can be mounted and disassembled on/from the RMT when needed to provide a specific set of task capabilities. The CRMS way of working implies that RMCs are dynamic entities, which evolve within the production horizon by reconfiguring the RMTs in terms of auxiliary modules arrangement.

This paper presents a mathematical optimisation model based on linear programming for the dynamic management of CRMSs. The main goal of the model is to analyse and balance the trade-off between the effort to reconfiguring the RMT hosting the part, in terms of auxiliary module installation and disassembly, versus the inter-cell part and auxiliary module flows. To do this, the proposed objective function minimises the inter-cell part travel time, the auxiliary module travel time and the reconfiguration time to install and disassemble the auxiliary modules. According to the industrial practice, in the model formulation, the auxiliary modules are scarce entities existing in a limited quantity. This aspect is new because in the existing studies the auxiliary modules, representing the core components of RMSs, are considered as existing in infinite amount, thus always available when needed. This assumption simplifies the definition and solving of optimisation models for their design and management but it is not in line with the industrial practice. In fact, industrial companies usually have a set of auxiliary modules, which includes a number of auxiliary module types and a limited number of auxiliary module units per type. Considering auxiliary modules as existing in limited quantity is crucial from the economic perspective, e.g. investment in equipment and tools, and because it strongly affects the production scheduling. Furthermore, a multi-scenario analysis evaluates the variation of the overall performances of the manufacturing system changing the number of the available auxiliary modules. In this way, this study extends previous research, e.g. Bortolini et al. [15], considering the existence of a limited number of module types and a finite number of auxiliary module units per type. To the Author's knowledge, the inclusion of auxiliary module availability constraints in the dynamic management of RMSs has never been explored by the past and recent literature.

According to this background, the reminder of this paper is structured as follows: Section 2 reviews the relevant literature on cellular manufacturing and RMS design and management. Section 3 introduces and describes the optimisation model for the dynamic management of RMSs, while the application of the model to a relevant case study adapted from the literature is in Section 4. Section 5 illustrates the multi-scenario analysis performed changing the number of available auxiliary modules. Finally, Section 6 concludes the paper with final considerations and remarks and future opportunities for research.

2. Literature review

2.1 Fundamentals on cellular manufacturing systems design

Cellular Manufacturing Systems (CMSs) emerged as a successful manufacturing strategy suitable for a mid-volume and a mid-variety production, joining the benefits of flexible and mass production strategies [16]. In these systems, families composed by similar products are created, while the processing machines are organised in manufacturing cells to reduce setup times, work-in-process inventories as well as the material handling costs [17, 18]. Several studies exist in current literature proposing optimal and heuristic approaches for the design and management of CMSs. Among the most relevant, Ateme-Nguema and Dao [19] faced the CMSs design problem aiming at minimising the dissimilarities among parts or machines introducing an hybrid mathematical approach solved using ant colony optimisation and tabu search algorithms. Luo and Tang [20] proposed a mathematical model based on iterated local search and ordinal optimisation to maximise the grouping efficacy indicator. Ghezavati and Saidi-Mehrabad [21] faced the integrated cell formation problem and group scheduling decisions with the aim to minimise the total costs. Yilmaz et al. [22] and Yilmaz and Durmusoglu [23] explore the batch scheduling problem in a CMS environment including worker resources, defining optimisation and heuristic approaches to apply the model to larger instances. However, in conventional CMSs, once the manufacturing cells are designed, their physical reorganisation in response to changing production and market requirements is difficult. To overcome such limitation, recent literature includes the modularity attribute in the manufacturing cells design using modular machines to achieve reconfigurability in manufacturing [12, 13].

2.2 Design and management of cellular reconfigurable manufacturing systems

In the field of next generation manufacturing systems, reconfigurable manufacturing represents a challenging area to investigate. It is one of the most widespread research topic explored by the European Union Framework Program for Research and Innovation (Horizon 2020) and mentioned as one of the main challenges by the Committee on Visionary Manufacturing Challenges for the year 2020 [24]. In the field of optimisation models for RMS design and management, a wide set of studies exists [25-28]. Youssef and ElMaraghy [29] developed a novel 2-step algorithm for RMS configuration selection. The main goal is to determine the best configurations for the possible demand scenarios over the considered time horizon and to select those configurations that allow minimising the reconfiguration effort. Then, Youssef and ElMaraghy [30] extended the previous formulation to include the effects of machine availability and optimise the availability of the alternative RMS configurations and the capital cost. Goyal et al. [31] introduced a multi-objective model focused on auxiliary module interactions and RMTs capability to estimate the reconfigurability and task capability of the reconfigurable machines. The proposed approach supports the optimal RMT assignment for a single part flow line allowing the parallel working of similar RMTs. Bensmaine et al. [32] faced the problem of the selection of candidate RMTs among an available set to manufacture a group of products based on their working cycles. Such a selection is based on both an economic optimisation, i.e. minimisation of the global cost, and technical optimisation, i.e. minimisation of the global completion time. Moghaddam et al. [33] addressed the configuration design of RMSs, where the product demand changes within its whole production horizon and, consequently, the system configuration has to vary accordingly to match efficiently the current demand at the minimum cost. To reach this goal, the Authors proposed a 2-step method to manage the first configuration design of the manufacturing system and the required reconfigurations according to the dynamic and changing demand rate, proposing a mixed integer linear programming formulation supporting the selection of the best available transformation for the identified configurations. Saxena and Jain [34] introduced an advanced methodology for RMS configuration design, optimising the total management cost of the manufacturing system including the capital cost of the machine investment, the operating and reconfiguration costs as well as the salvage value over time. Dou et al. [35] defined an approach based on a genetic algorithm to design and optimise a multi-product flow-line RMS configuration, with the goal to minimise its capital cost. Hasan et al. [36] focused on determining the optimal configurations of RMSs and on identifying optimum sequence of product families according to the maximum benefit earned for a specific system configuration. Dou et al. [37] proposed a mixed integer non-linear programming model to face the concurrent optimisation of configuration design and scheduling of RMSs. Another group of researchers proposed to arrange RMSs in cellular production patterns [13, 15, 38]. In traditional CMSs, the machine cell design is an activity performed usually during the initial setup of the CMS environment and the defined layout does not change during the production life cycle. In the past years, this working way was successful given the existing industrial and market features, e.g. low request of product personalisation, stable market demand, etc. However, switching from the past era to the recent Industry 4.0 era governed by new trends, e.g. mass personalisation, dynamic market demand, etc., traditional CMSs appear as rigid systems and the redesign of the facilities, i.e. machines and equipment, arranged in each production cell to face new industrial and market needs becomes difficult. To face such limitations, recent research suggests introducing the modularity feature in the design of the machines, i.e. RMTs, to be included in the manufacturing cells, as an attribute enabling reconfigurability [12, 13]. In this field, Pattanaik et al. [12] and Pattanaik and Kumar [38] defined an approach based on clustering techniques for designing and managing RMCs through adjustable machines. Bai et al. [39] defined an approach supporting the creation of virtual production cells in a reconfigurable environment characterised by a wide set of product orders. Xing et al. [40] defined a method for the design and control of CRMSs, exploring the creation of RMCs, deriving from the dynamic clustering of manufacturing resources. Eguia et al. [41, 42] developed an optimisation model supporting the design and management of CRMSs to determine the part flow and the auxiliary module allocation minimising the total inter-cell part movements and the overall production costs. Bortolini et al. [15] proposed an optimisation model supporting the CRMS design, which identifies the optimal part flow and the auxiliary modules allocation exploring the trade-off between the part flows among

RMTs and the effort to install and disassemble the auxiliary modules, i.e. reconfigurability. However, the proposed approach considers auxiliary modules as existing in infinite amount, i.e. always available when needed. To overcome this limitation, addressing the real industrial practice and filling a literature gap, the model presented in this paper considers auxiliary modules as scarce resources, thus, existing in limited quantity, i.e. available if not all used by other RMTs. This aspect is crucial because it plays a key role in production scheduling and efficiency. In this way, the objective function of the model minimises the parts and auxiliary module inter-cell travel time and the time required for the RMT reconfiguration, i.e. installation/disassembly of the auxiliary modules. The problem description and the model formulation are in next Section 3.

3. Model description and analytic formulation

RMSs arranged in a cellular production structure, i.e. CRMSs, include RMCs with a set of RMTs. Such RMTs host a number of basic modules, permanently fixed, and a variable number of auxiliary customised modules. These modules represent dynamic and kinematical entities, which can be installed or disassembled when needed to provide a large set of task capabilities to the RMT. According to the past and recent literature within RMS design and management [13, 15], in this study the reconfigurability concept is modelled through the modularity level of the RMTs.

Fig. 1 illustrates a general frame of a CRMS highlighting the RMT structure and two examples of configurations, namely groups of auxiliary modules providing a specific task capability to the RMT and matching one or more tasks in part work cycle.

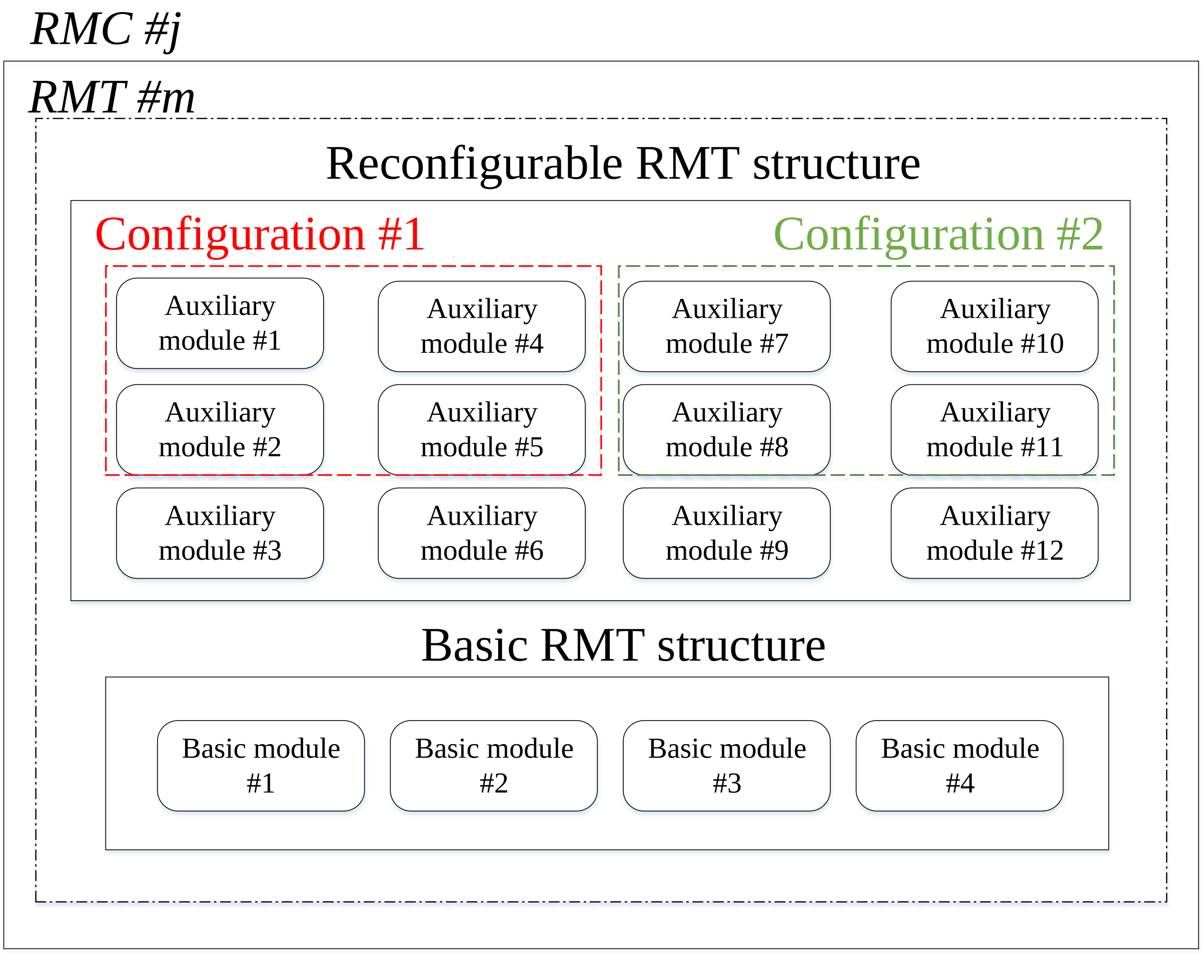

Fig. 1. General structure of a CRMS.

3.1 Analytic formulation: assumptions, notations and mathematical model

According to the industrial practice, the model starting point is an existing CRMS. The model aims to explore and best manage the trade-off among the inter-cell part flows among RMTs, i.e. inter-cell travel time, and the effort to install and disassemble the modules on/from the RMT on which the part is located in that moment, i.e. RMT reconfiguration. Relevant input data used to explore this trade-off are the information about the part work cycles and the compatibility among tasks, RMTs and modules. To reach this goal, the optimisation model minimises the sum of the inter-cell part travel time, the inter-cell auxiliary module travel time and the RMT reconfiguration time, i.e. auxiliary modules assembly/disassembly, defining the part batch flows and the best dynamic, i.e. changeable within the periods, assignment of the auxiliary modules to the RMTs.

According to the standard literature [12, 13, 15], the following assumptions are adopted:

- the part work cycles, i.e. process plan, are known;
- the compatibilities among tasks, RMTs and auxiliary modules are known;

- K types of auxiliary modules and a limited number of module units per type exist, meaning that such modules are scarce resources existing in a limited quantity, i.e. they are available if not all used by other RMTs;
- the RMT-RMC layout is given and the model acts at the tactical level of dynamic management. This assumption is in line with the standard industrial practice because companies have designed layouts and re-layout projects are usually economically, i.e. cost, and technically, i.e. time, expensive;
- part flows among RMTs in batches according to their work cycles. For each part, a new batch is started as soon as the previous one is finished;
- the model is dynamic. At the end of each period, all batches move forward to the next task of their work cycle;
- deterministic working times, part travel and reconfiguration times are given.

The following notations are used.

- Indices

h	auxiliary modules, $h = 1, \dots, H$
i	parts, i.e. products, $i = 1, \dots, M$
j	RMCs, $j = 1, \dots, N$
k	auxiliary module types, $k = 1, \dots, K$
m	RMTs, $m = 1, \dots, Z$
o	task counter for part work cycle, $o = 1, \dots, O_i$
t	counter for periods, $t = 1, \dots, T$

- Parameters

A_{hk}	1 if auxiliary module h is of type k; 0 otherwise $[binary]$
G_{omk}	1 if RMT m can process task o through an auxiliary module of type k; 0 otherwise $[binary]$
MAC_{mj}	1 if RMT m is assigned to RMC j; 0 otherwise $[binary]$
R	maximum number of modules per RMT and period $[integer]$
r_{it}	task parameter for the batch of part i in period t [in $1, \dots, O_i$]
t_{ijj_1}	inter-cell travel time to move the batch of part i from RMC j to RMC j_1 $[min/batch]$
Z_{kjj_1}	travel time for auxiliary module type k from RMC j to RMC j_1 $[min/module]$
τ_{om}	time to process task o on RMT m $[min/op]$
δ_i	batch size of part i $[pcs/batch]$
λ_{mk}	installation time of module type k on RMT m $[min/module]$
μ_{mk}	time to disassemble a module type k from RMT m $[min/module]$
η	duration of each period $[min/period]$

- Decisional Variables

D_{hjj_1t}	1 if auxiliary module h moves from RMC j to RMC j_1 in period t; 0 otherwise $[binary]$
F_{ijj_1t}	1 if a batch of part i flows from RMC j to RMC j_1 in period t; 0 otherwise $[binary]$
V_{mht}	1 if module h is on RMT m in period t; 0 otherwise $[binary]$
W_{mit}	1 if RMT m processes a batch of part i in period t; 0 otherwise $[binary]$
X_{mht}	1 if module h is installed on RMT m in period t, 0 otherwise $[binary]$

Y_{mht}	1 if RMT m disassembles module h in period t, 0 otherwise [$binary$]
σ_{miht}	1 if RMT m works a batch of part i using module h in period t, 0 otherwise [$binary$]

3.2 Optimisation model description

The analytic model is as follows.

$$min\Omega = \sum_{t=1}^{T}\sum_{m=1}^{Z}\sum_{h=1}^{H} X_{mht}\cdot\left(\sum_{k=1}^{K}\lambda_{mk}\cdot A_{hk}\right) + \sum_{t=1}^{T}\sum_{m=1}^{Z}\sum_{h=1}^{H} Y_{mht}\cdot\left(\sum_{k=1}^{K}\mu_{mk}\cdot A_{hk}\right)$$
$$+\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{t=1}^{T-1} F_{ijj_1t}\cdot t_{ijj_1} + \sum_{h=1}^{H}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{t=1}^{T-1} D_{hjj_1t}\cdot\left(\sum_{k=1}^{K} Z_{kjj_1}\cdot A_{hk}\right) \qquad (1)$$

(1) minimises the global time required for module installation on the RMTs, i.e. first term, for module disassembly if not needed, i.e. second term, the part travel time, i.e. third term, and the auxiliary module travel time, i.e. fourth term. The following feasibility constraints complete the model formulation:

$$\sum_{m=1}^{Z} W_{mit} = 1 \qquad \forall t,i \qquad (2)$$

(2) prevents parts to be manufactured in more than one RMT simultaneously.

$$\sum_{h:A_{hk}=1} \sigma_{miht} = W_{mit}\cdot\sum_{o:r_{it}=o} G_{omk} \qquad \forall\ i,t,m,k \qquad (3)$$

(3) ensures that, if RMT *m* has to process part *i* in period *t*, then a module unit *h* of type *k* has to be present on that machine to process that part.

$$V_{mht} \le \sum_{i=1}^{M} \sigma_{miht} \qquad \forall m,h,t \qquad (4)$$

(4) sets the disassembly process of module *h* from RMT *m* if not needed for the processing of the part batch *i* in period *t*. In detail, if $\sum_{i=1}^{M}\sigma_{miht} = 0$, i.e. no part batches are processed on RMT *m* with module unit *h* in period *t*, module unit *h* has not to be present on RMT *m*, i.e. $V_{mht} = 0$.

$$\sigma_{miht} \le V_{mht} \qquad \forall i,m,h,t \qquad (5)$$

(5) allows RMT *m* to work part *i* in period *t* with the module type *k* if it is present on that machine in that period.

$$\sum_{m=1}^{Z} V_{mht} \leq 1 \qquad \forall h,t \qquad (6)$$

(6) guarantees that each module *h* is present in at most one RMT in each period.

$$W_{mit} \leq \sum_{k=1}^{K} \sum_{o:r_{it}=o} G_{omk} \qquad \forall\, m,i,t \qquad (7)$$

(7) enables the batches to be present on RMTs if the auxiliary module type *k* needed for the processing of the current task is installed on that RMT.

$$\sum_{h=1}^{H} V_{mht} \leq R \qquad \forall m,t \qquad (8)$$

(8) defines the greatest number of auxiliary modules *h* that can be concurrently present on each RMT per period.

$$\sum_{m=1}^{Z} \sum_{h=1}^{H} A_{hk} \cdot V_{mht} \leq \sum_{h=1}^{H} A_{hk} \qquad \forall k,t \qquad (9)$$

Per each period *t* and module type *k*, (9) forces not to overcome the available number of module of that type.

$$V_{mh1} \leq X_{mh1} \qquad \forall m,h \qquad (10)$$

$$V_{mhT} \leq Y_{mhT} \qquad \forall m,h \qquad (11)$$

$$X_{mht+1} \geq V_{mht+1} - V_{mht} \qquad \forall m,h,t = 1,\dots,T-1 \qquad (12)$$

$$Y_{mht} \geq V_{mht} - V_{mht+1} \qquad \forall m,h,t = 1,\dots,T-1 \qquad (13)$$

(10)-(13) allow the installation and disassembly of auxiliary modules on/from RMTs.

$$F_{ijj_1t} \leq \sum_{m=1}^{Z} \sum_{k=1}^{K} \sum_{o:r_{it}=o} G_{omk} \cdot MAC_{mj} \qquad \forall i,j,j_1,t = 1,\dots,T-1 \qquad (14)$$

$$F_{ijj_1t} \leq \sum_{m=1}^{Z} \sum_{k=1}^{K} \sum_{o:r_{it+1}=o} G_{omk} \cdot MAC_{mj_1} \qquad \forall i,j,j_1,t = 1,\dots,T-2 \qquad (15)$$

Equations (14) and (15) allow each part to flow from cell *j* to cell j_1 if *j* and j_1 can work that part.

$$W_{mit} \leq \sum_{j=1}^{N} \sum_{j_1=1}^{N} F_{ijj_1t} \cdot MAC_{mj} \qquad \forall i, m, t = 1, \dots, T-1 \qquad (16)$$

$$W_{miT} \leq \sum_{j=1}^{N} \sum_{j_1=1}^{N} F_{ijj_1T-1} \cdot MAC_{mj_1} \qquad \forall i, m \qquad (17)$$

$$\sum_{j=1}^{N} \sum_{j_1=1}^{N} F_{ijj_1t} = 1 \qquad \forall i, t = 1, \dots, T-1 \qquad (18)$$

$$\sum_{j_1=1}^{N} F_{ij_1j\,t} = \sum_{j_1=1}^{N} F_{ijj_1t+1} \qquad \forall i, j, t = 1, \dots, T-2 \qquad (19)$$

(16)-(17) link the variables W_{mit} and F_{ijj_1t}, while (18)-(19) ensure the part batch straight flow.

$$\sum_{h=1}^{H} \sum_{k=1}^{K} (X_{mht} \cdot \lambda_{mk} \cdot A_{hk} + Y_{mht} \cdot \mu_{mk} \cdot A_{hk}) + \qquad \forall m, t \qquad (20)$$

$$\sum_{i=1}^{M} \sum_{o:r_{it}=o} (W_{mit} \cdot \tau_{om} \cdot \delta_i) \leq \eta$$

(20) guarantees not to overcome the working time available per machine and period.

$$V_{mht} \leq \sum_{j=1}^{N} \sum_{j_1=1}^{N} D_{hjj_1t} \cdot MAC_{mj} \qquad \forall h, m, t = 1, \dots, T-1 \qquad (21)$$

$$V_{mhT} \leq \sum_{j=1}^{N} \sum_{j_1=1}^{N} D_{hjj_1T-1} \cdot MAC_{mj_1} \qquad \forall h, m \qquad (22)$$

$$\sum_{j=1}^{N} \sum_{j_1=1}^{N} D_{hjj_1t} = 1 \qquad \forall h, t = 1, \dots, T-1 \qquad (23)$$

$$\sum_{j_1=1}^{N} D_{hj_1j\,t} = \sum_{j_1=1}^{N} D_{hjj_1t+1} \qquad \forall h, j, t = 1, \dots, T-2 \qquad (24)$$

(21)-(22) link the variables V_{mht} and D_{hjj_1t}, while (23)-(24) set the auxiliary module flows among the available RMCs.

$$\sum_{m=1}^{Z}\sum_{k=1}^{K}\left(X_{mht}\cdot\lambda_{mk}\cdot A_{hk}+Y_{mht}\cdot\mu_{mk}\cdot A_{hk}\right)$$

$$+\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{k=1}^{K}D_{hjj_1t}\cdot Z_{kjj_1}\cdot A_{hk}$$

$$+\sum_{m=1}^{Z}\sum_{i=1}^{M}\sum_{o:r_{it}=o}\sigma_{miht}\cdot\delta_i\cdot\tau_{om}\leq\eta \qquad \forall h,t \qquad (25)$$

(25) guarantees that the total time each module *h* spends for assembly and disassembly, for its flow among RMTs and for the part processing does not exceed the available time per machine and period.

$$F_{ijj_1t}\ binary \qquad \forall i,j,j_1,t \qquad (26)$$

$$D_{hjj_1t}\ binary \qquad \forall h,j,j_1,t \qquad (27)$$

$$W_{mit}\ binary \qquad \forall i,m,t \qquad (28)$$

$$V_{mht}, X_{mht}, Y_{mht}\ binary \qquad \forall m,h,t \qquad (29)$$

$$\sigma_{miht}\ binary \qquad \forall m,i,h,t \qquad (30)$$

Finally, (26)-(30) set the consistence of the decisional variables.

The application of the model to a relevant operative case study adapted from the literature together with the discussion of the key results are in next Section 4.

4. Case study

The optimisation model introduced and described in Section 3 is applied to a case study representative of an operative industrial scenario and adapted from the literature in the field of cellular manufacturing [43, 44]. The data set includes a 34 x 16, i.e. number of parts x number of tasks, incidence matrix. 5 RMCs and 5 RMTs, named from A to E in the following, are available, i.e. each RMC includes one RMT. In addition, a library of 10 auxiliary module types is considered, including 20 module units. The effect of varying the number of the available module units per type is analysed and discussed in the next Section 5. The initial auxiliary modules configuration, i.e. number of units per auxiliary module type, is as follows: 1 module for type 1, 2 modules for types 2 to 8, 3 modules for type 9 and 2 modules for type 10. Data about part work cycles, their daily production volumes and the auxiliary modules installation and disassembly times are collected in Appendix A.

The task-RMT-module compatibility matrix is Table 1. Specifically, this table shows the execution modes for the tasks, i.e. the RMTs needed for their processing, the required modules, in round brackets, while the unitary processing times, in minutes, are in squared brackets.

Table 1 Compatibility data among tasks, RMTs and modules.

Tasks (o)	(auxiliary modules) – [unitary processing times in minutes]				
	RMT A	*RMT B*	*RMT C*	*RMT D*	*RMT E*
1	(1) – [0.24]		(1, 10) – [0.14]		(10) – [0.24]
2		(9, 10) – [0.20]			(9) – [0.22]
3	(5) – [0.16]	(2) – [0.14]		(2, 5) – [0.12]	
4	(4) – [0.22]	(4, 5) – [0.22]		(5) – [0.18]	
5		(7) – [0.24]		(7, 8) – [0.22]	(7, 8) – [0.12]
6	(3, 4) – [0.14]			(3) – [0.20]	
7	(1, 2, 4) – [0.20]		(1, 2) – [0.12]		
8		(3, 5, 8) – [0.14]	(3, 5) – [0.18]		
9			(4) – [0.20]		(4, 8) – [7]
10	(8) – [0.16]	(1, 8) – [0.12]		(1) – [0.12]	
11				(2, 6) – [0.14]	(6) – [0.14]
12		(6, 9) – [0.18]	(6) – [0.24]		
13	(10) – [0.16]				(1, 10) – [0.16]
14			(3, 9) – [0.22]	(3, 6, 9) – [0.16]	
15	(4, 6, 8) – [0.18]				(4, 6) – [0.24]
16		(2, 5, 10) – [0.20]	(5) – [0.18]	(2, 5) – [0.16]	

As example, task 1 can be processed on RMT A with an auxiliary module of type 1 and a unitary processing time up to 0.24 minutes or on RMT C with two auxiliary modules of type 1 and 10 and a unitary processing time up to 0.14 minutes or on RMT E with an auxiliary module of type 10 and a unitary processing time of 0.24 minutes.

The inter-cell travel times, i.e. the time to move a batch of part and/or auxiliary modules from RMC j to RMC j_1, in minutes, are in the symmetric matrix in next Table 2.

Table 2 Inter-cell travel times (minutes).

Cell Id.	RMC A	RMC B	RMC C	RMC D	RMC E
RMC A	-	17	16	22	8
RMC B	17	-	6	11	19
RMC C	16	6	-	2	18
RMC D	22	11	2	-	18
RMC E	8	19	18	18	-

Among the other relevant data, the available time per period and RMT, i.e. parameter η, is equal to 4 hours. In addition, $R = 20$ and $T = 24$, i.e. 12 days. 125'280 decisional variables and 329'894 constraints rise from the considered input data. In the solving phase, the model is coded in AMPL language and processed adopting the solver Gurobi Optimizer© v.4.0.1.0 on an Intel® Core^{TM} i7 CPU @ 2.40GHz and 8.0GB RAM workstation. The solving time is of about 22 seconds. In such a model formulation, the use of optimisation methods is suitable for instances including up to about 40 parts composed by about 7 operations in their work cycles. By increasing the size of the numerical instance, the use of optimisation approaches may become difficult, rising the need to explore the use of heuristic and meta-heuristic methods. Next paragraph 4.1 summarises the main results for the considered case study.

4.1 Key model outcomes

This sub-section shows the key outcomes and results achieved by applying the model to the adopted case study. Minimising the objective function Ω, the reconfiguration time covers the 21.68% of the total value, i.e. 12.39% for the auxiliary modules installation (521.25 minutes) and 9.29% for the auxiliary modules disassembly (390.94 minutes). The inter-cell part flows take the 73.85% of the objective function value, while the auxiliary module flows take the remaining 4.47%.

Table 3 highlights the existing inter-cell flows among the RMCs, considering that each flow is for a part batch shipping at the end of a takt, i.e. working period.

Table 3 Inter-cell flows among RMCs.

		Destination				
	Cell Id.	RMC A	RMC B	RMC C	RMC D	RMC E
Origin	RMC A	-	0	18	8	2
	RMC B	0	-	19	6	0
	RMC C	14	24	-	119	20
	RMC D	14	0	128	-	16
	RMC E	0	0	13	22	-

The inter-cell part flows widely affect the objective function value, i.e. 73.85%, showing the benefit to move the part batches to other RMCs containing the necessary auxiliary modules rather than reconfiguring the RMT. Focusing on the RMT use, Fig. 2 illustrates the number of parts each RMT processes per period.

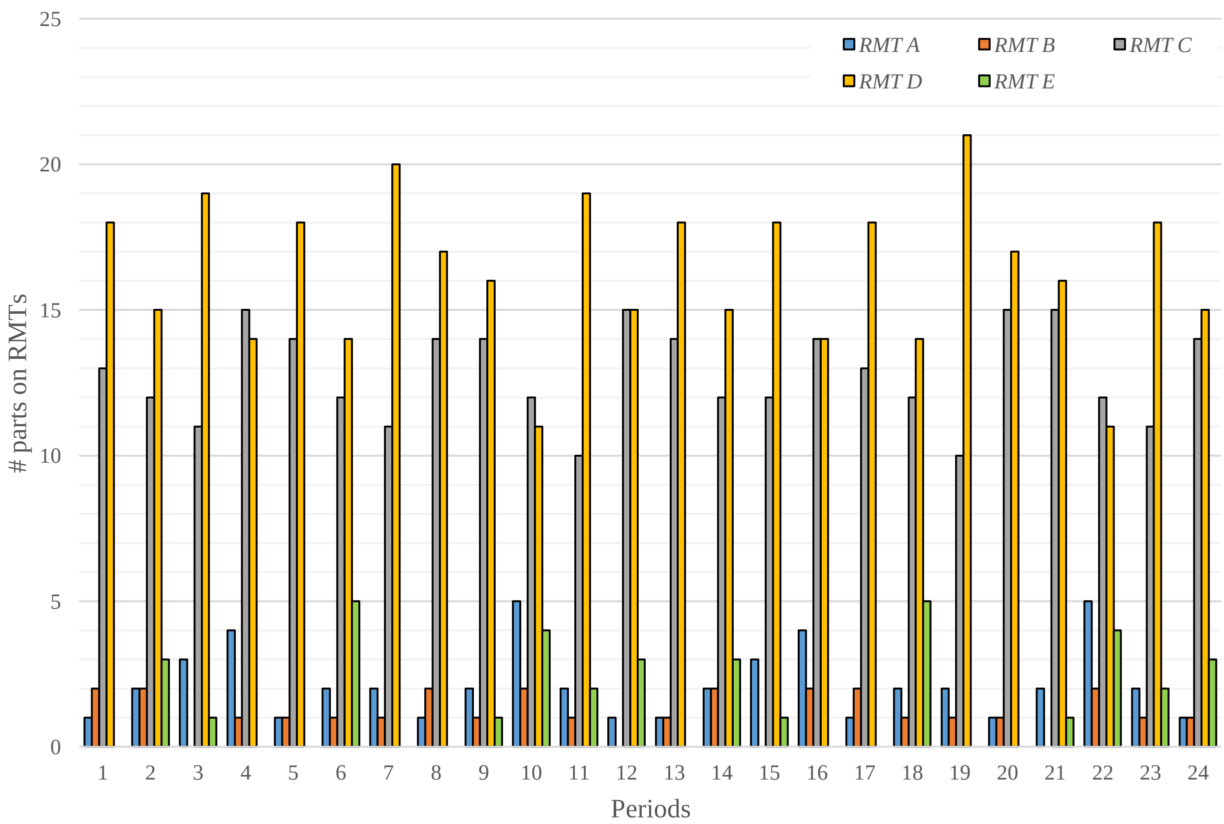

Fig. 2. RMT-parts assignment in each period.

Results prove that in a major set of periods more than one part is processed on the same RMT. RMT C and RMT D are the most charged, working, on average, 13 and 16 parts, respectively, in each periods. Because of RMT reconfiguration is among periods, the presence of more parts on the same RMT allows concluding about the key role of auxiliary modules to create useful structures suitable for multiple part processing. Finally, Fig. 3 shows the number of auxiliary modules each RMT hosts in each period.

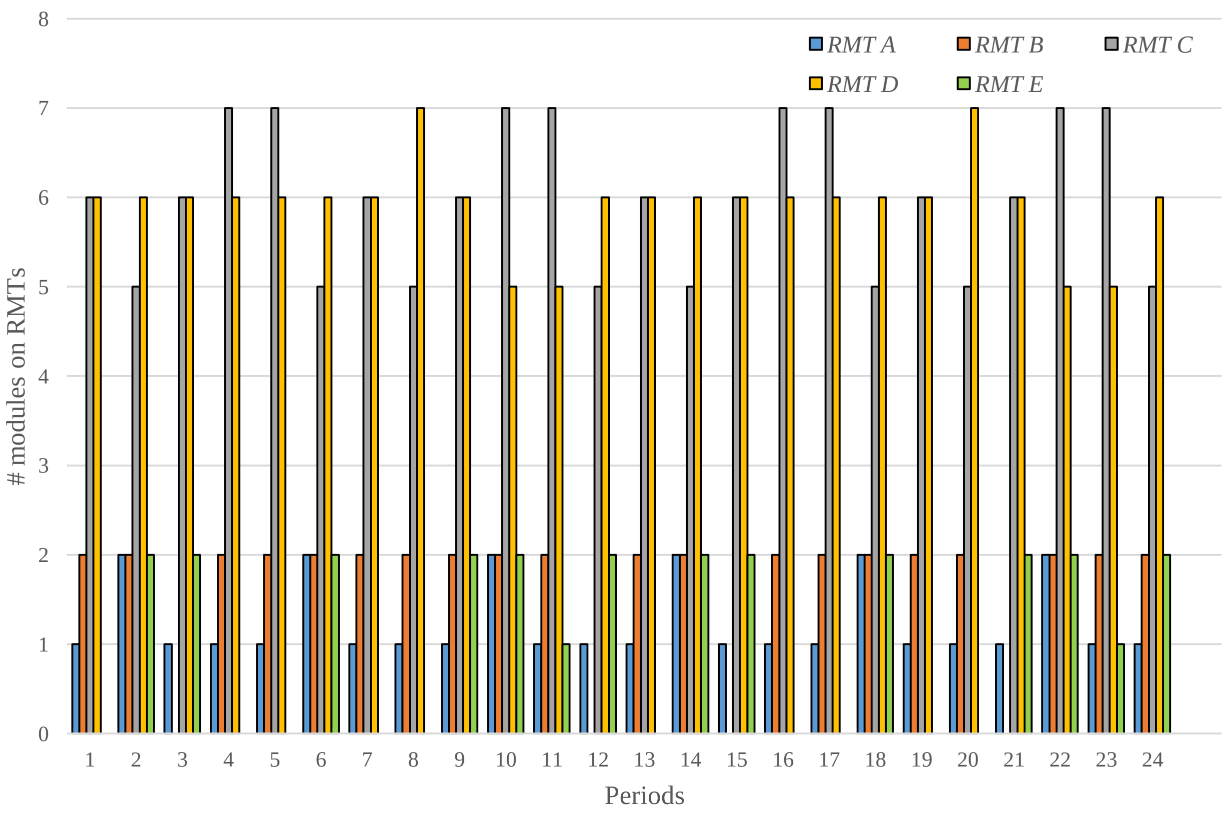

Fig. 3. RMT-auxiliary modules assignment in each period.

As for parts, results highlight that in almost each period, more than one auxiliary module is installed on the same RMT, e.g. RMT C and RMT D host, on average, 6 auxiliary modules per period, remarking the benefit of implementing RMSs to reduce the total processing time.

5. Auxiliary module multi-scenario analysis

The multi-scenario analysis is performed varying the number of the available auxiliary modules per type assessing the system performances. At first, the minimum number of required modules per type, i.e. AM_k, has been statically determined minimising the number of auxiliary modules in the CRMS. Results show that one module is necessary for types 1, 2, 7, 8 and 10, while two modules are necessary for types 3, 4, 5, 6 and 9. The multi-scenario analysis is developed in the range $[AM_k, AM_k + 1]\ \forall k$, getting a total of 1024 scenarios in which the number of auxiliary modules varies from 15, i.e. $\sum_{k=1}^{K} AM_k$, to 25, i.e. $\sum_{k=1}^{K} (AM_k + 1)$.

All scenarios are grouped in clusters having the same number of auxiliary modules. 11 clusters are created, from Cluster #1 characterised by scenarios with 15 auxiliary modules, i.e. minimum static number, to Cluster #11 including scenarios with 25 auxiliary modules. Details are in Table 4.

Table 4 Multi-scenario analysis, clusters.

Cluster ID.	Total number of auxiliary modules	# scenarios in each cluster
#1	15	1
#2	16	10
#3	17	45
#4	18	120
#5	19	211
#6	20	251
#7	21	210
#8	22	120
#9	23	45
#10	24	10
#11	25	1

All scenarios are iteratively solved using Gurobi Optimizer© v.4.0.1.0 solver on an Intel® Core™ i7 CPU @ 2.40GHz and 8.0GB RAM workstation. The average solving time per scenario ranges from 10 to 30 seconds.

5.1 Findings and results

Table 5 shows the average values of the objective function for each cluster together with its components, while for brevity, details for each scenario are not included.

Table 5 Clusters aggregate data (minutes).

Cluster ID.	Avg. reconfiguration time	Avg. part flow time	Avg. auxiliary module flow time	Avg. total time (objective function)
#1	904.96	6922.00	510.00	8336.96
#2	753.34	6383.50	235.90	7372.75
#3	715.14	5731.56	144.87	6591.57
#4	717.89	5089.36	109.56	5916.80
#5	733.03	4459.19	95.91	5288.13
#6	748.04	3849.30	88.09	4685.43
#7	756.75	3301.23	77.00	4134.98
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#10	724.85	1988.50	22.20	2735.55
#11	615.74	1774.00	0.00	2389.74

Fig. 4 plots the results including the range bars to highlight the variation intervals of each objective function component. Bars are null for Cluster #1 and Cluster #11 because of they include one scenario.

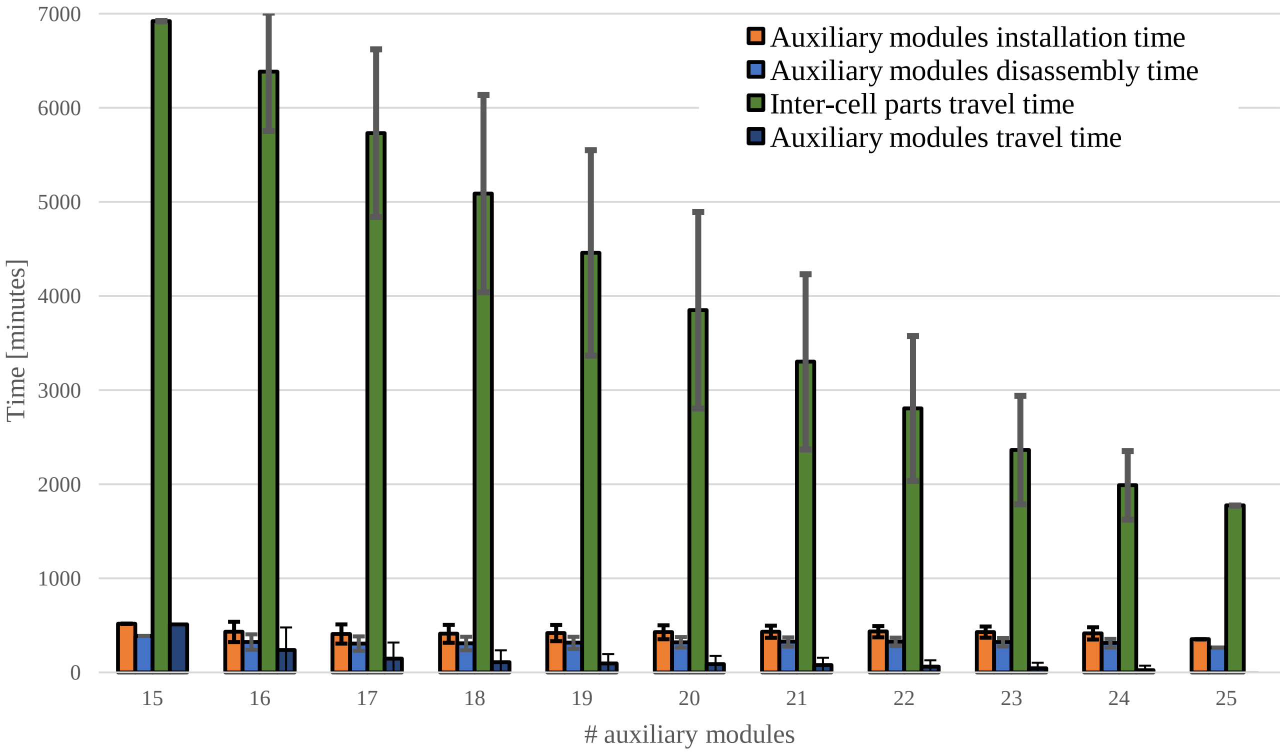

Fig. 4. Objective function component trend for the considered clusters.

Increasing the number of the available auxiliary modules, the average auxiliary module flow decreases, moving from 510.00 minutes in Cluster #1 to 0.00 minutes, i.e. absence of auxiliary module flows, in Cluster #11. Moreover, the presence of a greater number of modules reduces the average part flow, i.e. from 6922.00 minutes in Cluster #1 to 1774.00 minutes in Cluster #11, and the average reconfiguration time, i.e. from 904.96 minutes in Cluster #1 to 615.74 minutes in Cluster #11.

These considerations lead the objective function value to decrease of about 71.34% moving from Cluster #1, i.e. 8336.96 minutes, to Cluster #11, i.e. 2389.74 minutes. This implies that the minimum value of the objective function occurs in correspondence of the maximum value of available auxiliary modules. It is up to the decision makers to select the production configuration best managing the trade-off between time performances, i.e. global time needed for RMT reconfiguration, inter-cell parts travel and auxiliary modules travel time, and cost performances for auxiliary modules purchase and use. As in real industrial contexts, given a set of trade-off effective solutions, the decision makers need to select the solution that best balances the specific items, e.g. costs, processing times, etc., under consideration. Decision support systems to face this choice are an interesting next step rising from the present research.

6. Conclusions and future research

Reconfigurable Manufacturing Systems (RMSs) rose as an effective answer to the emerging industrial trends generating increased product variety, variable production batches and dynamic market demand. RMSs are usually organised in a cellular production pattern, called Cellular Reconfigurable Manufacturing Systems (CRMSs), including dynamic cells, called reconfigurable machine cells (RMCs), in which machines are organised in a logical, instead of physical, way. RMCs include intelligent machine structures, called reconfigurable machine tools (RMTs), characterised by a modular and adjustable structure through a set of basic and auxiliary modules that allow increasing the set of feasible tasks.

The aim of this paper is to define and apply an optimisation model for the dynamic management of a multi-product multi-period CRMSs to best balance the inter-cell part flows among RMTs already equipped with the required modules, the RMT reconfiguration, i.e. the effort to install and disassemble the auxiliary modules on/from the current RMT, and the auxiliary module flows among RMTs. According to the industrial practice, in the model formulation, the auxiliary modules are scarce entities existing in a limited quantity. To the Author's knowledge, the inclusion of auxiliary module availability constraints in the dynamic management of RMSs has never been explored by the past and recent literature.

A relevant case study, adapted from the literature of cellular manufacturing, applies the model and a final multi-scenario analysis assesses the impact of varying the number of the available auxiliary modules on the system performances. Results show the joint presence of multiple parts, up to 40% of the total mix, on the same RMT and period. Because of RMT reconfiguration is among periods, the presence of more parts on the same RMT allows concluding about the key role of auxiliary modules to set up intelligent structures suitable for multiple part processing.

The inclusion of the economic dimension in designing and managing CRMSs and the model application to larger real industrial case studies are among the future research activities to perform. By increasing the size of the numerical instances, the use of optimisation algorithms becomes difficult. Heuristic and meta-heuristic methods are of interest and among the next steps of this research.

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Appendix A

Table A.1 Part production volumes and work cycles.

Part (i)	δ_i [pcs/batch]	Work cycle
1	5	2-9-6-9-8-16-14-2
2	15	8-13-11-8
3	50	9
4	8	4-15-5-4
5	50	6-14
6	120	3-6-16-3
7	150	8-5-6
8	75	9-2-16
9	500	8-12
10	130	8-6-10-8
11	124	7-6-10
12	58	4-6-5-6
13	124	5-8
14	150	5
15	1400	3-14-6-3
16	4	9-16
17	90	4-6-8-5-6-15
18	34	8-11
19	39	5-12
20	31	4-6-5-8
21	41	7-10
22	120	10
23	1	11-12-8
24	4	2-9-8
25	39	4-5
26	75	11-12
27	4	8-10
28	32	5-15-6-5
29	150	3-6
30	1130	14-3
31	31	3
32	43	6-10
33	50	9-2-6-9
34	28	5-8-15

Table A.2 Installation and disassembly time of available auxiliary module types, in minutes.

RMT	Auxiliary module type (k)	λ	μ
1	1	3.32	2.49
1	2	3.73	2.79
1	3	3.56	2.67
1	4	3.94	2.95

1	5	3.92	2.94
1	6	3.41	2.55
1	7	-	-
1	8	4.22	3.16
1	9	-	-
1	10	4.41	3.30
2	1	3.87	2.90
2	2	4.22	3.16
2	3	6.10	4.57
2	4	3.90	2.92
2	5	4.50	3.37
2	6	5.00	3.75
2	7	4.70	3.52
2	8	6.12	4.59
2	9	6.02	4.51
2	10	3.85	2.88
3	1	3.90	2.92
3	2	7.20	5.40
3	3	9.00	6.75
3	4	8.60	6.45
3	5	9.20	6.90
3	6	7.75	5.81
3	7	-	-
3	8	-	-
3	9	6.20	4.65
3	10	8.50	6.37
4	1	4.60	3.45
4	2	5.80	4.35
4	3	6.34	4.75
4	4	-	-
4	5	7.79	5.84
4	6	8.12	6.09
4	7	8.87	6.65
4	8	9.10	6.82
4	9	9.60	7.20
4	10	-	-
5	1	9.40	7.05
5	2	-	-
5	3	-	-
5	4	9.10	6.82
5	5	-	-
5	6	10.20	7.65
5	7	7.60	5.70
5	8	8.80	6.60
5	9	9.30	6.97
5	10	12.00	9.00

Figure

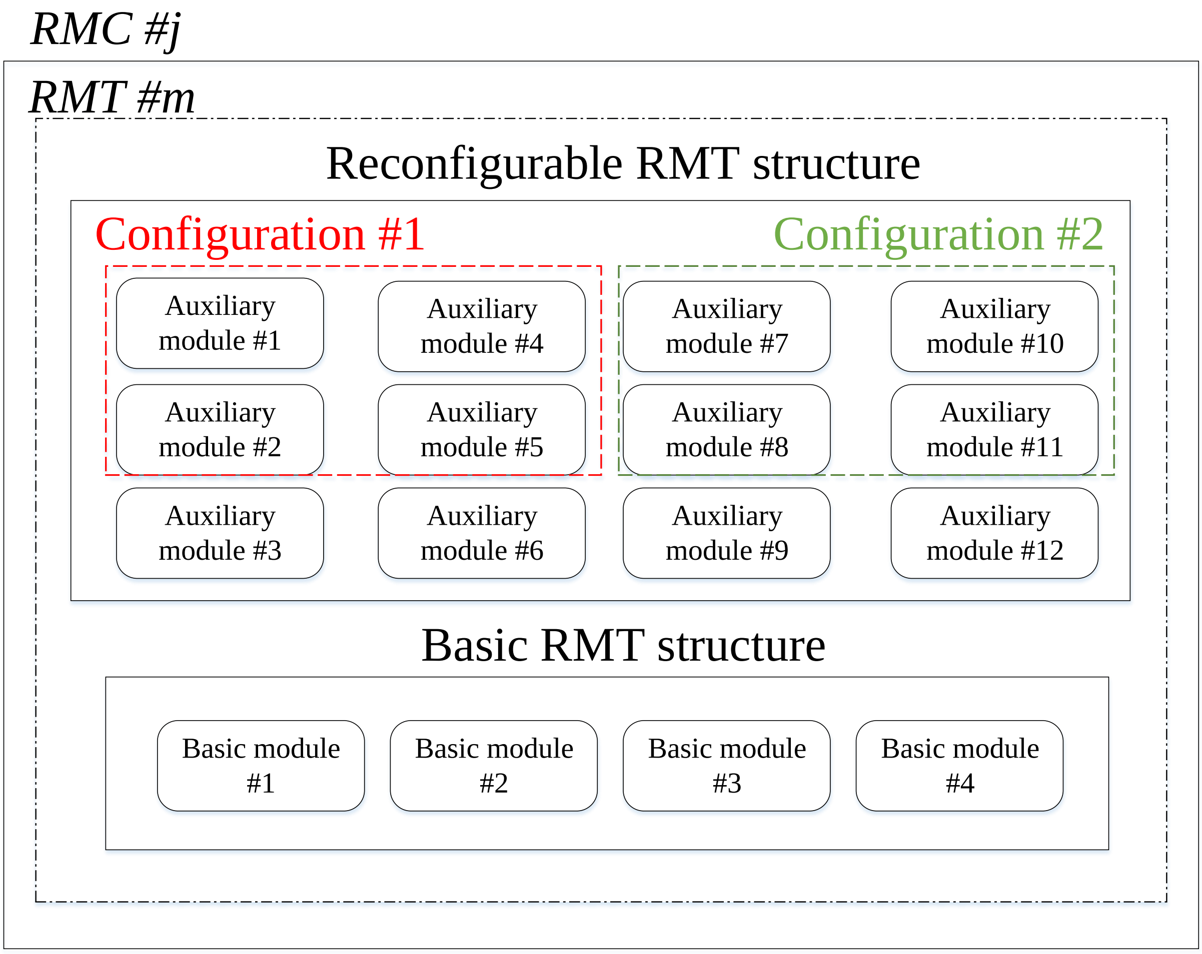

Fig. 1. General structure of a CRMS.

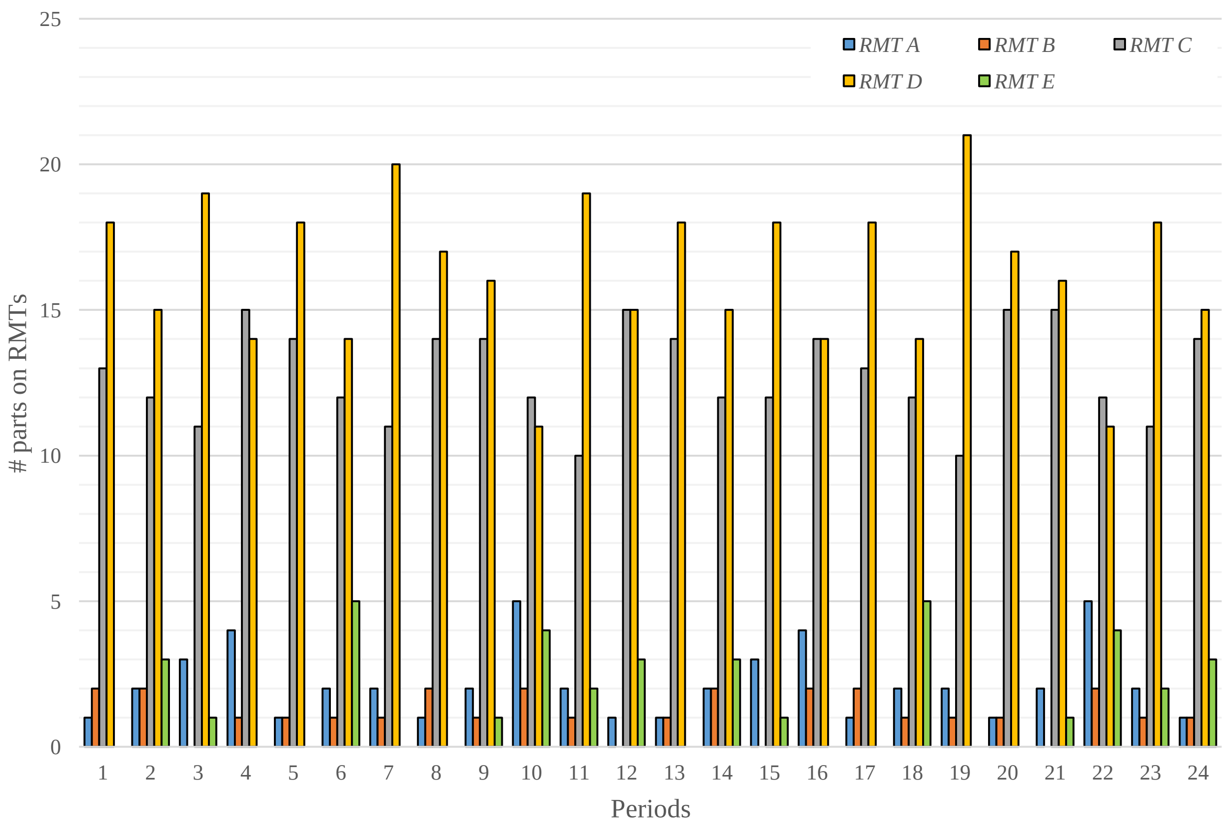

Fig. 2. RMT-parts assignment in each period.

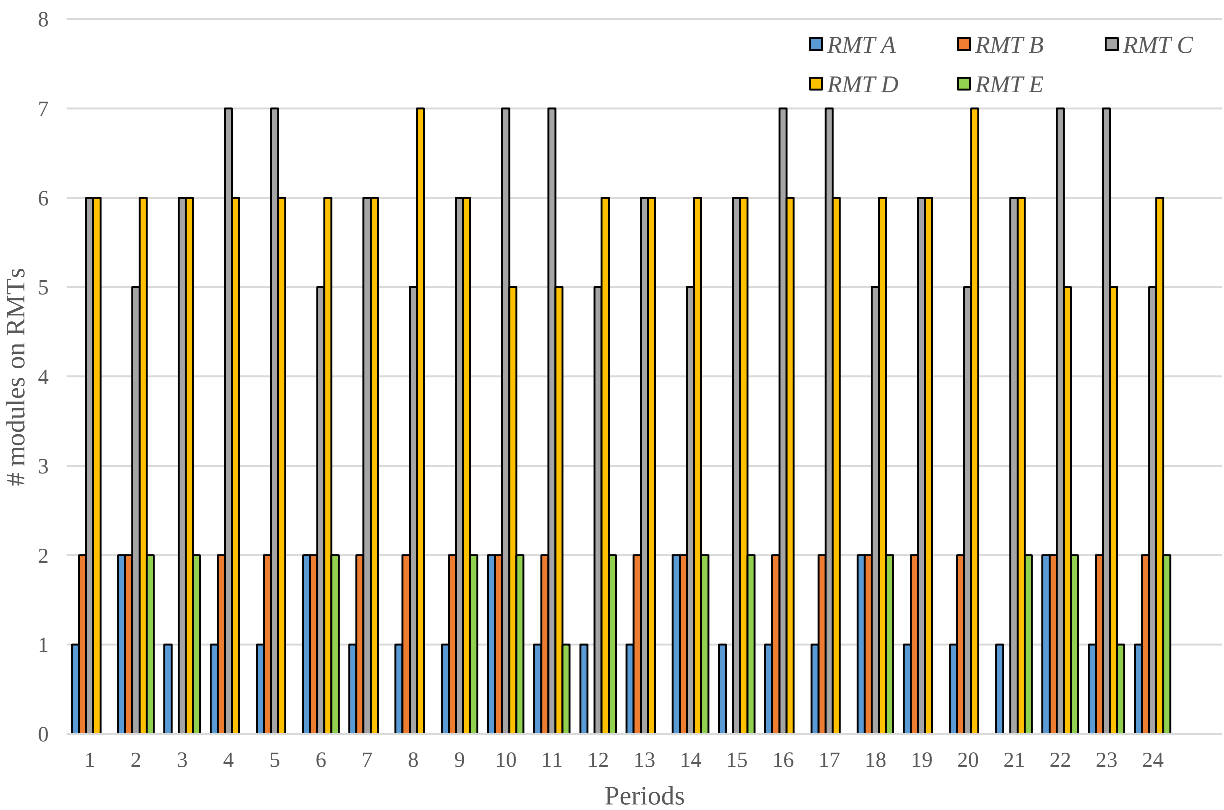

Fig. 3. RMT-auxiliary modules assignment in each period.

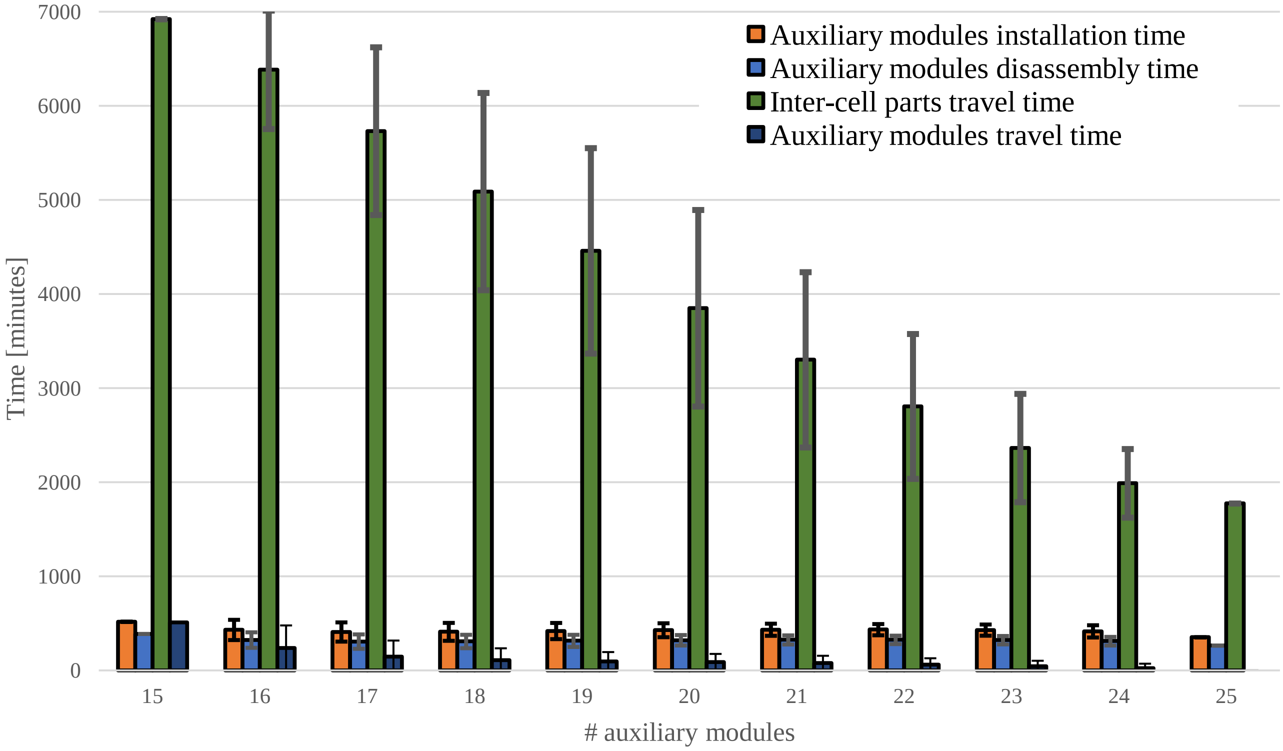

Fig. 4. Objective function component trend for the considered clusters.

Table

Table 1 Compatibility data among tasks, RMTs and modules.

Tasks (*o*)	(auxiliary modules) – [unitary processing times in minutes]				
	RMT A	*RMT B*	*RMT C*	*RMT D*	*RMT E*
1	(1) – [0.24]		(1, 10) – [0.14]		(10) – [0.24]
2		(9, 10) – [0.20]			(9) – [0.22]
3	(5) – [0.16]	(2) – [0.14]		(2, 5) – [0.12]	
4	(4) – [0.22]	(4, 5) – [0.22]		(5) – [0.18]	
5		(7) – [0.24]		(7, 8) – [0.22]	(7, 8) – [0.12]
6	(3, 4) – [0.14]			(3) – [0.20]	
7	(1, 2, 4) – [0.20]		(1, 2) – [0.12]		
8		(3, 5, 8) – [0.14]	(3, 5) – [0.18]		
9			(4) – [0.20]		(4, 8) – [7]
10	(8) – [0.16]	(1, 8) – [0.12]		(1) – [0.12]	
11				(2, 6) – [0.14]	(6) – [0.14]
12		(6, 9) – [0.18]	(6) – [0.24]		
13	(10) – [0.16]				(1, 10) – [0.16]
14			(3, 9) – [0.22]	(3, 6, 9) – [0.16]	
15	(4, 6, 8) – [0.18]				(4, 6) – [0.24]
16		(2, 5, 10) – [0.20]	(5) – [0.18]	(2, 5) – [0.16]	

Table 2 Inter-cell travel times (minutes).

Cell Id.	RMC A	RMC B	RMC C	RMC D	RMC E
RMC A	-	17	16	22	8
RMC B	17	-	6	11	19
RMC C	16	6	-	2	18
RMC D	22	11	2	-	18
RMC E	8	19	18	18	-

Table 3 Inter-cell flows among RMCs.

		Destination				
	Cell Id.	RMC A	RMC B	RMC C	RMC D	RMC E
Origin	RMC A	-	0	18	8	2
	RMC B	0	-	19	6	0
	RMC C	14	24	-	119	20
	RMC D	14	0	128	-	16
	RMC E	0	0	13	22	-

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4	8	4-15-5-4
5	50	6-14
6	120	3-6-16-3
7	150	8-5-6
8	75	9-2-16
9	500	8-12
10	130	8-6-10-8
11	124	7-6-10
12	58	4-6-5-6
13	124	5-8
14	150	5
15	1400	3-14-6-3
16	4	9-16
17	90	4-6-8-5-6-15
18	34	8-11
19	39	5-12
20	31	4-6-5-8
21	41	7-10
22	120	10
23	1	11-12-8
24	4	2-9-8
25	39	4-5
26	75	11-12
27	4	8-10

28	32	5-15-6-5
29	150	3-6
30	1130	14-3
31	31	3
32	43	6-10
33	50	9-2-6-9
34	28	5-8-15

Table A.2 Installation and disassembly time of available auxiliary module types, in minutes.

RMT	Auxiliary module type (*k*)	λ	μ
1	1	3.32	2.49
1	2	3.73	2.79
1	3	3.56	2.67
1	4	3.94	2.95
1	5	3.92	2.94
1	6	3.41	2.55
1	7	-	-
1	8	4.22	3.16
1	9	-	-
1	10	4.41	3.30
2	1	3.87	2.90
2	2	4.22	3.16
2	3	6.10	4.57
2	4	3.90	2.92
2	5	4.50	3.37
2	6	5.00	3.75
2	7	4.70	3.52
2	8	6.12	4.59
2	9	6.02	4.51
2	10	3.85	2.88
3	1	3.90	2.92
3	2	7.20	5.40
3	3	9.00	6.75
3	4	8.60	6.45
3	5	9.20	6.90
3	6	7.75	5.81
3	7	-	-
3	8	-	-
3	9	6.20	4.65
3	10	8.50	6.37
4	1	4.60	3.45
4	2	5.80	4.35
4	3	6.34	4.75
4	4	-	-
4	5	7.79	5.84
4	6	8.12	6.09
4	7	8.87	6.65
4	8	9.10	6.82
4	9	9.60	7.20
4	10	-	-
5	1	9.40	7.05
5	2	-	-

5	3	-	-
5	4	9.10	6.82
5	5	-	-
5	6	10.20	7.65
5	7	7.60	5.70
5	8	8.80	6.60
5	9	9.30	6.97
5	10	12.00	9.00