

Reconfigurable Manufacturing Systems as a Solution for Modern Flexible Production

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Abstract: - The rapid evolution of global markets, the diversification of demand, and the reduction of product life cycles impose increasingly high demands on modern manufacturing systems. In this context, traditional systems, characterized by structural rigidity, can no longer effectively respond to current needs regarding the flexibility and adaptability of production. The paper aims to analyze reconfigurable manufacturing systems (RMS) from a conceptual and structural perspective, highlighting their role in modern production. In this regard, the fundamental characteristics of RMS are presented, such as modularity, scalability, integrability, convertibility, and diagnosability. The paper also includes a comparative analysis of the main types of manufacturing systems and proposes a set of performance indicators for evaluating RMS systems, such as reconfiguration time, production capacity, and system efficiency. The results of the analysis emphasize that reconfigurable manufacturing systems represent an effective solution for achieving a balance between productivity and flexibility, contributing to the development of adaptive and competitive production systems.

Key-Words: - reconfigurable manufacturing systems; flexibility of manufacturing systems; business; industrial flexibility; automation; management of the manufacturing system.

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1 Introduction

The increased volatility of global markets, the diversification of product demand, and the continuous reduction of product life cycles have generated significant challenges for traditional manufacturing paradigms [1], [2]. Conventional production systems, characterized by rigid structures and limited adaptability, can no longer effectively respond to the demands of the modern, dynamic, and competitive industrial environment. In recent years, the emergence of the concept of Industry 4.0 has accelerated the transformation of manufacturing systems towards intelligent, interconnected, and data-driven environments [3], [4]. Technologies such as cyber-physical systems, digital twins, and artificial intelligence enable real-time monitoring, decision-making, and optimization of production processes [5], [6]. In this context, adaptability, scalability, and rapid response capacity are becoming essential requirements for modern manufacturing systems. Flexible manufacturing systems (FMS) have been developed to partially meet these requirements, allowing the production of multiple product families with reduced setup times [7]. However, FMS often involves high investment costs and may include redundant functionalities that

are not fully utilized in specific applications [8]. On the other hand, dedicated manufacturing systems (DMS) offer high productivity but lack the flexibility needed to cope with fluctuating demand and frequent introduction of new products [9].

Reconfigurable manufacturing systems (RMS) have emerged as a promising paradigm that aims to combine the high productivity of dedicated systems with the flexibility of FMS systems, while reducing their limitations [10], [11]. RMS are designed based on modular architectures that allow rapid adjustment of production capacity and functionality by adding, removing, or reconfiguring system components [12]. The defining characteristics of RMS include modularity, scalability, integrability, convertibility, diagnosability, and customization [11]. Despite the growing interest in RMS, much of the existing literature remains either at the conceptual level or focuses on specific technical implementations. Thus, there is a need for an integrated approach that correlates architectural principles with performance evaluation methods and practical applicability in the context of modern manufacturing [13], [14].

The main objective of this paper is to analyze reconfigurable manufacturing systems (RMS) from a conceptual and structural perspective, highlighting

their role in the context of modern production characterized by flexibility and adaptability.

In this sense, the paper aims to:

- define and clarify the concept of reconfigurable manufacturing system;
- highlight the essential characteristics of these systems;
- provide a comparative presentation of the main types of manufacturing systems (dedicated, flexible, and reconfigurable);
- position RMS systems in relation to other types of manufacturing systems;
- highlight future research directions in the field of adaptive systems.

By achieving these objectives, the paper contributes to a better understanding of the role and importance of RMS systems within modern industrial production.

The structure of the paper is as follows: section 2 presents the flexibility of manufacturing systems; section 3 is about reconfigurable manufacturing systems; 4 is presented comparative analysis of manufacturing systems, section 5 presents reconfigurable machining systems features, in section 6 are presented performance indicators of RMS systems, section 7 is about design problems for reconfigurable manufacturing systems, in section 8 contains future research directions and section 9 presents the conclusion of this paper.

2 Flexibility of Manufacturing Systems

Flexibility is the capacity to modify a technological system in order to adapt to new manufacturing possibilities. The use of computers in all areas of enterprise activity (production, design, work planning, management) has led to the emergence of a new concept: CIM (Computer-integrated manufacturing), with three interdependent structural components: computer-aided design (CAD); computer-aided process planning (CAPP); computer-aided manufacturing (CAM).

The flexible manufacturing system (FMS) is a complex, computer-controlled system composed of automatically controlled machine tools, automatic tool and part handling facilities, and automated measuring and testing equipment, which, in conditions of reduced setup times, can process any product belonging to a specific product family within the limits of a predetermined capacity and manufacturing program.

There are several industrial manufacturing systems in the world, such as dedicated manufacturing systems, flexible manufacturing systems, cellular manufacturing systems, reconfigurable manufacturing systems, multitask manufacturing systems.

Each of these systems corresponds to a stage of development and presents various advantages.

Dedicated Manufacturing Systems (DMS)

The history of dedicated manufacturing systems begins with the implementation of mass production, when it was necessary to produce identical parts in very large numbers. Thus, each of the industrial machines that make up a factory performs a specific operation or produces a single part. This manufacturing system was not flexible and did not allow the introduction of a part other than the one initially designed for production. When it was necessary to introduce another product, the machines had to be changed, which meant high costs for the new machines and considerable replacement time, which meant important costs.

Flexible Manufacturing Systems (FMS)

A flexible manufacturing system is generally represented by a number of numerically controlled machines and a control system assisted by one or more computers. A flexible manufacturing system is capable of producing one or more families of parts continuously without human intervention. The system is thus flexible to change production, without purchasing new equipment.

Cellular Manufacturing Systems

Cellular manufacturing systems are those systems that aim to improve productivity through a grouping of machines and personnel to produce a specific class of parts. The advantages of these systems are the great variety of products that are manufactured in small series.

3 Reconfigurable Manufacturing Systems

Flexible manufacturing systems (FMS) consist of expensive general-purpose, numerically controlled (CNC) machines that can produce a wide variety of products, varying in production volume. Because the specific applications are not known to the machine manufacturers, FMSs are built with all functional possibilities. This creates a waste of capital.

To reduce capital waste, a new category of manufacturing systems called "reconfigurable manufacturing systems" (RMS) has been developed in which both the machine tools and the manufacturing system as a whole have the following set of basic characteristics: modularity, convertibility, integrability, scalability, diagnosability, and customization.

Reconfigurable technological systems attempt to combine the high productivity of dedicated systems with the market adaptability of flexible systems in order to bring the economic efficiency of small-scale production to the level of mass production. To this end, the component modules of the reconfigurable technological system are to be small in number and universal. By combining them, any configuration can be achieved, and for this reason, they will be used permanently, so that none of them is stationary and stagnant capital is avoided, [15], [16].

The concept of a reconfigurable manufacturing system is a trend in the field of machine tools, which has attracted the attention of manufacturers, who need a system that is more flexible than a dedicated production line and faster than a complex of CNC machines. The machines used are called reconfigurable because they are composed of modules that, once programmed, can produce different parts, but from the same family of parts.

Reconfigurable machines thus make the link between dedicated machine systems, which can produce a single product on a large scale, and numerically controlled (CNC) machine systems, which allow for relative flexibility, but which have the disadvantage that the changeover required to produce a new part takes considerable time.

The Ann Arbor Engineering Research Center at the University of Michigan, together with more than 30 industry partners, is working to develop a new manufacturing system that will meet consumer demands by reconfiguring the manufacturing system itself [8]. The potential of this system can be fully exploited when CNC control is combined with the high productivity of dedicated systems, using a systematic exploitation method.

The reconfigurability can be defined as the ability to adapt production capacity to new circumstances by rearranging or changing components in the system. Components can be mechanical components, sensors, or controllers. We distinguish two classes of machines, namely Adjustable Capacity RMT – the reconfigurable machine with adjustment capacity, and Adjustable Functionality RMT, which allows the creation of diverse families of parts.

The concept of a reconfigurable system was introduced to meet the new challenges in modern manufacturing systems. A system of this type can be re-integrated into a new production in a very short time, using hardware and software modules. The reconfigurability allows the addition, exclusion, or modification of specific production units, control, software, or modification of the machine structure for an optimal adaptation to market requirements. For the system to have the quality of reconfigurable it has to meet certain conditions. These include: modularity for both hardware and software components, integrability (designing the system and components for both rapid integration and the introduction of new technologies), diagnosability (the ability to quickly identify quality problems and failures in the system), customization (designing to adapt to the production of a specific product through hardware and software components), and convertibility.

Reconfigurable Machining Systems (RMS) are designed to meet the following requirements [17]:

- to reduce the start-up time of production for a new part or family of parts;
- to be flexible enough to adapt to market changes;
- to allow the reconfiguration of the manufacturing system according to the product to be manufactured;
- to allow new software technologies to be implemented in existing systems.

Unlike flexible systems, reconfigurable systems have the advantage that there is no stagnant capital during their operation, in that there are no modules that are not used for current production. When switching to the manufacture of another family of parts, appropriate modules are purchased.

4 Comparative Analysis of Manufacturing Systems

To better understand the positioning of reconfigurable manufacturing systems within existing paradigms, it is necessary to carry out a comparative analysis between the main types of manufacturing systems: dedicated systems (DMS), flexible systems (FMS), and reconfigurable systems (RMS). Dedicated systems are characterized by high productivity and low costs per unit of product, but have very low flexibility. Flexible systems offer greater adaptability, but involve significant initial

investments and may include redundant functionalities.

Reconfigurable systems achieve a compromise between these two approaches, offering the possibility of structural and functional adaptation according to production requirements, without involving high costs or long implementation time.

Table 1 presents a synthetic comparison between the three types of manufacturing systems.

Table 1. Comparison of the main characteristics of DMS, FMS and RMS

Characteristic	DMS	FMS	RMS
Flexibility	Low	High	Adaptive
Productivity	High	Medium	High
Initial Cost	Low	High	Medium
Scalability	Limited	Moderate	High
Reconfiguration Time	Very high	Medium	Low
Complexity	Low	High	Medium

Source: created by the author

5 Reconfigurable Machining Systems Features

The architecture of manufacturing systems must be changed to cope with these new changes. The ways in which changes can be made to the system architecture are through the concept of a flexible system and a modular system.

The concept of a flexible system is based on the idea of using components with high flexibility. The concept of a modular system involves the development of a hardware architecture that can be modified by assembling different modules. The parameters corresponding to the assembly are called dynamic parameters. This concept also means that the topology of the system can be changed by adding or removing modules, so that the multitude of tasks that the system can perform increases to infinity. A typical example would be a modular robotic system, which is built on the basis of the modular system concept.

A reconfigurable manufacturing system is designed to allow rapid changes in hardware and software components, to adjust production capacity and the functionality of the part family, to respond to sudden changes in the market or legislation [17], [18]. From a modular system perspective, an RMS consists of modular components. The architecture is "open" in the sense that it is capable of reducing or increasing the number or types of modules. The system is also capable of selecting a set of modules and assembling them in different configurations. Each configuration is able to fulfill the requirements

for a specific task in an optimal way. From the point of view of flexible systems, some of the system modules have adjustable components, such as the translation axes of a CNC or the actuators of a robot. Therefore, an RMS integrates adjustable components based on a modular architecture, resulting in maximizing the capabilities of the system. Compared to mass production systems, an RMS has flexibility in variable production; compared to flexible manufacturing systems, an RMS has flexibility in production capabilities. An RMS is an ideal paradigm for manufacturers that allows for variation in production in small volumes and at low cost.

As shown in Figure 1, an RMS possesses a number of key characteristics [8], such as "modularity", "scalability", "integrability", "convertibility", and "diagnosability". Modularity involves both the hardware and software levels of the component elements.

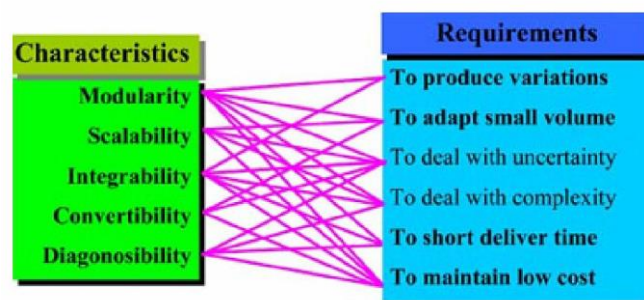


Fig. 1: Characteristics attributed to reconfigurable systems

Source: [8]

Scalability means that the system is able to change its production volume, depending on market needs.

Integrability means that the system components are designed so that they can be integrated into future architectures of new technologies.

Convertibility allows for rapid changes in terms of production change.

Diagnosability defines the ability to identify quality and reliability problems.

The reconfigurability of systems, viewed from the machine level to the entire corporation level, can be classified in terms of the levels of action considered. As shown in Figure 2, at inferior levels reconfigurability is achieved by changing hardware resources, and reconfigurability at superior levels is achieved by software resources [11], [17]. To achieve desired performance levels, it is necessary to fulfill reconfigurability at both the software and hardware levels.

Reconfigurable Manufacturing Systems (RMS) represent an advanced manufacturing concept designed to respond rapidly to market changes by adjusting system capacity and functionality [19], [20]. Unlike traditional systems, RMSs are designed around a modular structure that allows for rapid modification of hardware and software components.

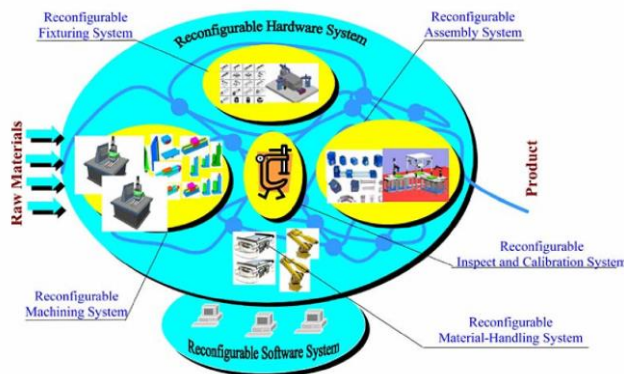


Fig. 2: Example of an RMS system application
Source: [17]

6 Performance Indicators of RMS Systems

The performance evaluation of reconfigurable manufacturing systems can be carried out through specific indicators, which allow the analysis of their efficiency and adaptability.

A first relevant indicator is the reconfiguration time (T_r), which represents the time required to adapt the system to a new production configuration. Reducing it is essential to increase the flexibility of the system.

Mathematically, it can be expressed as:

$$T_r = \sum t_i \quad (1)$$

where t_i represents the duration of each reconfiguration operation.

The production capacity (P) can be expressed as the ratio between the quantity of products produced and the total production time, highlighting the performance of the system under dynamic conditions:

$$P = Q / T \quad (2)$$

where Q is the number of products produced, and T is the total production time.

Another important indicator is the system efficiency (E), defined as the ratio between the actual operating time and the total available time:

$$E = T_{util} / T_{total} \quad (3)$$

where T_{util} represents the actual operating time, and T_{total} is the total available time.

The use of these indicators allows a theoretical evaluation of the performance of RMS systems and facilitates their comparison with other types of manufacturing systems.

7 Design Problems for Reconfigurable Manufacturing Systems

The design issues for a reconfigurable machine tool are: architecture design, configuration design, and design control in terms of the life cycle.

Architectural design determines the components of the system and the interactions between modules. The system architecture must be designed in such a way as to produce as many variants as possible, so that the system can cope with changes and with unforeseen costs. Architectural design is considered in the system design phase.

Configuration design determines the configuration of the system for a specific task. A configuration is a set of selected modules. Configuration design is considered in the system use phase for a specific task. Control design determines the control variables of the process so that the current configuration can be used to perform the current task.

Tomorrow's processes will increasingly take place in complex networks, often operating across company boundaries and internationally. Knowledge-based manufacturing involves not only using knowledge to optimize specific production processes and resources, but also integrating this knowledge and transferring it through knowledge platforms and competent networks to other areas where it can be an advantage.

The target of current research is the development of manufacturing systems that have the ability to modify their control subsystem, in accordance with the changes that occur in terms of the technological properties of the processed material, the mechanical properties of the materials of the tools/active elements used, as well as the market success of the product obtained after processing.

The manufacturing industry uses a portfolio of dedicated and flexible manufacturing systems to mass produce its products. Dedicated manufacturing lines (DMLs) are based on inexpensive fixed automation. Each dedicated line is designed to produce a single component with high productivity

and relatively low cost. However, with the introduction of new products at a high frequency and the high fluctuation of product demand, situations may arise in which manufacturing lines do not operate at full capacity. In these cases, the capital in the workshop and a large part of the capital investment are wasted.

The ideas on which this new technique is based are the following:

- First, the (RMTs) that are part of the RMS must have a modular structure and the modules have a high level of integrability, so that, using a library with a small number of modules, any of the component RMTs can be quickly obtained (convertibility). In other words, with the same available modules, a wide range of RMTs can be obtained, and each RMT is able to ensure the necessary productivity (scalability). In this way, wasted capital is reduced.
- Secondly, the RMT programming, monitoring, and control system must be modular and have an open architecture, so that its structure can be easily reconfigured, adding or removing modules as needed (modularity).
- thirdly, in order for the RMS to be able to offer the above capabilities, it is necessary that its scope of use be restricted to a specific family of parts (customization).
- Finally, the control system must have the ability to detect sources of deviations that affect product quality and to reduce their effect (diagnosability).

In the context of Industry 4.0, reconfigurable manufacturing systems can be integrated with advanced technologies such as cyber-physical systems, digital twins, and data-driven platforms. These technologies enable real-time monitoring of production processes, predictive analytics, and dynamic optimization of system configuration. Thus, RMS becomes an essential component of smart factories, contributing to increased flexibility, efficiency, and responsiveness to changes in the economic environment.

8 Future Research Directions

The evolution of reconfigurable manufacturing systems is closely correlated with the development of digital technologies and the increasingly dynamic requirements of the industrial environment.

In the specialized literature, several relevant research directions are highlighted, including the integration of artificial intelligence to optimize reconfiguration processes, the use of digital twins to

simulate and validate manufacturing system configurations, as well as the development of cyber-physical systems capable of real-time monitoring and control.

Also, an important direction is the development of autonomous manufacturing systems, capable of dynamically adapting their configuration, depending on variations in demand and operating conditions. The integration of RMS systems into intelligent and interconnected industrial ecosystems is also a major area of interest, with the potential to contribute to increasing the efficiency, flexibility, and sustainability of production processes. These research directions highlight the essential role of RMS systems in the future development of smart factories.

9 Conclusion

The paper aimed to analyze reconfigurable manufacturing systems (RMS) from a conceptual and structural perspective, in the context of the current requirements of modern industrial production.

Following the analysis, it is highlighted that RMS systems represent an effective solution for achieving a balance between productivity and flexibility, overcoming the limitations of dedicated and flexible manufacturing systems. Through their fundamental characteristics – modularity, scalability, integrability, convertibility, and diagnosability – these systems allow rapid adaptation to changes in demand and technological developments.

The comparative analysis highlighted the positioning of RMS systems as an optimal alternative between the rigidity of dedicated systems and the complexity of flexible systems, offering significant advantages in terms of adaptability and efficient use of resources.

Also, the integration of RMS systems in the context of Industry 4.0 highlights their potential to become essential components of smart factories, by using digital technologies to monitor and optimize production processes.

The introduction of performance indicators, such as reconfiguration time, production capacity and system efficiency, provides a basis for the theoretical evaluation of these systems and for their comparison with other types of manufacturing systems. In conclusion, reconfigurable manufacturing systems represent a promising direction in the evolution of production systems, contributing to the development of flexible, efficient

and adaptable industrial processes to the requirements of the current economic environment.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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The author solely contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

I declare no conflicts of interest that are relevant to the content of this article.

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