DIRECTIONS OF MANUFACTURING SYSTEMS' EVOLUTION FROM THE FLEXIBILITY LEVEL POINT OF VIEW

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Summary: Manufacturing flexibility is one of the key determinants of development of modern production systems. The article presents the importance of flexibility factor in the process of manufacturing systems development during the 20^{th} century. In particular, craft manufacturing, dedicated manufacturing systems (DMS) and flexible manufacturing systems (FMS) were characterized. Finally, actual problems and trends in production system design were noticed and probable directions of development of manufacturing systems in 21^{st} century were indicated.

Keywords: flexibility, dedicated manufacturing system, flexible manufacturing system, reconfigurable manufacturing system, focused flexibility manufacturing systems.

1. Introduction

The 20^{th} century was a period of continuous challenges that both production companies and designers of manufacturing systems had to stand up to these. It was a result of technical and technological progress unknown in history so far, process of globalization moving forward in frantic pace, increasing level of competition, and also changeable and more and more superior requirements of customers. The same, both methods of production and organization of manufacturing systems were a subject of constant evolution.

One of the key factors, which determined the level of competitiveness of manufacturing plants in every moment in history was the ability to flexible production of goods compatible with the requirements of customers. During the last century it can be noticed both moments when flexibility was completely inessential, and these one when skills for rapid adaption to changeable requirements of customers decided not only about the level of competitiveness and possibility of companies development but was a critical determinant of surviving on the market.

In the 21st century manufacturing companies face increasingly frequent and unpredictable market changes driven by global competition, including the rapid introduction of new products and constantly varying product demand. To remain competitive, companies must design manufacturing systems that not only produce high-quality products at low costs, but also allow for rapid response to market changes and consumer needs [1].

This article presents main stages of development of production methods and manufacturing systems. Especially, the element of flexibility was analyzed as a determinant of designing and developing the manufacturing systems. Finally, the new directions of development of manufacturing systems were presented and some problems which have to be taken into account in these new concepts were indicated.

2. Definition and types of flexibility

Flexibility is an attribute of various types of manufacturing systems. This factor has been defined differently even in the field of engineering, but generally flexibility means ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost-effective manner [2].Thus, flexibility for an engineering system is the ease with which the system can respond to uncertainty in a manner to sustain or increase its value delivery. Uncertainty is a key element in the definition of flexibility. Uncertainty can create both risk and opportunities in a system, and it is with the existence of uncertainty that flexibility becomes valuable [3]. Different approaches to flexibility and their meanings are shown in Tab. 1.

Tab. 1. Different approaches to flexibility and their meanings [4]

Approach	Flexibility meaning
Manufacturing	• The capability of producing different parts without major retooling • A measure of how fast the company converts its process or processes from making and old line of products to produce a new product • The ability to change a production schedule, to modify a part, or to handle multiple parts
Operational	• The ability to efficiently produce highly customized and unique products
Customer	• The ability to exploit various dimension of speed of delivery
Strategic	• The ability of a company to offer a wide variety of products to its customers
Capacity	• The ability to rapidly increase or decrease production levels or to shift capacity quickly from one product or service to another

When taking into account the problem of flexibility in the process of manufacturing systems design it is possible to distinguish three levels of manufacturing flexibility [13]:

1. Basic flexibilities:
   - *Machine flexibility* – the ease with which a machine can possess various operations,
   - *Material handling flexibility* – a measure of the ease with which different part types can be transported and properly positioned at the various machine tools in a system,
   - *Operation flexibility* – a measure of the ease with which alternative operation sequences can be used for processing a part type.
2. System flexibilities:
   - *Volume flexibility – a measure of a system's capability to be operated profitably at different volumes of existing part types,*
   - *Expansion flexibility – the ability to build a system and expand it incrementally,*
   - *Routing flexibility – a measure of the alternative paths that a part can effectively follow through a system for a given process plan,*
   - *Process flexibility – a measure of the volume of the set of part types that system can produce* without incurring any setup,

– *Product flexibility – the volume of the set of part types that can be manufactured in a* system with minor setup.

3. Aggregate flexibilities:

– *Program flexibility – the ability of a system to run for reasonably long periods without external intervention,*

– *Production flexibility – the volume of the set of part types that a system can produce without major investment in capital equipment,*

– *Market flexibility – the ability of a system to efficiently adapt to changing market conditions*.

3. Craft manufacturing

Until the 20th century the craft manufacturing was the only method of producing goods. This type of production is not important from the manufacturing system's design point of view (in craft manufacturing it is difficult to discuss about manufacturing systems) but it is very interesting when focus on the task of flexibility. Craftsmen used high skilled workers and simply but flexible tools to produce goods precisely desired by customer. Most often it was an unique product. An example products are: furniture made against specific order, decoration elements or sport cars. Generally, even now people like the idea of craft manufacturing, but this method of production is connected with one obvious problem: goods made by craftsmen are rather exclusive goods and for most people these are too expensive [5].

When focus on the problem, it is possible to distinguish some basic features of craft manufacturing:

– *Workers (craftsmen) are highly qualified in design, machine and assembly tasks (more of the workers to get craft skills learnt by practice working in craft companies).*

– *Craft companies were deeply decentralized but located near big cities. More of produced parts were manufactured in small workshops.*

– *The production was coordinated by the owner of craft company who was responsible for direct contacts with customers, workers, suppliers etc.*

– *The machine tools for drilling, turning or other mechanical operations performed on metal or wooden parts were very universal.*

– *The volumes of production were very small (in case of car production 1000 or less cars were produced annually).*

– *All of the products* (even made using the same project) were different because craft methods moved high variability.

So, when summarize the characteristics of craft manufacturing it can be concluded that this method was in other hand very flexible, but on the other hand very expensive.

4. Dedicated Manufacturing Systems (DMS's)

In the 1900s the way of production had dramatically changed. The main reason was implementation by Henry Ford system of mass production and dedicated manufacturing lines. In 1907 the Model T was born. The launch marked one of the first instances where a large number of accurately machined mechanical components were combined to form a product. The product was sufficiently inexpensive to purchase that it sold in significant volumes (for that time). Indeed, during the sixteen-year life of Model T, over 19 million vehicles were sold. At the height of production, over a million cars were being manufactured each year. But, of course, the Model T, perhaps unjustifiably, gained a certain amount of notoriety, because at one stage Henry Ford was supposed to have said about his brainchild "you can have any colour, so long as it's black" [5]. What this meant was, that everyone could obtain the product, relatively cheaply, but there was no variety.

The conception of mass production introduced by Henry Ford, contributes to development of dedicated manufacturing systems which generally appear in two forms [6]:

– *Continuous manufacturing systems.*
– *Intermittent* manufacturing systems.

4.1. Continuous manufacturing systems

In this system the items are produced for the stocks and not for specific orders. Before planning manufacturing to stock, a sales forecast is made to estimate likely demand of the product and a master schedule is prepared to adjust the sales forecast according to past orders and level of inventory. Here the inputs are standardized and a standard set of processes and sequence of processes can be adopted. Due to this routing and scheduling for the whole process can be standardized. After setting of master production schedule, a detailed planning is carried on. Basic manufacturing information and bills of material are recorded. Information for machine load charts, equipment, personnel and material needs is tabulated. In continuous manufacturing systems each production run manufactures in large lot sizes and the production process is carried on in a definite sequence of operations in a pre-determined order. In process storage is not necessary which in turn reduces material handling and transportation facilities. First in first out priority rules are followed in the system. In short, here the input-output characteristics are standardized allowing for standardization of operations and their sequence. Chief characteristics of continuous systems are:

– *This systems do not involve diverse work, due to which routing standardized route and schedule sheets are prepared.*
– *In case of standard products meant for mass production, master route sheets are prepared for more effective co- ordination of various departments.*
– *Scheduling is required to rate the output of various standard products in their order of priority, operations and correct sequence to meet sales, requirements.*
– *Work relating to dispatching and follow-up is usually simple. Dispatch schedules can be prepared* well in advance in such systems.

Continuous systems can be divided into two types of manufacturing systems, namely mass and flow production systems and process production systems (Fig. 1).

4.2. Intermittent manufacturing systems

In this system, the goods are manufactured specially to fulfill orders made by customers rather than for stock. Here the flow of material is intermittent. Intermittent production systems are those where the production facilities are flexible enough to handle a wide variety of products and sizes. These can be used to manufacture those products where the basic nature of inputs changes with the change in the design of the product and the production process requires continuous adjustments. Considerable storage between operation is required, so that individual operations can be carried out independently for further utilization of men and machines. Chief characteristics of intermittent systems are:

- *Most products are produced in small quantities;*
- *Machines and equipment are laid out by process;*
- *Workloads are generally unbalanced;*
- *Highly skilled operators are required for efficient use of machines and equipment;*
- *In-process inventory is large;*
- *Flexible* to suit production varieties.

Intermittent systems can be further divided into three types of production systems, namely project production systems, jobbing production systems, and bath production system (Fig. 1).

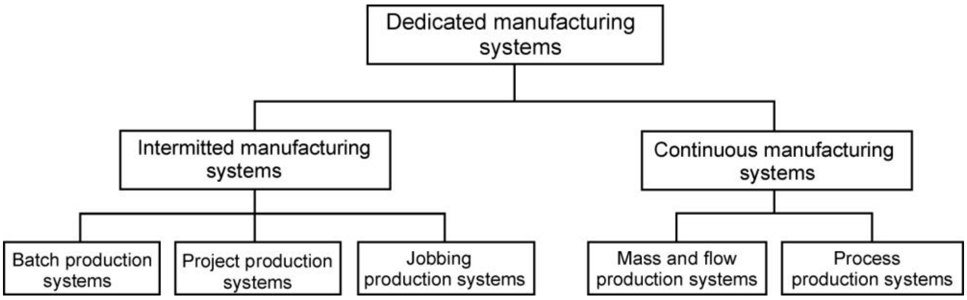

Fig. 1. Classification of dedicated manufacturing systems

When analyze the flexibility level of dedicated manufacturing systems, it is worth to notice that continuous manufacturing systems are typically rigid where the level of flexibility is around "zero". The intermittent systems, where the need of flexibility has been already noticed, are designed as a "customer focused", taking into account the problem of variation and changeability of customers' orders.

5. Flexible Manufacturing Systems (FMS's)

In the middle of the 1960s, market competition became more intense and more complex. With significantly shortened product life cycles, manufacturers found that they can no longer capture market share and gain higher profits by producing large volumes of standard products for a mass market. Success in manufacturing required the adoption of methods of production that can provide a fast and flexible response to unanticipated changes. Many companies were confronted with the challenge of changing their manufacturing orientations to meet demands of current market place. As a solution to this challenge, the idea of Flexible Manufacturing System (FMS) was proposed [3].

A Flexible Manufacturing System (FMS) is a group of numerically-controlled machine tools, interconnected by a central control system. The various machining cells are interconnected, via loading and unloading stations, by an automated transport system (Fig. 2). Operational flexibility is enhanced by the ability to execute all manufacturing tasks on numerous product designs in small quantities and with faster delivery [7]. It has been described as an automated job shop and as a miniature automated factory. In other words, it is an automated production system that produces one or more families of parts in a flexible manner [8].

The first FMS named ‘System24’ was already introduced in England in 1960s. It was designed to produce light flat alloy components, the market for which it was felt was going to develop significantly [9].

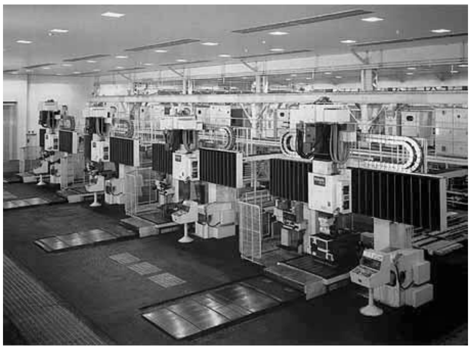

Fig. 2. An example of Flexible Manufacturing System [10]

The Flexible Manufacturing Systems are designed as a set of integrated subsystems (see Fig. 3), to meet three specific goals:

1. It has to be capable of manufacturing a large variety of components, virtually at random.
2. It has to be capable of both loading and unloading tools and work-pieces automatically.
3. It has to be capable of operating, virtually unattended for long periods.

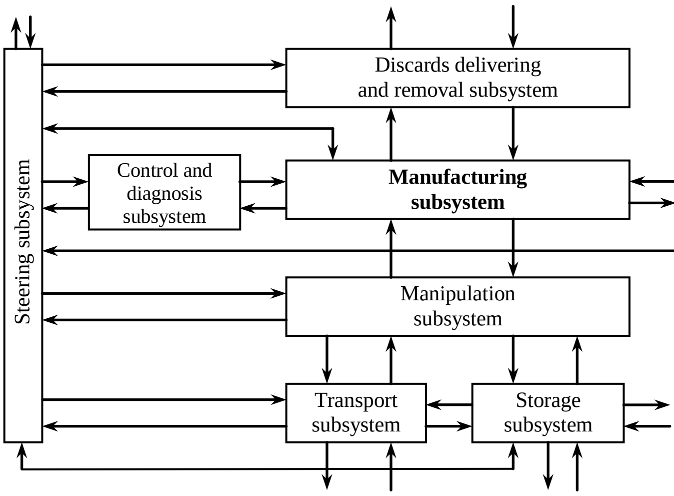

Fig. 3. A functional structure of an FMS [11]

FMSs are still oriented to produce a large variety of parts in small quantities and they are conceived to react to most of the possible products changes. Unfortunately the cost of investment to acquire an FMS is very high and it considerably affects the cost to produce a part; indeed its flexibility is frequently to high and expensive for needs of a producer of parts. The high financial and organizational impact of FMSs has reduced their diffusion in the past; indeed the initial outlay is so high it severely strains the financial resources of the firms.

6. Modern conceptions in manufacturing systems design

Nowadays, most medium and high-volume manufacturing industries currently use of portfolio of Dedicated Manufacturing Systems (DMS's) and Flexible Manufacturing Systems (FMS's) to produce their products. Generally, DMS's, or transfer lines, are based on fixed automation and produce the core products of the company at high-volume. These lines are customized hardware lines that can control cutting tools in fixed directions determined at the design stage. They are designed to produce a single product and cannot be changed. Each dedicated line typically produces a single part (e.g., a pump housing). The dedicated lines are economical when large numbers of the same part are to be produced for a period of several years or more.

FMS's produce a variety of products on the same system. They typically consist of computer numerically controlled (CNC) machines, and other programmable automation. CNC machines often use large tool magazines and several axes-of-motion to provide general flexibility which has the potential to produce a variety of parts of different types. But in many cases not all these axes-of-motion are utilized in the production of each part, which means that the machine is underutilized and its initial cost is partially wasted. Typically, the structure of each FMS and the structure of its CNC machines cannot be changed. The production capacity of FMS's is fixed and is usually lower than that of dedicated lines, because their initial cost is higher.

However, medium and high-volume manufacturers are now facing new market conditions characterized by: (i) pressure to quickly introduce new products at low costs, and (ii) large fluctuations in product demand. To cope with these needs and to stay competitive, manufacturing companies must possess a new type of manufacturing system that is suitable taking into account flexibility, capacity and functionality.

To avoid mentioned above problems conceptions of Reconfigurable Manufacturing System (RMS) and Focused Flexibility Manufacturing System (FFMS) were invented.

6.1. Reconfigurable Manufacturing System (RMS)

Idea of RMSs was invented in 1999 in the Engineering Research Center for Reconfigurable Manufacturing Systems (ERC/RMS) at the University of Michigan College of Engineering [12].The RMS main goal is summarized by the statement – *Exactly the capacity and functionality needed, exactly when needed*.

A reconfigurable manufacturing system (RMS) having an adjustable structure is designed based upon market demand and can be readily changed from a first desired production capacity to a second desired production capacity to manufacture a desired amount of product from a family of products [13]. RMSs are marked by six core reconfigurable characteristics, as summarized in Tab. 2.

In general, reconfigurable manufacturing systems, are designed at the outset for 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 in response to sudden changes in market or regulatory requirements [14]. Such a reconfigurable manufacturing system is generally indicated in Fig. 4.The system (10) typically includes a plurality of workstations (12) including reconfigurable milling machines (14). The system also includes a control system including an operation station (16) and reconfigurable controllers (18) for controlling the reconfigurable machines (14). The operator station (16) is in communication with the reconfigurable controllers (18) and the reconfigurable controllers (18) are in communication with each other The system further includes a reconfigurable material handling system including a gantry robot (20), at least one wireless AGV (22), and an array of antenna receivers and transmitters (23) in communication with the AGV (22). The AGV is also in communication with at least one of the reconfigurable controllers (18). The RMS allows the integration of new production technology such as a laser machining system (24) which has its own reconfigurable controller (18) which is in communication with the operator station (16) and one of the other reconfigurable controllers (18) [13].

Tab. 2. Characteristics and principles of reconfigurable manufacturing systems [14]

Reconfigurable characteristics	**Description**
Customization (flexibility limited to part family)	System or machine flexibility limited to a single product family, thereby obtaining customized flexibility
Convertibility (design for functionality changes)	The ability to easily transform the functionality of existing systems and machines to suit new production requirements.
Scalability (design for capacity changes)	The ability to easily modify production capacity by adding or subtracting manufacturing resources (e.g. machines) and/or changing components of the system.
Modularity (components are modular)	The compartmentalization of operational functions into units that can be manipulated between alternate production schemes for optimal arrangement.
Integrability (interfaces for rapid integration)	The ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that facilitate integration and communication.
Diagnosability (design for easy diagnostic)	The ability to automatically read the current state of a system to detect and diagnose the root causes of output product defects, and quickly correct operational defects.

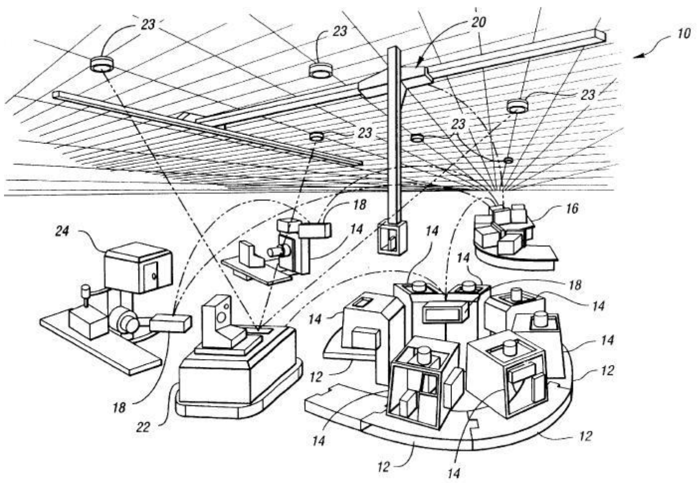

Fig. 4. An example of structure of Reconfigurable Manufacturing System [13]

As distinguished from flexible manufacturing systems (FMSs), an RMS has the structure which allows for rapid adjustment of production capacity and functionality, in response to new market circumstances, by basic change of its hardware and software components. So, while the structure of DMLs and FMSs are static, RMSs are dynamic with level of flexibility, capacity and functionality directly fitting the needs of the system in any moment of its life (Fig. 5).

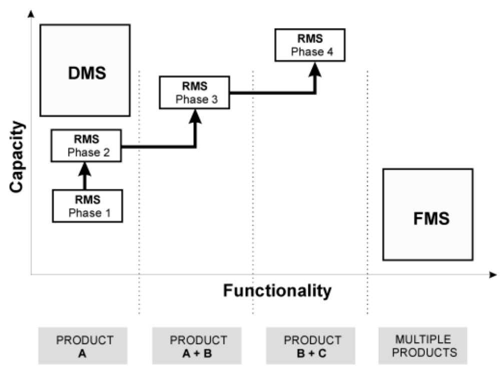

Fig. 5. Capacity and functionality of different forms of manufacturing systems [14]

RMSs can be noticed as an answer to the need for facing continuous changes in the production problems. In fact, reconfigurability describes the operating ability of a production system or device to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements.

However, despite the concept of reconfigurable resources is highly innovative it is quite difficult to be pursued considering available software and hardware technologies. Unfortunately, this approach is also not always cost-effective. Firstly, the reconfigurability option should be designed in order to accomplish its implementation when changes occur. Secondly, any reconfiguration along the system life-cycle leads to face not only the installation costs but also operating costs related for instance to the ramp-up phase, typically characterized by machine malfunctioning and breakdown, lost production and learning [15].

6.2. Focused Flexibility Manufacturing System (FFMS)

The second modern conception of manufacturing systems design is a conception of Focused Flexibility Manufacturing Systems (FFMSs). FFMSs represent also a competitive answer to cope with the need of customized flexibility and they guarantee the optimal trade-off between productivity and flexibility [16]. Moreover, the customization of flexibility on specific production problems leads to the minimization of the system cost during its life-cycle. Indeed, the flexibility degree in FFMSs is related to their ability to cope with volume, mix and technological changes, and it must take into account both present and future changes [17].

The required level of system flexibility impacts in the architecture of the system and the explicit design of flexibility often leads to hybrid systems, i.e. automated integrated systems in which parts can be processed by both general purpose and dedicated machines. This is a key issue of FFMSs and results from the matching of flexibility and productivity that characterize FMSs and DMSs, respectively.

FFMSs are hybrid systems, in the sense that they can be composed both of general purpose and dedicated resources. This innovative architecture derives from the consideration that system flexibility is related both to the flexibility of each single selected resource and to the interaction among the resources which compose the system. For instance, a flexible system can be composed of dedicated machines and highly flexible carries. The whole FFMS design approach is presented in Fig. 6.

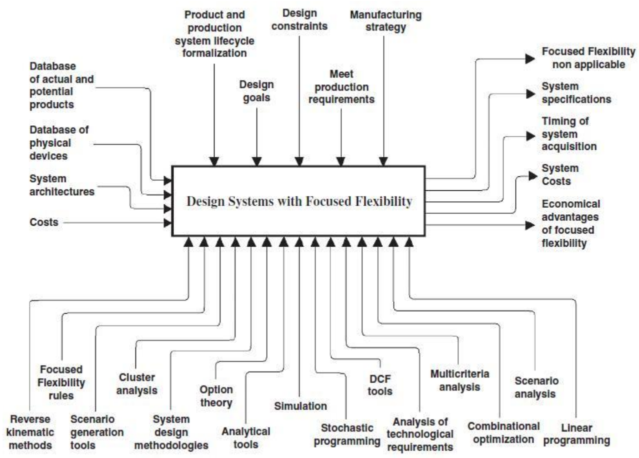

Fig. 6. Focused Flexibility Manufacturing Systems design diagram [16]

At first sight FFMSs could appear to be similar to Reconfigurable Manufacturing Systems (RMSs); the difference between these two classes of systems is in the timing of flexibility acquisition. Deciding about flexibility and reconfigurability means to consider two options. The first option deals with designing a dedicated system in which the reconfiguration option can be implemented in the future when production changes occur. This leads to design a system with the minimum level of flexibility required to cope with the present production problem. In this case FFMSs and RMSs have similar performance. The alternative option is to purchase more flexibility than the amount strictly required by the present production problem in order to avoid future system reconfigurations and ramp-ups. In this case, FFMSs have some "extra" flexibility designed to cope with future production changes, i.e. degree of flexibility designed to cope with future production changes, i.e. a degree of flexibility tuned both on present and future production problems.

7. Conclusions

Manufacturing companies in the 20th and the 21st century face increasingly frequent and unpredictable market changes driven by global competition, violent technical and technological development and constantly varying product demand. Consequently, both manufacturing methods and organization of manufacturing systems have changed during this time. The 20th century begins with craft manufacturing as only way of production.

Since the 1920s has begun fast development of different forms of organization of production and manufacturing systems design. When analyze used forms of production systems during the last century it can be noticed that flexibility has very different importance. Traditionally, dedicated manufacturing systems (DMS) have been adopted for the production of a small family of part types required by the market in high volumes. DMSs are characterized by low scalability and therefore they are typically dimensioned on the maximum market demand that the company forecasts to satisfy in the future (volume flexibility). As a consequence, in many situations DMSs do not operate at full capacity. On the other hand, flexible manufacturing systems have been adopted to produce a large variety of parts in small quantities and they are conceived to react to most of the possible changes. The investment to acquire an FMS is very high and it considerably affects the cost to produce a part; indeed its flexibility may be to high and expensive for the needs of a producer (see Tab. 3).

Tab. 3. Comparison of different forms of manufacturing systems

	DMS	FMS	FFMS	RMS
System structure	Fixed	Changeable	Changeable	Changeable
Machine structure	Fixed	Fixed	Fixed	Changeable
System focus	Part	Machine	Machine	Part family
Scalability	No	Yes	Yes	Yes
Flexibility	No	General	Focused	Customized
Simultaneously operating tools	Yes	No	No	Possible
Productivity	Very high	Low	Average	High
Cost per part	Low	Reasonable	Medium	Medium
Cost of investment	Average	Very high	Average	High

Nowadays manufacturing flexibility has a strategic role for firms that want to compete in a reactive or proactive way [17]. In fact, the ability of designing production systems whose flexibility degree is customized on the present production problem and at, the same time, it takes into account future product evolutions, can lead to competitive advantage.

From the scientific perspective, focusing the flexibility of a production system on the specific needs represents a challenging problem. Indeed, the customization of system flexibility provides economic advantages in terms of system investment costs, but on the other hand, tuning on the production problems reduces some of the safety margins which allow decoupling the various phases of manufacturing system design. Therefore, manufacturing system flexibility must be rationalized and it is necessary to find out the best trade-off between productivity and flexibility by designing manufacturing systems endowed with the right level of flexibility required by the production problem. In consequence, from the designer of modern manufacturing systems point of view it is very important to answer following questions:

- Are the conceptions of FFMS and RMS proper for modern companies?
- Which of conception – FFMS or RMS is much suitable for defined company?
- How to define the desired level of system's flexibility?
- Which of the types of flexibility are the most important in the process of system design?
- How to forecast the way of development of manufactured parts?
- How to plan and optimize the cost of manufacturing system in its life-cycle?

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