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# Understanding reconfigurability of manufacturing systems: An empirical analysis

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ABSTRACT

The need for more responsive manufacturing systems to deal with high product variety and large fluctuations in market demand requires new approaches that enable the system to react to changes quickly and efficiently. Reconfigurability is an ability that allows the addition, removal or rearrangement of manufacturing system components and functions to better cope with high product variety and significant fluctuations in market demand in a cost effective way. This paper empirically investigates the understanding of reconfigurability in industrial manufacturing companies and tests and validates its core characteristics using a questionnaire survey, which was carried out with Portuguese companies. Findings show the existence of five core characteristics of reconfigurability. The implications of these characteristics, concerning the implementation of Reconfigurable Manufacturing Systems, are also analysed and discussed.

## 1. Introduction

In the 1980s, the concept of *flexible manufacturing systems* was introduced in order to respond to the need for mass customization and greater responsiveness to the changes in products, production and market, driven by aggressive economic competition on a global scale, more demanding customers and the rapid pace of change in process technology [1,2]. A cost-effective response to market changes, which can be created by part family focus and customized flexibility, requires a manufacturing approach that is able to react to changes quickly and efficiently and that enables the operation of simultaneous tools [3]. By the end of the 1990s, the concept of a *reconfigurable manufacturing system* had emerged as an attempt to achieve responsive systems, capable of producing high quality products at low costs, by providing an adjustable structure, changeable functionalities, scalable capacity and flexibility [3–5]. Reconfigurable Manufacturing Systems (RMS) are designed at the outset for a rapid change in structure to adjust the production capacity and functionality quickly within a part family in response to sudden changes in manufacturing requirements [3]. An RMS is also designed to produce a particular family of products and to cope with situations where productivity and responsiveness are of vital importance. Its main components for machining are CNC machines and Reconfigurable Machine Tools (RMT), which are controlled, coordinated and operated in an open-architecture environment [3].

In sum, at an operational/tactical level, reconfigurability can be seen as the ability to rearrange manufacturing elements in order to adjust to new environmental and technological changes [6] and, at a tactical/strategic level, as an engineering characteristic that deals with the design of machines and systems for customized products in a cost effective market [7].

RMS assume a relevant role in manufacturing systems by providing a way to achieve a rapid and adaptive response to change, which is a key enabler of competitiveness [8]. Nowadays, disruptive technologies, such as cloud computing, Internet of Things (IoT), big data and analytics, augmented reality and additive manufacturing are permeating the manufacturing industry and making it smart and capable of addressing current challenges, such as increasingly customized requirements, improved quality, and reduced time to market [9]. Thus, it can be expected that these novel technologies, preconized by the concept of industry 4.0, might significantly contribute to increase the reconfigurability of manufacturing systems.

Several authors state that an ideal RMS should possess core characteristics to increase the speed of its responsiveness when faced with unpredicted events, such as sudden market changes or machine failures [4,7,10,11]. Nevertheless, there is no consensus regarding the number and types of RMS core characteristics yet. In fact, in [3] five RMS characteristics are presented: modularity, integrability, customization, convertibility and diagnosability. Later, in [12] scalability is introduced as a new RMS characteristic. These six characteristics have been considered as the core characteristics of RMS by most authors [5,13–15].

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However, other different characteristics have been, to a lesser extent, put forward such as mobility, universality, compatibility, flexibility and self-abilities (e.g. self-adaptation) [4]. Therefore, it is possible to consider that RMS must possess several distinct characteristics and that the sum of these characteristics determines the ease and the cost of reconfiguring manufacturing systems.

Several authors argue that RMS possess the advantages of both dedicated lines and flexible systems [5,10,16,17]. Furthermore, Mehrabi [18] present the challenges expected to be faced by manufacturing systems and how RMS will have a core role in responding to these challenges. Thus, it is expected that RMS will attract the interest of a large number of companies [11]. Additionally, as the need for more reconfigurable systems increases, knowing the various characteristics of RMS becomes of foremost importance in the interest of the manufacturer to be prepared and equipped to evaluate and decide the extent of reconfigurability for their production systems [7]. Therefore, a better understanding of RMS and their core characteristics is required to help companies to assess their present level of reconfigurability and to provide guidelines to improve it in either existing or new manufacturing systems.

Although RMS have been discussed over the last decades in the scientific literature, there are only a few empirical studies concerning how this concept could be transferred and implemented by industry. This paper is intended to make a contribution to this understanding by conducting an exploratory survey to identify the core characteristics of RMS. The analysis was developed based on the six characteristics mentioned by the majority of authors that, despite being identified in the literature, had not been tested empirically. The survey results are analysed and discussed to assess to what extent each of the characteristics identified are present in the manufacturing systems of the companies surveyed. Furthermore, a discussion of how each of the core characteristics identified of RMS might be impacted by the novel technologies put forward by the concept of industry 4.0 is presented, providing insights into how they can contribute to increasing the reconfigurability of manufacturing systems.

The remainder of this paper is organized as follows: Section 2 provides a literature review on the topic of RMS. Section 3 presents the research methodology and the analysis of reliability and validity of the questionnaire. The data collected are analysed and discussed in section 4. Finally, section 5 presents the conclusions, the limitations of this research and suggestions for future studies.

## 2. Literature review

The current production scenario, characterized by aggressive competition and rapid evolution in process technologies, requires more flexible, robust, reconfigurable and easily upgradable systems that rapidly adjust their production capacity and functionality, integrate new technologies and launch new product models quickly, supporting an agile response to the changing conditions through their dynamic reconfiguration on the fly (i.e., without stopping, reprogramming, restarting the processes or the other system components) [8,18,19]. In order to stay competitive, manufacturing companies must remain highly sensitive to market (fluctuations) and be able to react quickly to market changes by introducing products that meet customer needs in a timely manner and by producing high quality products at low costs [5,11].

A cost effective approach that encompasses these capabilities is RMS, whose capacity and functionality can be modified exactly when needed [10]. RMS are cost effective because they boost productivity and increase the lifetime of a manufacturing system [5]. They are created at the design stage to be capable of making rapid changes in the structure and hardware/software components to adjust the production capacity and functionality quickly in response to sudden changes in irregular market demand [11]. RMS may be able to overcome both Dedicated Manufacturing Systems (DMS) and Flexible Manufacturing Systems (FMS), by providing a significant reduction of costs and time in the launching of new products and in the integration of new manufacturing processes into existing systems [20].

RMS are an attempt to achieve changeable functionality and scalable capacity, by proposing a manufacturing environment where components, machines, cells or material handling units can be added, removed, modified or interchanged as needed to respond quickly to changing requirements [15]. However, the objectives of RMS go beyond the rearrangement of its components. This type of system allows, inclusively, the reduction of the time required for designing new systems and for reconfiguring existing ones, and the rapid modification and integration of new technology or functions into existing systems. Additionally, RMS may contribute to the reduction of product costs, continuous improvement in product quality and increased flexibility and responsiveness [5,18].

Koren [3] proposed the concept of RMS and established that it must be designed using hardware and software modules that can be integrated quickly and reliably, thus facilitating the reconfiguration process. RMS should also use modular equipment to achieve the system functionality required for the production of a part family through scalability and reconfiguration as needed, when needed, to meet market demands [4,13]. To achieve these design goals, RMS must have some core characteristics.

When this concept emerged, five core characteristics were described and considered essential for RMS, namely modularity, integrability, convertibility, diagnosability and customization [3]. Several authors supported and enhanced these characteristics [6,18,20,21]. Although [3] and [18] mentioned the increasing need for an adjustable structure for manufacturing systems, enabled by rapid changes in the system production capacity, scalability was only later introduced as another core characteristic of RMS [4]. The six core characteristics of RMS considered by the majority of authors are described hereafter.

*Modularity* means that all its major components are modular (e.g. structural elements, axes, controls, software, hardware and tooling) and the compartmentalization of operational functions into units can be manipulated between alternate production schemes for optimal configuration arrangement [3,10,13]. *Integrability* is related to the ability to readily integrate these modular components, by a set of mechanical, informational and control interfaces that facilitate integration and communication, which also allow the future integration of new technologies [10,18]. *Customization* has two main aspects: customized control, obtained through the integration of control modules with the aid of open-architecture technology, which provides the exact control functions needed; and customized flexibility, where machines are built around family parts and that provides only the flexibility needed to produce those specific parts [3,22]. *Convertibility* is the characteristic that allows the system, in an operating mode, to change quickly between existing products or different batches, by changing tools, part-programs and fixtures, possibly requiring manual adjustment, allowing the system to adapt for future products. It also concerns the ability to transform the existing functionalities of machines to suit new production requirements easily [3,18]. *Scalability* concerns the ability to modify production capacity incrementally by adding/removing resources or changing system components, rapidly and economically [4,10,23]. *Diagnosability* refers to the detection of unacceptable quality of parts and reliability problems, which are critical factors regarding the reduction of ramp-up time in RMS. As production systems become more reconfigurable and are modified more frequently, the ability to read the current state of a system to detect and diagnose the root cause of output product defects automatically and then quickly correct operational defects, becomes essential in order to rapidly tune the newly reconfigured system [3,10,18].

As mentioned previously, although RMS have been discussed over the last decades, there are only a few empirical studies concerning how this concept could be transferred and implemented by industry. Some efforts have been made to quantify some of the core characteristics of