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# Reconfigurable Manufacturing System: A systematic view of highly productive

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**Abstract**

To cope with the agility to respond the dynamic change in the market, we propose a manufacturing system with machining centres (MCs) in a square array layout. The machining processes of the target products are grouped into some processing groups, and any processing groups of any products can be processed by any MCs with proper tool arrangements. The selection of MCs is made by an auction mechanism. The main types of flexibility in manufacturing systems are discussed and contrasted with the various reconfiguration aspects including hard (physical) and soft (logical) reconfiguration. The types of changeability and transformability of manufacturing systems, their components as well as factories, are presented along with their enablers and compared with flexibility and reconfigurability. The importance of having harmonized human-machine manufacturing systems is highlighted and the role of people in the various manufacturing paradigms and how this varies in pursuit of productivity are illustrated. Finally, the industrial and research challenges presented by these manufacturing paradigms are discussed.

***Keywords Changeability · Flexibility · Manufacturing systems · Reconfiguration***

## I. Introduction

The history of manufacturing systems shows their evolution over the years in response to an increasingly dynamic and global market with a greater need for flexibility and responsiveness. Unpredictable market changes cause frequently varying manufacturing systems requirements. Reconfigurable Manufacturing Systems (RMS) were proposed to meet these requirements and provide a degree of capacity scalability and functional adaptability [1-2]. Most manufacturing industries now use a portfolio of Dedicated Manufacturing Lines (DML) and Flexible Manufacturing Systems (FMSs) to produce their products. RMS is intended to combine the high throughput of DML with the flexibility of FMS and react to changes quickly and efficiently. The characteristics of RMS and FMS are outlined and both paradigms are compared. There are many aspects of manufacturing systems reconfiguration that present important research challenges. They include reconfiguration of the factory communication software, new machine controllers, building blocks and configuration of modular machines, modular processes and configuration of the production system. The main focus of the research presented in this paper is the selection of system-level configurations. A distinguishing feature of RMS is that its configuration evolves over time in order to provide the functionality and capacity needed,

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when it is needed [3-4]. These configuration changes can be in the form of adding/removing machines to/from the system, adding/removing axes/spindles to/from machine tools, changing configuration of machine tools, changing the system layout, and changing the material handling systems.

It is desirable to change configuration when demand changes in order to minimize the unused capacity and functionality. In addition, there should be a high degree of reconfiguration smoothness between each two consecutive configurations in order to minimize the cost, time, and effort of reconfiguring the system. This paper proposes a novel ‘‘RMS Configuration Selection Approach’’ that selects RMS configurations according to the current situation, in terms of demand requirements, targeting the best achievable system performance levels while taking into consideration the smoothness of the anticipated reconfiguration process from one configuration to the next expected configuration. The proposed approach was implemented using MATLAB software and a toolbox was developed for this purpose.

## II. Manufacturing systems flexibility

Flexibility attracted much attention from researchers to better understand and clarify its concept. As a result, many definitions emerged in the literature. Early definitions related to the flexibility of manufacturing systems are based on the notion of adaptability to uncertainties [5]. Flexibility can be viewed as the capacity of a system to change and assume different positions or states in response to changing requirements with little penalty in time, effort, cost, or performance. The use of manufacturing flexibility as a strategic objective, the relationship of flexibility with uncertainties, the use of taxonomies as a vehicle for furthering understanding of the types of flexibility, and their measurement as well as the assessment of the effectiveness of the proposed flexibility and robustness measures were studied. 2.1. Manufacturing flexibility classification Review of the literature identifies at least 10 types of manufacturing systems flexibilities. These are:

1. Machine flexibility: Various operations performed without set-up change,
2. Material handling flexibility: Number of used paths / total number of possible paths between all machines,
3. Operation Flexibility: Number of different processing plans available for part fabrication,
4. Process Flexibility: Set of part types that can be produced without major set-up changes, i.e., part-mix flexibility,
5. Product Flexibility: Ease (time and cost) of introducing products into an existing product mix. It contributes to agility,
6. Routing Flexibility: Number of feasible routes of all part types/Number of part types,
7. Volume Flexibility: The ability to vary production volume profitably within production capacity,
8. Expansion Flexibility: Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system,
9. Control Program Flexibility: The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software,
10. Production Flexibility: Number of all part types that can be produced without adding major capital equipment. This classification

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promotes better understanding of various types of flexibility although some of them are inter-related. It should be noted that the expansion flexibility is consistent with the current understanding of manufacturing systems reconfigurability.

## III. Manufacturing systems life cycle

The significant reduction in product development time brought about by the use of CAD tools was not paralleled in the design and development of manufacturing systems. These systems must be designed to satisfy certain requirements and constraints that vary over time. Recent improvements in productivity were attributed more to improvements in the design and operation of manufacturing systems, as well as the design of products, than to manufacturing processes or technology improvements. Some modern design theories and methodologies, such as the design axioms have been applied to the design of manufacturing systems. In the context of manufacturing systems, one can envisage a life cycle, as outlined in Fig. 1, which includes the initial system design and synthesis, modeling, analysis and simulation, realization and implementation, operation [6-7],

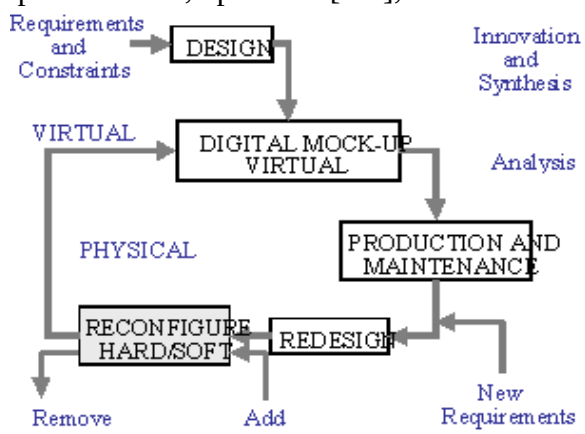


**Fig. 1 Manufacturing systems life cycle (ElMaraghy, 2000)**

and re-design/reconfiguration phases. Both soft and hard reconfiguration and flexibility can extend the utility, usability, and life of manufacturing systems.

### A. Manufacturing system reconfiguration

The changing manufacturing environment characterized by aggressive competition on a global scale and rapid changes in process technology requires careful attention to prolonging the life of manufacturing systems by making them easily up-gradable and into which new technologies and new functions can be readily integrated. [8] A reconfigurable manufacturing system (RMS) is a visionary challenge for manufacturing enterprises and is considered as the next manufacturing paradigm. They would use modular equipment as building blocks to realize the required system functionality for the production of a part family. Instead of providing a general flexibility through the use of equipment with built-in high functionality, as in FMSs, RMSs provide customized flexibility through scalability and reconfiguration as needed when needed to meet market requirements. Table 1 summarizes the three major types of manufacturing systems and their definitions.

The system configurations of reconfigurable manufacturing systems can be similar to dedicated or flexible systems, or a combination of both. While RMS may lie between DMS and FMS in terms of capacity and functionality, this is not its distinguishing feature. The key feature of RMS is that, unlike DMSs and FMSs, its capacity and functionality are not fixed 1) reducing leadtime for launching new systems and reconfiguring existing systems, and (2) rapid manufacturing modification and quick integration of new

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technologies and/or new functions into existing systems using basic process modules (hardware and software) that would be rearranged quickly and reliably. Components

**Table 1** Summary of three types of manufacturing systems

| Systems | Definitions and objectives |
|---|---|
| Dedicated | A machining system designed for production of a specific part |
| manufacturing | type at high volume. |
| lines (DMLs) | Cost-effectiveness is the driver achieved through pre-planning and optimization. |
| Flexible | A Flexible Manufacturing System is an integrated system of |
| manufacturing | machine modules and material handling equipment under |
| systems (FMSs) | computer control for the automatic random processing of palletized parts. The objective is to cost-effectively manufacture several types of parts, within pre-defined part families that can change over time, with minimum changeover cost, on the same system at the required volume and quality. |
| Reconfigurable | A Reconfigurable Manufacturing System is designed for rapid |
| manufacturing | change in structure in order to quickly adjust production capacity |
| systems (RMSs) | and functionality, within a part family, in response to changes in market requirements. The objective is to provide exactly the functionality and capacity that is needed, when it is needed. |

may be machines and conveyors for entire production systems, mechanisms for individual machines, new sensors, and new controller algorithms. Open-architecture control (reconfigurable software) and modular machines (reconfigurable hardware) are key enabling technologies for RMS.

For a manufacturing system to be readily reconfigurable, the system must possess certain key characteristics including: i) *Modularity* of component design, ii) *Integrability* for both ready integration and future introduction of new technology, iii) *Convertibility* to allow quick changeover between products and quick system adaptability for future products, iv) *Diagnosability* to identify quickly the sources of quality and reliability problems, v) *Customization* to match designed system capability and flexibility to applications, and vi) *Scalability* to incrementally change capacity rapidly and economically [9-10]. The new generation manufacturing systems will need new and effective tools to adapt to possibly frequent changes, new product introduction, and short runs without seriously impairing production.

The motivation for introducing reconfigurable manufacturing systems is based on the belief that

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some economic benefits can be obtained by increasing reusability and reducing the excess capacity and/or excess functionality present in other types of manufacturing systems [11].

## IV. Flexibility and reconfigurability

The design, characteristics, and potential merits of RMSs and how they compare with other manufacturing paradigms have been occupying researchers and practitioners at this stage of manufacturing systems evolution. A panel of experts from industry and

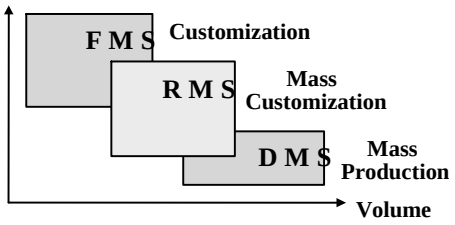


**Fig. 2 Manufacturing Paradigms—A hypothesis (Hu, 2005)**

Academia was assembled recently to discuss and debate these issues. They were asked to address the similarities and differences between RMS and FMS, the definitions of flexibility [12], reconfigurability, and changeability, and how to characterize a manufacturing system's responsiveness. These opinions are summarized in the following sections.

### A. Flexible and reconfigurable manufacturing system

An RMS is designed at the outset for a possible rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family. An FMS is a system whose machines are able to perform operations on a random sequence of parts of different types with little or no time or other expenditure for changeover. In practice, FMSs consist of processing stations and material handling systems that are entirely under computer control (CNC, DNC) [13-14]. In summary, RMS is a manufacturing system with customized flexibility and FMS is a manufacturing system with general flexibility. It was hypothesized that RMS would be positioned between DMS and FMS as shown in Fig. 2.

### B. RMS key characteristics

The key characteristics of RMS, including modularity, integrability, flexibility, scalability, convertibility, and diagnosability, were emphasized as prerequisites to enable reconfigurable manufacturing systems to work as intended and achieve the desired reduction in time and cost (see Fig. 3). The concept of reconfigurable machine tools (RMTs) [15-16], which are designed with customized flexibility that enable combining the advantages of high productivity of dedicated stations with the flexibility of CNCs was presented and compared as summarized in Table 2. These are illustrated with an example of a proposed design of a reconfigurable machine tool (RMT) with reconfigurable spindle heads developed at the NSF Engineering Research Center for Reconfigurable Manufacturing Systems at University of Michigan, Ann Arbor.

### C. Flexibility is the future of reconfigurability

It can be noted that there are sufficient common grounds in philosophy and application between the FMS and RMS paradigms to support the notion that they represent

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**Table 2** Characteristics of dedicated, flexible and reconfigurable manufacturing systems

| | Dedicated | RMS/RMT* | FMS/CNC |
|---|---|---|---|
| System structure | Fixed | Adjustable | Adjustable |
| Machine structure | Fixed | Adjustable | Fixed |
| System focus | Part | Part Family | Machine |
| Flexibility | No | Customized | General |
| Scalability | No | Yes | Yes |
| Simultaneous operating tools | Yes | Yes | No |
| Cost | Low | Intermediate | High |

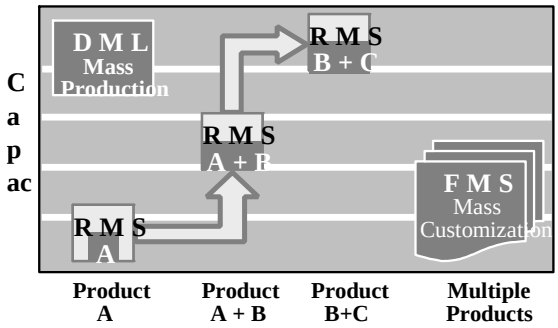


**Fig. 3 Positioning of reconfigurable manufacturing systems regarding capacity and functionality.**

a continuum and to predict that: "the Future Reconfigurable Manufacturing Systems will be More Flexible". Some manufacturing support functions and intelligent software will be necessary to achieve effective reconfiguration, such as: 1) Software that can help select the best equipment (machine tools) based on their capabilities, accuracies, and flexibilities and the best materials, tooling, coolant, fixtures/fixturing to be used to machine any particular component, 2) Future CAD/CAM will recognize geometrical shapes in downloaded customer CAD files and automatically generate CNC part programs that will include appropriate speeds, feed rates, tools and fixtures selections, and process/operation sequencing, 3) Tooling, fixturing, gauging equipment, and supplies could be *automatically retrieved* from inventory stores in an ASRS and introduced into the process at appropriate times, and 4) The process of each ID coded part could be *automatically tracked* through the various manufacturing stages, allowing manufacturing and cost analysis at every stage of production.

Manufactures should, therefore, stay current to make effective use of the latest hardware and software manufacturing/reconfigurable tools that address their present and projected needs and avoid overbuying.

### D. Reconfiguration with available technology

The machine tool industry, represented by one of its successful players, voiced an opinion that there is a compelling value proposition for reconfiguration, the only qualification being cost and availability. It is clear that reconfigurable machine tools (RMTs) are an essential enabler of RMSs. However, the current stateof-the-art is such that broadly reconfigurable machine tools are not yet available as the required technology is still in various stages of development. It was suggested that there are ways to achieve many of the potential benefits of reconfigurable manufacturing systems, and make the users of machine tools and manufacturing systems more profitable while this new technology is under development. For example, it is possible to replace non-reconfigurable machine tools (NRMTs) by machines of alternate configurations provided that certain system features are implemented to

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facilitate their deployment. Re-deployable NRMTs should be able to be removed and replaced in a single shift, when major services are performed off-line. It would be easy to implement such a "plug and play of machines" scenario for a specific machine envelope, where all machine tools share common footprint and pitch, common foundation specification (preferably a slab), common material handling interface, and common chip removal interface. For example, it was suggested that such re-deployable facilities should have a simple slab floor for all machines, 150 mm to 1500 mm cube machines, round or prismatic, pump over of chips and coolant, and known pitch of machines (e.g., 1.2 meters for 150 mm cube machines, 1.5 meters for 350 mm cube machines, and 1.7 meters for 600 mm cube machines).

In summary, while RMTs represent an important building block in any RMS and make it possible to achieve many of its benefits, they require many enabling technologies to become an affordable reality. In the meantime, using concepts such as those discussed earlier, NRMTs that utilize existing technology can be intelligently used to help reap a significant portion of the anticipated benefits of reconfigurable manufacturing systems.

### E. Changeability, reconfigurability and flexibility of manufacturing systems

The concept of having a flexible, reconfigurable and changeable factory infrastructure to support the re-deployment of machines and reconfiguration of systems discussed above resonated strongly with the notion of changeability, including that manifested in plant physical structures and buildings. Changeability of manufacturing systems has been a focus of discussion and analysis within the International Academy for Production Engineering (CIRP) academic and industrial community for a number of years. It resulted in a classification of changeability and its drivers and enablers as well as its relationship with flexibility and reconfiguration, as shown in Figs. 4 and 5. It is important to assess the degree of changeability of current and planned factories, given some prevailing major trends in industry including: (i) the shift from a high number of variants towards mass customization, (ii) the ever decreasing product life cycles, (iii) the increased importance of delivery reliability overload time and utilization, (iv) the widening gaps between the life cycles of products, technology, and equipment, and

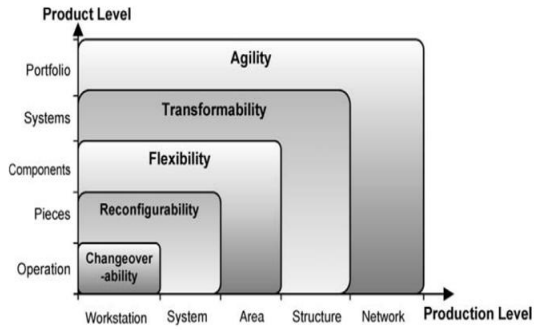


**Figure 4. Types of manufacturing system changeability**

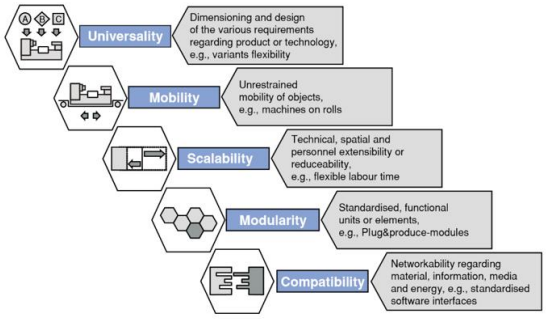


**Fig. 5 Enablers of manufacturing systems transformability (Wiendahl, 2005)**

(v) the change of location of a production system several times within the life cycle of a product

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because of globalization. Therefore, manufacturing systems not only should have the ability to be transformed fast, due to new technologies and demands, but they are also expected to change their facilities and even locations. In addition, they are expected to produce instantly high quality while coping with these changes. Therefore, both the internal and/or external change drivers play a role in determining the level(s) of the factory (machine, group, area, structure, or site) to be changed. This change is not only limited to the technical systems but it is also essential to extend it to the organization and employees to achieve an adequate level of changeability. Hence, this transformation process becomes an important business process that must be pre-planned and managed effectively.

Manufacturers would be wise to conduct an internal evaluation of their existing transformation enablers (i.e., degrees of freedom) to assess the potential for change within their systems and quantify their existing level/degree of changeability. Market demands and external factors, on the other hand, determine the necessary change requirements and the target degree of changeability. These internal and external views should be continuously compared to achieve equilibrium between the market requirements and production performance and to devise plans and strategies to achieve the desired and justifiable degree of changeability.

**V. Discussion**

Reconfigurable manufacturing is a new manufacturing systems paradigm that aims at achieving cost-effective and rapid changes by designing the manufacturing system and its machines for a part family and with specific features to facilitate reconfiguration. Part families are also a pre-requisite for successful flexible manufacturing systems, as they rely on the economy of scope achieved through capitalizing on similarity in geometry and/or processing, sometimes through the application of group technology.

The enabling technologies for RMSs and some of its main building blocks such as RMTs are under development. Dialogue regarding the standards required for modularity, interchangeability, and easy integration should take place between technology developers and suppliers of peripheral equipment. NRMTs should be studied in parallel to exploit their potential and immediate benefits through careful planning and rationalization and to complement the Reconfigurable Machine Tools (RMTs) when they become available and affordable. Other available incremental hardware augmentation solutions and soft/logical reconfiguration options should also be exploited in the meantime.

It has become essential to achieve changeable functionality and scalable capacity over the life cycle of a manufacturing system. Physical or hard re-configuration achieved through plug-in modules of machines and associated control systems, and adding or removing entire machines or cells can be costly and is still under development. Logical or soft re-configuration includes many aspects of flexibility that can be achieved through good system design and software solutions. This approach is by nature less costly and should always be exploited before resorting to other more complex solutions. In all cases, a trade-off cost/benefit analysis should always be conducted to select the most

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appropriate approach for the anticipated life cycle of a manufacturing system.

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