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Reconfigurable manufacturing systems: Literature review and research trend

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ABSTRACT

The current manufacturing environment aims at getting an increasing variety of customised, high-quality products in flexible batches. The dynamic market demand, the short product lifecycle and the flexibility need mark the transition from the traditional manufacturing systems to the so-called Next Generation Manufacturing Systems (NGMSs). Reconfigurable Manufacturing Systems (RMSs) are within NGMSs and seem to match to these current market trends. RMSs allow rapid change in structure, hardware and software configuration to adjust, promptly, their production capacity and functionality.

This paper presents a structured and updated systematic review of the literature about RMSs, highlighting the application areas as well as the key methodologies and tools. The review further provides a schematic of RMS research, identifying five emerging and promising research streams ranging from conceptual models to empirical applications. Compared to previous reviews, focusing on specific aspects of the RMS design and management, this study covers multiple areas and topics and it links reconfigurable manufacturing to the upcoming *Industry 4.0* fourth industrial revolution. Finally, important issues and new trends in the literature are outlined to stimulate researchers and practitioners in developing studies in this field strongly linked to the *Industry 4.0* environment.

1. Introduction

Within the current industrial environment, manufacturing companies are facing radical changes forcing to improve their standard in product and process design and management. High flexibility, dynamic market demand, increasing customisation, high-quality products, flexible batches and short product life cycles are among the key factors driving the transition from the traditional manufacturing systems to the so-called Next Generation Manufacturing Systems (NGMSs) [1,2,3,4]. Dedicated Manufacturing Systems (DMSs), Flexible Manufacturing Systems (FMSs) and Cellular Manufacturing Systems (CMSs) show increasing limits in adapting themselves to the most recent market features. DMSs produce the company core products at a high production rate with low flexibility. Product features are supposed to be constant during the system lifetime and customisation is costly and difficult to implement [5,6]. FMSs consist of automated numerically controlled workstations connected through a proper handling system managed through a central control unit. The main advantage of FMSs is their flexibility in managing resources to manufacture a large variety of parts. However, in the most of the cases, the throughput of these systems is lower than for DMSs and the dedicate equipment increases the part full cost [6]. CMSs overcome some limitations of the previous systems. They involve the use of multiple independent working cells dedicated to product families with similar processing requirements [7]. Despite this benefit, CMSs are designed to produce a specific set of products with stable demand level and sufficiently long lifecycle [8].

To face the limits of the existing systems, NGMSs have to join high flexibility, reconfigurability and artificial intelligence properties to respond to the dynamic market changes [3]. In 1999, Professor Koren firstly defines Reconfigurable Manufacturing System (RMS), as the NGMS '*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*' [9,10].

Table 1 compares the expected features of DMSs, FMSs, CMSs and RMSs highlighting that RMSs aim at gathering the main advantages of traditional manufacturing systems combining flexibility to high throughput.

As a basis and background of the present review paper, Table 2 shows a list of existing reviews published in the field of RMSs, recently.

Table 2 shows that the target of the previous reviews is on specific aspects of RMSs, e.g. design methodologies, key attributes, etc. Connection among theory and practice, analytic models and applications are still missing and expected. To this purpose, this paper presents an

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Table 1
Comparison among the features of the existing manufacturing systems, adapted from [5].

	DMS	FMS	CMS	RMS
Cost per part	Low	Reasonable	Medium	Medium
Demand	Stable	Variable	Stable	Variable
Flexibility	No	General	General	Customised
Machine structure	Fixed	Fixed	Fixed	Changeable
Product family formation	No	No	Yes	Yes
Productivity	Very high	Low	High	High
System structure	Fixed	Changeable	Fixed	Changeable
Variety	No	Wide	Wide	High

Table 2
Recent reviews on RMSs and target.

Authors	Year	Target	Reference
Bi et al.	2008	Design methods for RMSs	[11]
ElMaraghy	2006	Analysis of flexibility in FMSs and RMSs	[12]
Rosio and Safsten	2013	Design methods for RMSs	[13]
Renzi et al.	2014	Artificial intelligence for the RMS design	[14]
Huettemann et al.	2016	RMS-based assembly systems	[15]
Andersen et al.	2017	Design methods for RMSs	[16]
Singh et al.	2017	Analysis of RMS key attributes	[17]

updated comprehensive literature review on the current state of the art on RMSs analysing a wide range of publications covering multiple areas and topics about RMS design, management and industrial application. The goal is to highlight the main research streams, the application areas and the methodologies supporting the RMS design and management. For these reasons, the main contributions and elements of innovation of this paper in the field of RMSs are: (1) to propose a structured and updated literature review covering the range from 1999 to 2017, (2) to connect theory and practice about the design and management of such systems, (3) to cover multiple areas and topics of RMSs, e.g. design, management, scheduling, etc., and (4) to link reconfigurability to the *Industry 4.0* environment.

According to this goal, the reminder of this paper is organised as follows: the next Section 2 defines the RMSs and their features; Section 3 introduces the research approach, while Section 4 discusses the findings through a schematic of the RMS research perspectives. Finally, Section 5 concludes the paper with potential research directions and open questions and issues.

2. RMS features and market positioning

RMSs, as a recent class of manufacturing systems, have adjustable structure, both in the hardware and software architecture [9,18] and join the following six core features [5,11,19]:

- *Modularity*, the compartmentalisation of operational functions into units that can be manipulated among alternate production schemes for optimal arrangements;
- *Integrability*, the ability to connect modules rapidly and precisely by a set of mechanical, informative and control interfaces facilitating integration and communication;
- *Diagnosibility*, the system ability to self-reading its current state to detect and diagnose the root causes of product defects, quickly correcting them;
- *Convertibility*, the ability to easily transform the functionality of existing systems and machines to suit new production and market requirements;
- *Customisation*, the system and machine flexibility limited to a single product family, thereby obtaining customised flexibility;
- *Scalability*, the ability to modify easily the production capacity adding or removing resources and changing the system components.

These features make RMSs dynamic systems with the capacity and functionality to follow the market changes. Furthermore, RMSs, compared to the other manufacturing systems, allow producing a higher variety of customised products. Because of the link of the production system features to the market expectations is crucial, an extensive definition of RMS, including such aspect and extending the original definition provided by professor Koren in 1999 [9,10], is the following: *'RMS is a production system designed to match the dynamic market asking for high-quality products in variable quantities and at a reasonable cost. RMS has a changeable hardware and software structure allowing adjusting production capacity and functionality to combine high throughput rate, flexibility and cellular organisation pattern.'*

This definition emphasises the dynamism of RMSs and the link to both the market and the traditional manufacturing systems.

Research on RMSs increased in the recent past covering a wide set of research issues [20]. The most of the published papers presents methods to include some of the introduced features to existing manufacturing systems [21] with lower attention in providing methodologies for best designing new RMSs. Furthermore, a structured design methodology to include the reconfigurability knowledge in the system design is expected [13,16].

From the industrial perspective, few examples of RMS introduction into companies are available. Moreover, the current literature lacks of best practices driving industrial companies in the transition toward this new industrial paradigm. The greatest barrier toward the application of reconfigurable manufacturing is the resistance to change, especially by small and medium enterprises (SMEs). Such companies need to be trained to effectively adopt reconfigurable manufacturing. The so-called learning factories play a key role in linking academia to industry to spread the culture of innovation. In the last few years some prototypes of learning factories are established. They simulate small flexible and reconfigurable manufacturing and assembly systems with the purpose of practice and training for operators and students [22].

In parallel, reconfigurable manufacturing received great attention over the years by research councils located in many areas of the world through funding projects. Examples of relevant projects are *'Innovative manufacturing processes: flexible and reconfigurable manufacturing systems'* proposed by the Engineering and Physical Sciences Research Council (EPSRC) in 2012 and *'Mobile dual arm robotic workers with embedded cognition for hybrid and dynamically reconfigurable manufacturing systems'* proposed by the European Factories of the Future Research Association (EFFRA) in 2016. Within the context of European projects, relevant examples are the EU-funded projects *'Rapid reconfiguration of flexible production systems through capability-based adaptation, auto-configuration and integrated tools for production planning'* (RECAM) promoted in 2015 and *'Skill-based propagation of plug-and produce devices in reconfigurable manufacturing systems'* (SKILLPRO) promoted in 2016.

3. Research method

3.1. Location of articles and paper database

The search of the articles is conducted by inserting search strings in scientific search engines, *Google Scholar* (scholar.google.com) and *Scopus* (scopus.com) mainly, to find relevant contributions on the analysed topic. The analysis includes the most relevant literature contributions published between 1999 and 2017. In the phase of article screening, search strings include *'reconfigurable manufacturing system'*, *'RMS'* and *'reconfiguration'* as basic terms. After a first filtering of the articles based on their industrial oriented perspective, those published in ISI/Scopus international journals and indexed international conferences addressing the field of production planning and Supply Chain Management (SCM) are included in the review. A point of saturation is reached when articles continue to appear in the search. The selected articles are, further, categorised according to the specific electronic database (ED) they belong to. The main identified EDs are *Elsevier*