Lego-like reconfigurable machining system

New perspectives to optimize production capacity

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***Abstract*—Manufacturing industries in the 21st century will face unpredictable, high-frequency market changes driven by globalization. Consequently, industries have to shift to more cost-effective production systems. Reconfigurability can provide cost-effective and quick reaction to market changes. This paper discloses a new paradigm in Reconfigurable Machining Systems, RMS, that enables flexibility, by the principle of modularity, integrability, scalability and convertibility in an easy manner. The architecture, characteristics and advantages of the new Lego-like RMS are presented and discussed.**

Keywords—machine tool; reconfigurability; scalability

I. Introduction

Since the industrial revolution, manufacturing has been driven by economic motivations taking advantage of technological innovations. The balance between technologies and historical context has guided the organization of labor, as well as society. This paper explores the possibilities offered by a new paradigm in Reconfigurable Machining Systems, RMS; specifically, the proposed RMS allows to design scalable manufacturing systems whose production capacity can be dynamically adapted. This characteristic provides the necessary elasticity to face change in market demand.

II. Economic Framework

Economic theories, born in England with the industrial revolution, depict and explain the evolution of the industry and society since 1776 when Adam Smith published his magnum opus "*An Inquiry into the Causes of the Wealth of Nations*". Actually, the fall out of technological innovation and entrepreneurs permitted to increase the welfare of the population in the countries that endorsed industrialization; Fig. 1 from [1] shows the effect of industrial revolution on the income per person. Accordingly, it is noteworthy to consider the evolution of the economic theories in the last century as a key guide to understand the progress of the manufacturing industry, its efficiency in the use of resources, the production factors, its impact on the environment, labour organization and the society.

While classical economics considers basically three primary factors of production, land, labor and capital goods, neoclassical microeconomics suggests a more articulated classification of the production factors including capital (fixed, working and financial) and technology progress. The latter plays a fundamental role for an efficient transformation of physical inputs into physical outputs, explained by the production function. As the production throughput increases, the marginal product, i.e. the change of produced outputs respect to the change of the used inputs, goes along three phases:

- for low production output, the increment of input factors provides an increment of the outputs and of the marginal product;
- as production system employs more quantities of variable inputs, the rate of the output rise becomes lower and the marginal product decreases;
- by further increasing the use of variable inputs, the production output reach a maximum and eventually the production throughput falls and the marginal product becomes negative.

This behavior, reported in economics as diminishing returns, plays a fundamental role in the successful management of manufacturing companies: actually, industries based on scale economies, while historically provided valuable advantages to the social welfare and mankind, must nowadays face globalization, mass customization, economic crisis and environmental issues.

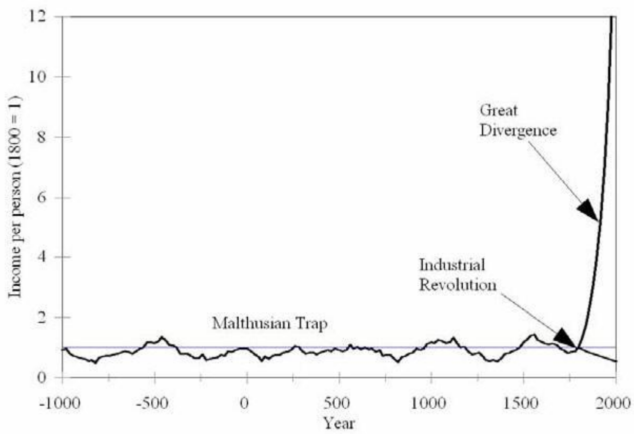

Fig. 1. World economic history from [1]

Ecological economics, by including the first and second law of thermodynamics, addresses sustainability as well as the efficient allocation of production resources; in particular, instead of the three classical primary factors of production, ecological economics considers:

- matter: the material used to manufacture products; matter is limited, cannot be created or destroyed, it can be reused, recycled;
- energy: a physical, non-material input of production ruled by entropy which establishes a scale of value for the energy forms and determines a degradation path; the total amount of energy is limited and cannot be created or destroyed;
- design intelligence: comparable to the neoclassical technological progress, design intelligence takes into account the experience, knowledge, creativity and efficiency used in manufacturing goods.

Within the economics framework, several factors nowadays influence the survival of manufacturing industries, essentially: globalization, customization, sustainability. Furthermore, the economic crisis experienced since 2008 by the industrialized countries, exacerbates the problem and makes every proposed solution more complex to actuate. Actually, Industrie 4.0, manufacturing computerization, cloud manufacturing, internet of things, etc. face several challenges and focus mainly on (i) interoperability, (ii) information transparency, (iii) technical assistance, and (iv) decentralized decisions [2]. These approaches, however, seem to overlook the real nature of production inefficiency: the product cost structure, and the improvement of the phases where the unit value added is really created, i.e. the matter (material) transformation processes.

A simple analysis of the cost structure that takes into account the classification of costs into fixed and variable, and the plant production capacity, shows that (Fig. 2):

- expansion of the plant production capacity, in order to satisfy market demands, requires relevant investments in plants, machining tools, essentially fixed costs, and consequently results in a discontinuity in the total cost curve where production capacity achieves a limit;
- this discontinuity could shift the break-even point (BEP) towards higher values of the manufactured quantity maintaining the same total revenue curve (from BEP_1 to BEP_2 in Fig. 2);
- whenever the marked demand decreases, the exceeding production capacity becomes an unproductive and unrecoverable cost.

The high variability characterizing the demand of customized products, involving both the produced quantity, both the products typology, prevents the adoption of organization approaches, such as Just In Time or lean manufacturing, that have been proven successful for mass and constant products demand.

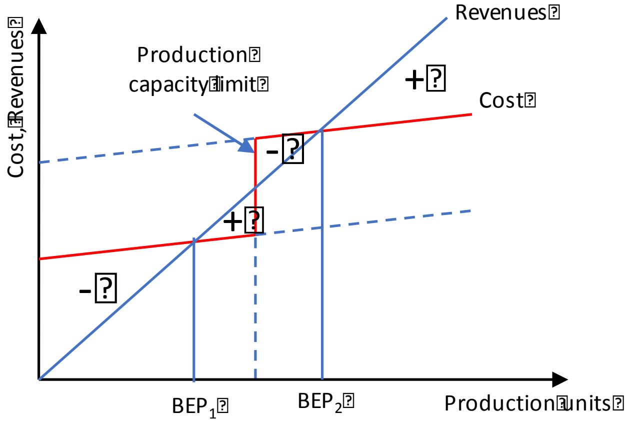

Fig. 2. Break Even Analysis with limit on production capacity

Considering the unit value added, manufacturing core function relates to the physical transformation of input material into finished goods; transformation technologies can be classified essentially into: removal, joining, adding, moving processes. Basically, the workpiece's value increases when the transformation is actually carried out, during the machining time; other time consuming phases, such as set-up, load/unload, although necessary, do not contribute to improve the product's value.

In order to overcome the issues related to the product cost structure and the unit value added a new manufacturing paradigm enabling scalability and elasticity in machine tools investments as well as integration of transformation technologies is required.

III. LEGO-LIKE RECONFIGURABILITY

Historically the evolution of machine tools has been driven by enabling technological innovations, and markets demand. Considering flexibility, machine tools are classified as:

- universal machines (multipurpose), conventional or numerically controlled; these machine tools have the greatest flexibility and are adapted to various different kinds of machining;
- automatic machines for manufacturing high production volumes; unfortunately, these machines require long setup times when the type of manufactured product changes;
- special, single-purpose machines; these machines have no flexibility as they are designed for a particular kind of machining.

In order to improve efficiency and provide high production capacity Dedicated Manufacturing Line (DML), characterized by high automation level, high throughput, are used. This approach however does not provide the necessary flexibility to face product variability and product proliferation.

In order to tackle demand variability and overcome the limitations connected to DML flexibility, in the last 50 years, solutions based on Flexible Manufacturing Systems (FMS) have been presented. FMSs usually include CNC machine tools connected by automated material handling system, and a central computer to control and optimize the parts flow within the system. Although FMS have a greater level of flexibility with respect to DML, they have high costs that are not justifiable when the production throughput requires lower production capacities than the rated capacities of the system.

Since the ‘70s, to overcome the limits of DML and FMS, several projects were carried out considering reconfigurability. The first example of reconfigurable system dates back to 1977: in Japan, the MITI began the FMC program (Flexible Manufacturing system Complex); this program terminated with the construction of an experimental factory in 1983 in Tsukuba. Other large-scale projects were set up by the European Union in the early 1990s, by the University of Hanover with the MOSYN (Modular Synthesis of Advanced Machine Tools) project, by the University of Stuttgart's with the “Special Research Program 467” that focused on transformable business structures for highly variable mass production and on developing the capacities and functionalities of machine tools so that they can be adapted to sudden changes in the market. Another project, MOTION (Modular Technologies for Intelligent Motion Unit with Linear Motor and Axis Control), studied the possibility of using identical modules on different machines and focused on the design of interfaces. Since 1996, the Engineering Research Center of Reconfigurable Machining Systems (ERC/RMS), developed RMS technology by considering (i) the reduction of design times of reconfigurable systems, (ii) the design of reconfigurable machines and of the related control systems, (iii) the reduction of ramp-up times. In the same decade, at the Carnegie Mellon University, the project called Reconfigurable Modular Manipulator System, addressed the development of plug-and-play modules which could be assembled in a large number of different configurations to adapt the kinematic and dynamic properties of the manipulator to a specific purpose.

In 1999 the concepts of Reconfigurable Machine Tool (RMT) and Reconfigurable Manufacturing System (RMS) were formalized by Koren et. al. [3]; essentially, RMT are characterized by a design approach focused on:

- rapid change in machine structure, hardware and software components,
- functionality to produce new parts of the same family,
- production capacity to match the market demand,

in order to achieve modularity, integrability, customized flexibility, scalability, convertibility, and diagnosticability [4, 5]. Since then, three typologies of RMT have been proposed:

- Modular machine tools RMT: they are based on a modular design of the elements contained within the machine tool, providing in this way the reconfigurability by changing the modules. Notwithstanding the modular design, work and time to update configuration are required;
- Multi-tool RMT: customized flexibility for a particular parts family is obtained by using a multi-spindles design, conceptually comparable to the multi-spindle gang drill;
- Arch-type RMT: this machine tool typology focuses on machining inclined surfaces providing by the arch geometry the possibility to cut with the tools, e.g. twist drill bits, milling tools, perpendicular to the surface.

The arrangement of several RMTs with a material handling system, such as conveyors, gantries modules, reconfigurable inspection modules, provides the elements to build a RMS.

Lego-like reconfigurability extends the paradigm characterizing RMT and RMS; specifically, Lego-like reconfigurability originates from basic considerations on the elements that are present in every machine tool:

- a device that supplies energy, by virtue of which a relative coupled motion is obtained between the tool used to provide the process and the workpiece;
- a device for fixing and orientating the workpiece;
- a device for conveniently fixing and orientating a tool;
- a device for controlling the three above mentioned elements;
- a device for operating the tool according to the used transformation process.

These elements permit to execute a relative coupled motion between the workpiece and the tool according to the employed process and the transformation required by the manufacturing cycle. Accordingly, whenever a kinematic architecture could provide a modular and scalable structure to dynamically host and integrate different processing technologies, a new class of dynamically reconfigurable machine tools can be conceived.

The relative coupled motion between the workpiece and the tool is often obtained by using at least one linear motion axis; the most used linear axes in machine tools belongs to two typologies: (i) the trapezoidal leadscrew coupled with a sleeve, and (ii) the ball and nut screw assembly. The former typology provides better properties when considering transmissible power, static and dynamic stiffness; the latter provides better characteristics considering friction and backlash.

Nevertheless, leadscrew axes require a holding structure able to support the screw; in fact, the screw shaft needs bearing blocks that set the maximum sleeve or nut motion range. This solution is affected by the constraint represented by the necessity of having maneuvering screws of different length in function of the useful travel that it is desired to give the machine. This feature limits the axis excursion that must be preset during the design phase: if the travel of the linear axis is increased, the leadscrew system requires at least the substitution of the screw shaft with another of greater length.

This geometrical constraint could be removed by topologically exchanging the role between the screw and the sleeve: specifically, instead of giving the sleeve the function of converting the screw rotation into a linear movement, this function could be assigned to the leadscrew [6]. This solution requires to transform the sleeve into a leadscrew rack, integral with the bed structure of the machine tool. The rack extends on the machine tool bed along the full length of the linear axis;

rack's shape is a helical circular toothed sector that engages with a rotating screw hosted on a movable cross-table (Fig. 3).

Whenever the longitudinal extension of the bed structure along the linear axis direction is an integer multiple of the teeth pitch of the leadscrew racks, two or more bed structures can be joined by means of coupling elements; in this way, the axis length of the machine tool can be extended in a Lego-like fashion (Fig. 4). The same kinematic rack-screw solution can be duplicated on the bed structure in order to host on the modular bed structures more cross-tables that can move independently on parallel racks lines (Fig. 5). On the movable cross-tables, various devices to fix, move or rotate the workpieces as well as the tools can be hosted; each cross-table contains the device (motor) to rotate the screws engaged with the leadscrew racks providing in this way the motion along the bed structures.

a)

b)

c)

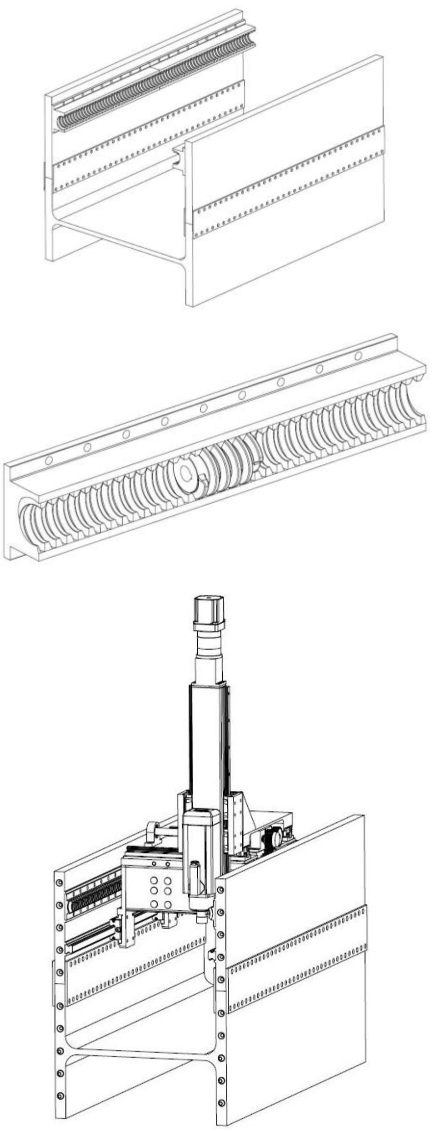

Fig. 3. a) Modular bed structure with two racks; b) screw-rack geometry; c) bed structure hosting one moving cross-table

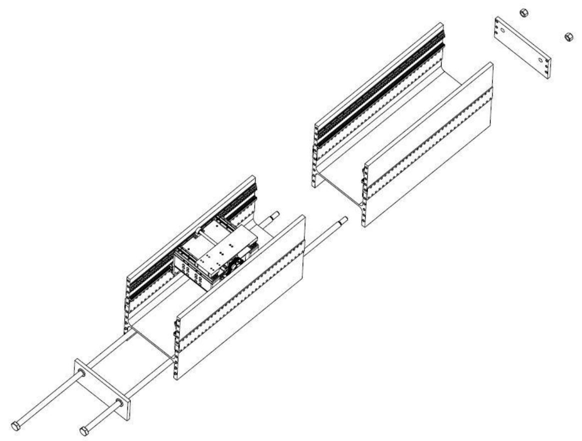

Fig. 4. Two Lego-like joined bed structure hosting one movable cross-table

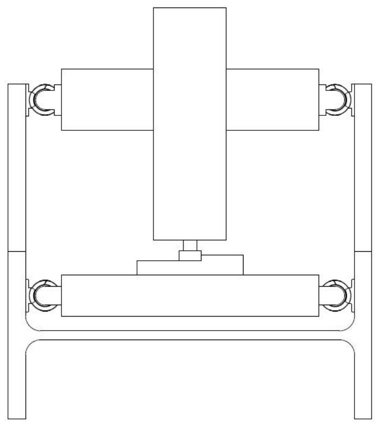

Fig. 5. Bed structure with two movable cross-tables: top milling spindle; bottom workpiece holder

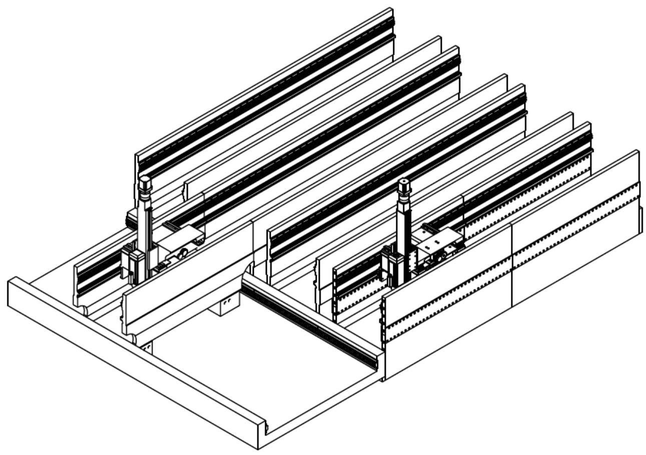

Fig. 6. Reconfigurable machining system with four lines, one distribution structure

Fig. 3 c) shows an example of cross-table equipped with a milling spindle: the cross-table provides two others motorized perpendicular axes permitting in this way to operate the bed structure and the cross-table as a 3D milling machine tool.

Thanks to the proposed kinematic architecture this modular system enables the integration of different processing and/or measuring technologies; actually, the addition or removal of a movable cross-table containing the devices to support a specific technology, can be performed by engaging/dis-engaging the table’s screws with the leadscrews racks; a direct, immediate reconfiguration of the machining system is therefore possible.

Furthermore, cross-tables distribution structures, such as the one represented in Fig. 6, extend the operative capability of the reconfigurable machining center allowing more complex layouts, including network configurations, other than the linear ones.

IV. Discussion

The proposed RMS can provide several capabilities ranging from:

- the basic functionality of a conventional machining tool, whenever a single bed structure module and one moveable working cross-table is used as shown in Fig. 3 c), to
- a network of parallel processing, interconnected machining centers, possibly integrating different processing and measuring technologies, able to operate concurrently and/or sequentially on the workpieces fed in the system.

The simplest configurations can be controlled by using the instruments already available to automate and govern the conventional CNC machine tools. As soon as the RMSs configuration become more complex, the available scheduling tools, developed for the job shop or line manufacturing organizations, must be modified in order to take into account the dynamic characteristics of the proposed Lego-like RMS, namely the possibility of instantaneously adding or removing another moveable cross-table with processing or workpiece holding capability. In fact, the Lego-like RMS management problem should be faced by at least two control layers:

- at the low level, the automation should be distributed in order to control the single moveable cross-table according to the executed function: this automation level addresses the basic functions required by the processing technology and permits to realize the relative coupled motion between the workpiece and the processing/measuring device;
- at the higher level, the control should be centralized in order to optimize the system performance according to the required manufacturing capacity, set by the market, and the management’s objectives, such as cost, led time etc. The high-level control should take into account the actual status of the networked elements, workpieces holding and processing cross-tables, inside the RMS, the technologies required by the manufacturing cycle for each processed workpiece, to dynamically satisfy the production program.

While low level automation can rely on the established control architecture used for the conventional CNC machine tools, the high-level control cannot use the job scheduling techniques developed till now for the existing industries, with job-shop, FMS or line manufacturing organization. The Lego-like RMS possibility of immediate reconfiguration through the addition or removal of processing components, i.e. capacity modification, requires indeed a new control approach.

In order to face the increased control complexity a new manufacturing model is required: the control should shift its focus from a fixed capacity layout to a variable capacity system. One possible solution could start from the Manufacturing Bill Of Material (MBOM) and the jobs route.

According to this model each processing step operates on one or more workpieces by a technological transformation to produce the required characteristics in the outputted workpieces. Formally a processing operation $o \in O$, that operates on one input workpiece $w \in W$ to obtain one output workpiece $w' \in W$ by using a technology $t \in T$, is described by the function

$$o: WxT \rightarrow W$$

where O, W and T, are respectively the sets of the operations, workpieces and technologies.

It should be observed that the number of input and output workpieces may vary according to the specific technological transformation. Table 1 reports a classification of the main technologies with their role, the number of input and output workpieces, and the processing function typologies.

Through a sequence of operations $os \in S$, performed on the workpieces (commodities), by using the technologies specified by the jobs route, the production $p \in P$, is carried out, and the finished good $w \in W$ is obtained; formally,

$$os = O_{i_1} x\, O_{i_2} x\, O_{i_3} x \ldots x\, O_{i_n} \qquad \text{sequence of operations}$$

$$p: W^m x\, S \rightarrow W \qquad \text{production}$$

Fig. 7 shows an example of production requiring a sequence of five processing operations: operations 1, 2 and 4 are shape modifications, operations 3 and 5 are assembly operations. The arrows indicate how the workpieces flow through the processing steps.

TABLE I. Technologies classification and functions

Technology class	***Technology role***	***Workpiece n.***		***Function***
		Input	***Output***	
Material removal	Shape modification: Turning, Milling, Gringing, Drilling, Etching, EDM, etc.	1	1	$o_1: WxT \rightarrow W$
	Workpiece parting: Turning, Sawing, etc.	1	> 1	$o_2: WxT \rightarrow W^n$
Joining	Welding, Bonding, Assembly, etc.	> 1	1	$o_3: W^n xT \rightarrow W$
Adding	FDM, SLS, etc.	0	1	$o_4: T \rightarrow W$
Moving	Deep drawing, etc.	1	≥1	$o_1: WxT \rightarrow W$ $o_2: WxT \rightarrow W^n$

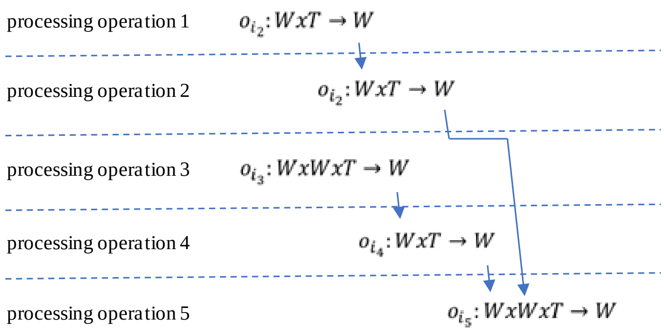

Fig. 7. Production through five processing operations: three shape modification and two assembly operations

A precedence constraint requires the availability of the workpieces processed by operations 2 and 4 in order to perform the last processing operation 5. The two processing sequences (o_{i_1}, o_{i_2}) and (o_{i_3}, o_{i_4}) can be performed in parallel.

For a conventional manufacturing system with preset machining tools capability, the job scheduling can be determined by using numerous decision supporting tools, such as integer programming. Whenever the machining tools capability can be changed instantaneously, as in the proposed Lego-like reconfigurable machining systems, the optimization task becomes more complex, since the number of moveable working cross-tables may vary dynamically on the basis of the total required capacity and their availability within the machining system. Consequently, the cognitive effort to face the dynamic scheduling problem becomes a challenge for the decision maker operating the reconfigurable system.

Several approaches for the high-level control of the Lego-like RMS could be proposed; the approaches can be classified into two categories based on:

- the conventional supply chain management, where only materials and commodities move along a network of manufacturing companies, or
- an innovative supply chain implementation where not only the materials and commodities (workpieces) flow along a network, but also the manufacturing capacity, i.e. the moveable working cross-tables necessary to perform the required transformations, moves concurrently with the workpieces. This approach would require the definition of kits, essentially sets (*W*, *T*) of workpieces and the technologies providing the necessary capacity to perform the operations according to the jobs route.

Considering the first approach, where the manufacturing capacity, i.e. moveable working cross-tables, is owned by the manufacturing company, the scheduling could rely on models with a power adequate to describe a morphing system; tools with adequate descriptive power, such as the two-levels Van Wijngaarden grammar [7], the Hierarchical Finite State Automata [8], or the Multi Agents Systems [9] should be investigated to verify their suitability.

The innovative supply chain approach requires the standardization of the bed modular structures and track leadscrews in order to easily reconfigure the system by replacing the kits each time that the products demand, the market strategy, or the technology have to be changed. Due to the easy of reconfiguration without requiring the intervention of specialist labour or complex tools, Lego-like RMS enables a new paradigm for a supply chain and capacity sharing.

V. Conclusion

Economic welfare and technology progress are strongly related: technology is one of the primary cause of the expansion of the production possibilities frontier, and manufacturing plays a central role in western world. Advances in manufacturing need disruptive innovations in the machine tools and equipment industry; in the next decades there will be probably some fundamental changes in manufacturing technologies, machine tools structures (modular structure), intelligent components (controllers, hardware and software, splindles, tooling), materials and interaction capability that will modify the existing business models [10].

In this paper, a new paradigm in reconfigurable machining center has been examined: the proposed Lego-like RMS enables the design of scalable manufacturing systems whose production capacity can be dynamically adapted. Important advantages of the proposed RMS are improved convertibility and rapid scalability to the desired production capacity as per the market demand; furthermore the proposed architecture provides a cost efficient way to change and integrate different processing technologies. The possibilities offered by the Lego-like reconfigurable machining system enable new manufacturing organization schemes, with a great impact on the manufacturing business, comparable to the role played by the temp agency model that nowadays permits an efficient matching of workers with jobs.

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