Architectural Holarchy of the Next Generation Manufacturing System

Gabriel Frumuşanu and Alexandru Epureanu

***Abstract*—Nowadays, the global energy network can generate and transmit, between any two points belonging to it, high quantity of energy. During recent years, a global information network, able to process, store, and transmit huge amounts of information, has been developed as well. These networks entirely cover the industrial space, already giving the opportunity to make permanently available, in any of its points, at any time, as much as needed, both energy and information. On the other hand, the mass customization trend has led to the pronounced increase of "manufacturing to order" (MTO) production, taking place in a higher and higher number of small & medium enterprises. At this level, a given manufacturing system cannot be quickly and appropriately configured to a given product, due to production high variability in range. As consequence, the manufacturing system is, quite always, more or less unadjusted to the manufactured product, its performance being significantly affected. Starting from here, the challenge is to make a conceptual rebuilding of the manufacturing system, aiming to increase its degree of appropriateness to products, by taking advantage from the opportunities brought by the existence of global energy & information networks. This paper approach is to see the next generation manufacturing system as holonic modular cyber-physical system. System architecture permanently accords to the manufactured product requirements. The function, procedure, topology and holarchy model of the system are presented. The main features of the system are also revealed.**

***Index Terms*—Manufacturing system, manufacturing holon, architectural topology, architectural holarchy, modular cyber-physical system.**

I. INTRODUCTION

In general approach, the supply chain means a system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities involve the transformation of natural resources, raw materials, and components into a finished product that is delivered to the end customer [1]. One of the most important activities in products supply chain is manufacturing, because it has a decisive impact onto entire supply chain performance. Manufacturing has various definitions. According to [2], manufacturing is the production of goods through the use of labor, machines, tools, and chemical or biological processing or formulation. At the same time manufacturing can be defined as the making of products from raw materials using various processes, equipment, operations and manpower according to a detailed plan [3].

In broad sense, the manufacturing system may be defined as an ensemble of facilities and assets, selected such as they are appropriate for supporting the manufacturing activity. More specific, the manufacturing system consists in a combination of manufacturing equipment and humans bound by a common material and information flow, Fig. 1. Design and manufacturing interfaces should also be considered, since manufacturing always begins with a design such a drawing, sketch, CAD file or any other way of communicating the features and characteristics of the product that is to be manufactured [4].

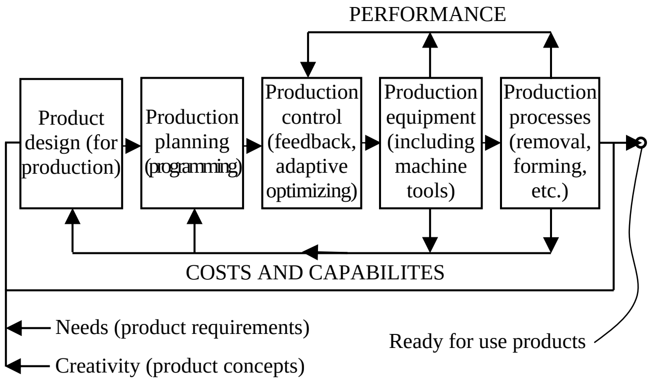

Fig. 1. The manufacturing system [4].

In economic approach, the manufacturing system is seen as a system in which raw materials are processed from one form into another, known as a product, gaining a higher or added value in the process and thus creating wealth in the form of a profit, [3]. This is illustrated in Fig. 2.

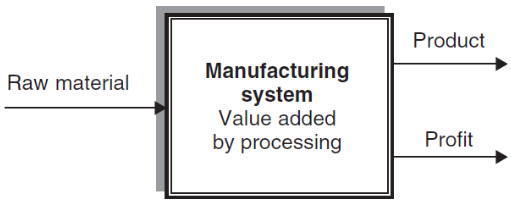

Fig. 2. Basic model of manufacturing system adding value [3].

Four distinct strategies within manufacturing can be revealed [3]:

- Make to stock (MTS) strategy, when product-focused manufacturing systems produce large quantities of few standard products, for which there is a predictable demand pattern,
- Assemble to order (ATO) strategy, when producing products with many options from relatively few major sub-assemblies and parts after having received customer orders. This entails manufacturing the above sub-assemblies and parts and holding them in stock until a

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customer order arrives. The specific product that customer requires is then assembled from appropriate sub-assemblies and parts,

- Make to order (MTO) strategy, when product manufacture follows customer specifications. Manufacture does not commence until the customer order is received.
- Engineer to order (ETO) strategy, which is an extension of MTO strategy, with the engineering design of the product based on the customer specifications.

In what concerns the global manufacturing trends, product complexity and variety continue to increase, product life-cycle are becoming shorter, markets have become multinational and global competition has been increasing rapidly, market conditions fluctuate widely and customers are consistently demanding high-quality, low-cost products and on-time delivery [5].

Under these circumstances, during recent years, a new marketing and manufacturing technique that combines the flexibility and personalization of custom-made products with the low unit costs associated with mass production occurred, namely mass customization [6]. Mass customization is directly related to MTO/ETO manufacturing strategies.

In principle, the choice between the main strategies, MTS and MTO, is decisively influenced by the frequency of changing the product, which involves modifications of the manufacturing system. From this point of view, MTS strategy has the advantage of enabling a very good fitting of the manufacturing system to the product, while in MTO strategy it is much more difficult to obtain this fitting, this leading to a performance loss. To be more specific, we should notice that the product change has certain (significant) costs, because it requires to change both the process (hence the process planning, which is not necessarily complicated), and the manufacturing system. The accordance of the manufacturing system to new products may be a difficult task, especially when is needed to be performed frequently.

During recent years, manufacturing into MTO strategy is more and more important due to increasing request for customized products, personalized solutions, turnkey solutions, and integrated solutions, which call for such a strategy. This led to the need of increasing the efficiency in adapting the manufacturing system to product change. The answer to this need is the development of modular-type manufacturing systems: the flexible manufacturing system (FMS) and the reconfigurable manufacturing system (RMS).

A flexible manufacturing system (FMS) is a manufacturing system in which there is some amount of flexibility that allows the system to react in case of changes, whether predicted or unpredicted [7]-[9]. This flexibility is generally considered to fall into two categories, which both contain numerous subcategories [10]-[12]. The first category is referred as *Routing flexibility*, which covers the system's ability to be changed to produce new product types, and ability to change the order of operations executed on a part [13], [14]. The second category is called *Machine flexibility*, which consists of the ability to use multiple machines to perform the same operation on a part, as well as the system's ability to absorb large-scale changes, such as in volume, capacity, or capability. Most FMS consist of three main systems: 1) *Work machines*, which are often automated CNC machines, connected by 2) *Material handling system*, to optimize parts flow, and 3) *Central control computer*, which controls material movements and machine flow. The main advantages of an FMS [7], [15] is its high flexibility in managing manufacturing resources like time and effort in order to manufacture a new product. Among FMS drawbacks, they should be noticed the high initial set-up cost, the substantial pre-planning, the requirement of skilled labour, and the complicated maintenance.

The reconfigurable manufacturing system (RMS) is designed for rapid change in structure, as well as in hardware and software components, in order to quickly adjust its production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements [16-20]. The RMS possesses six core characteristics: scalability (design for capacity changes), convertibility (design for functionality changes), diagnosability (design for easy diagnostics), customization (flexibility limited to part family), modularity (modular components), and integrability (interfaces for rapid integration) [16].

Despite bringing manufacturing in MTO strategy closer to manufacturing in MTS strategy from the point of view concerning the manufacturing system accordance to product, both FMS and RMS still show limitations in this matter:

- The modules composing FMS and RMS are each specific to a given operation / part-type, hence they are actually used only for limited time intervals (20 – 30% of system working time),

- The FMS / RMS adequation to a given product is often hard to be accomplished due to insufficient information concerning its previous cases of manufacturing, there is not enough experience accumulated.

So, there still remain a notable challenge: a more efficient adaptation of the manufacturing system when changing the product while working in MTO strategy of manufacturing. This paper aims to present a conceptual rebuilding of the manufacturing system, aiming to increase its degree of appropriateness to products, by taking advantage from the opportunities brought by the existence of global energy & information networks. This paper approach is to see the manufacturing system as holonic modular cyber-physical system, composed by modules of *general manufacturing use*, whilst system architecture changes according to the manufactured product requirements.

Next section introduces the manufacturing function, procedure and environment, according to this paper approach. The third section deals with the proposed model of architectural holarchy for the next generation manufacturing system. The fourth section presents the system operation, while the last section is for conclusion.

II. Functions, Procedure and Environment

This paper further actually proposes a *conceptual* architectural model of next generation manufacturing system. By *architectural model* of a certain system, we understand here the picture of system constitutive elements together with the functional relations among them. In manufacturing system case, the architectural model will be introduced as *topology* of system elements – further referred as *holons* – together with the diagram of the relations established among them during system operation.

A. System Function

Manufacturing means obtaining products by actions of transforming some raw materials. The transforming actions lay on natural phenomena (physical, chemical or biological), artificially provoked. Each such action requires both energy (in order to enable the transformation to take place) and information (in order to control the transformation such as the resulted product has the followed parameters). Both energy and information must have given forms and appropriate values of their features.

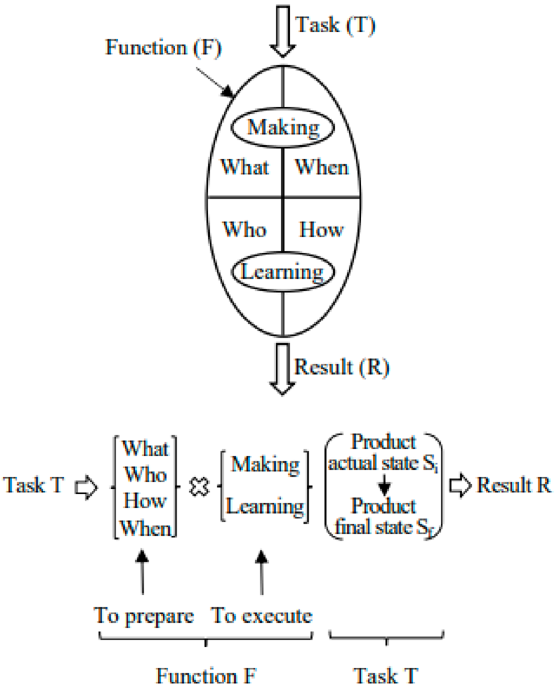

Fig. 3. Manufacturing system function.

Manufacturing system function *F* associates to a given task *T*, seen as argument, an expected result *R*, seen as function output, $F(T) = R$ (Fig. 3). The task is to change product initial state S_i into product final state S_f, through a manufacturing process. The product in its final state is the result. Function execution involves two component activities, taking place concomitantly: *making* and *learning*. Making refers to actually transforming the product, while learning – to ascertaining the transformation results. Before execution, four issues must be established, namely: *what*, which refers to the task definition, *who* – to the assets needed for task accomplishment (humans included), *how* – to the procedure following to be applied, and *when* – to the precedence conditions.

B. System Procedure

Firstly, it should be noticed that the product suffers successive state changes, starting from the initial, order-description state, until it reaches its final state, namely the real-object state (Fig. 4). The chain of product state changes derives from the manufacturing process chain of stages: design – planning – processing. The mentioned stages are accomplished by personnel from dedicated categories (product designer, process planner and machine operator, respectively), working on workstations that can be grouped in clusters specific to each stage.

C. System Environment

Manufacturing takes place in a specific environment (Fig. 5). In our vision, manufacturing environment should be comprised as the totality of the assets needed for obtain the product, disposed inside an organizationally structured space. This environment is surrounded by physical space, cyber space, social environment, and commercial environment. All the assets needed in order to carry out the manufacturing process are coming from these spaces and environments.

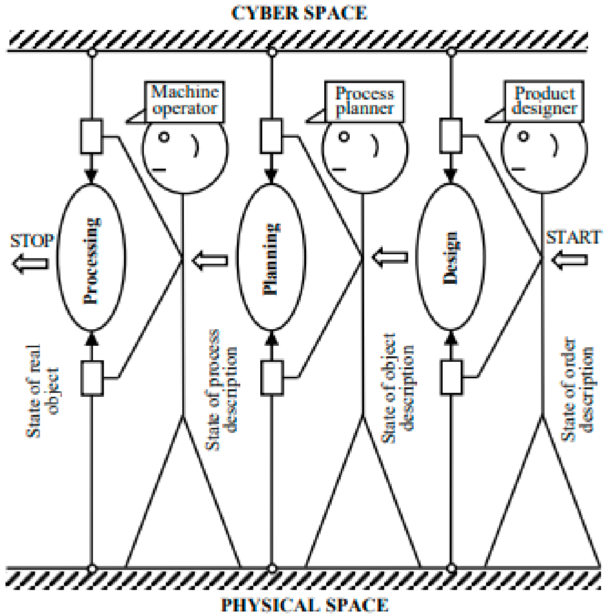

Fig. 4. Manufacturing procedure.

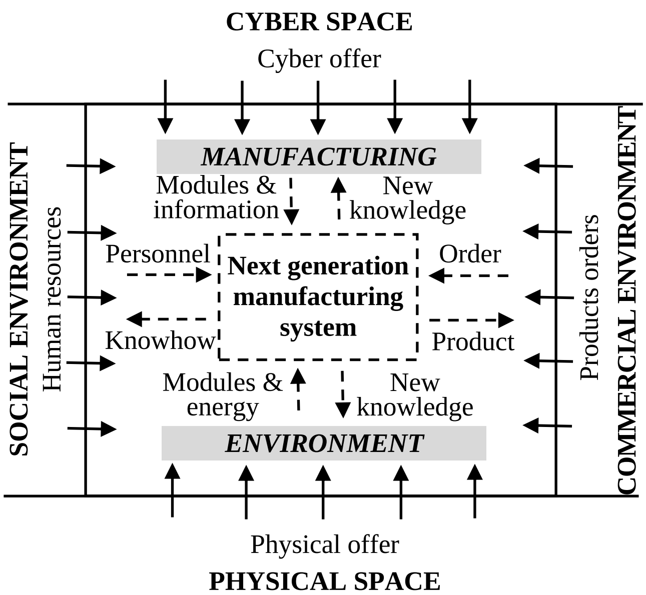

Fig. 5. Manufacturing environment.

The *commercial environment* is the source of products demands, through orders coming from the market. *Product* means, generally speaking, a commercial object, defined by attributes of utility, currently described through an order. In our approach the manufacturing system should be configured according to manufactured product requirements.

In the *physical space* we find the global energy network, which can generate and transmit, between any two points belonging to it, high quantities of energy, but also a wide range of manufacturing modules, able to convert this energy to required form & features values. Hence, energy is bought and manufacturing modules are hired from here to compose and run the manufacturing system.

In the *cyber space* there is the global information network, able to process, store, and transmit huge amounts of information of any kind. Similar to energy, the information, which is taken from the global network, also requires to be converted by dedicated modules, in order to become usable by the manufacturing system. Hereby, the cyber space provides the information needed to control the manufacturing system.

The *social environment* is approached as a pool of human resources, having diverse skills and qualifications, and which potentially could be needed as personnel to serve the manufacturing system.

Before starting to manufacture a certain product, the manufacturing environment is an empty space. Dedicated assets, specific to the product, are then selected and temporarily brought in this space by hiring and put together as manufacturing system. After delivering the required quantity of products, the assets are returned and the manufacturing space rebecomes empty, until a new product will be manufactured.

A given manufacturing system is created by associating to a certain order a combination of issues coming from the physical space, the cyber space, and the social environment, comprised as available assets. Once again, the next generation manufacturing system must be understood as an occasional, temporary structure.

It should be noticed that the manufacturing system not only receives inputs from the surrounding spaces and environments, but also delivers, as result of its functioning, new knowledge (to both physical and cyber spaces), knowhow (to social environment) and, of course, products (to commercial environment).

III. Architectural Holarchy

A. Manufacturing Holon

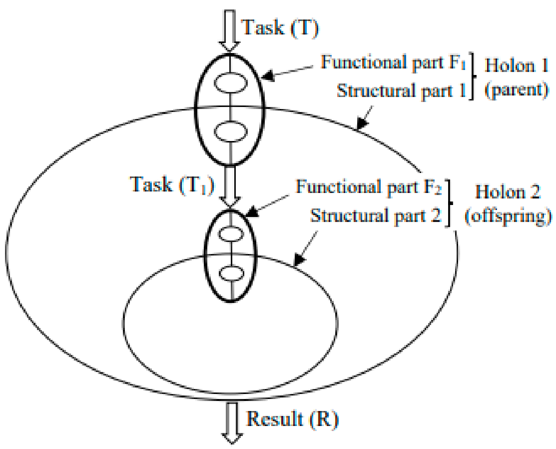

Fig. 6. Manufacturing holon.

Let us consider a generic manufacturing holon (Fig. 6), whose task T is to transform the product from an initial state S_i up to a final state S_f. This is accomplished in two stages. During first stage, the holon 1 configures the received task, which is transformed into the task T_0, following to be executed by itself, and the task T_1 that is released. The variables of the tasks resulted by configuring are different to the ones of T task. The released task further generates offspring holons, which remain inside holon 1 pocket. The execution of T_0 is accomplished by the functional part F_1 of the holon 1, while the rest of T task – by the offspring holons.

The task configuring process may successively repeat, while new generations of holons will be created until, at a given time, the initial task T is completely accomplished and the result R is delivered. For simplicity, in Fig. 6 we considered only a single offspring holon, 2, which receives from holon 1 the T_1 task.

So, we can state that the general manufacturing holon is composed by two parts: the *functional part*, accomplishing T_0 task, and the *structural part*, meaning all offspring holons, which simultaneously or successively execute the rest of T, until the result R is delivered.

B. Functional Dimension of the Architectural Holarchy

The manufacturing system function (see Fig. 3) retrieves to any holon from system structure. The function F is supported by a set of *work-modules*. Each of them means an ensemble of components of general use, able to support a *process function* f (of manufacturing use), comprised as causal relation relating a set of process variables.

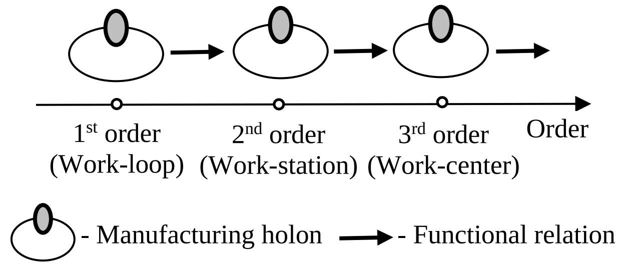

Fig. 7. Functional topology.

The *functional configuration* means to configure the manufacturing system function F, such as it can be supported by a certain set of manufacturing modules, having each a given function f. At first, the set of F_1, F_2, … functional parts, which describe F, result by its configuring. Then, manufacturing modules are selected in order to support the functional parts from above. Each such module supports its manufacturing function f_k.

On one hand, the complexity of holon function depends on the complexity of its task. On the other hand, holon function results by composing the component modules functions. The manufacturing holon complexity is reflected by its order, in connection with the number of functional parts resulted after its functional configuring. This further determines the number of f_k module manufacturing functions needed to be composed for describing these functional parts.

For sample, relation (1) corresponds to a first order holon, having a single functional part, supported by three modules. Relation (2) corresponds to a second order holon, with two functional parts supported by four modules, while (3) characterizes a third order holon, with three functional parts and five modules.

$$F = \{F_1\} = f_1 \circ f_2 \circ f_3 \tag{1}$$

$$F = \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = f_1 \circ f_2 \circ \begin{Bmatrix} f_3 \\ f_4 \end{Bmatrix} \tag{2}$$

$$F = \begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix} = f_1 \circ \begin{Bmatrix} f_2 \\ f_3 \circ \begin{Bmatrix} f_4 \\ f_5 \end{Bmatrix} \end{Bmatrix} \tag{3}$$

C. Structural Dimension of the Architectural Holarchy

The structural dimension reveals the content of the manufacturing holon structural part. This dimension results by configuring the task T, configuring that leads to T_0 task and a certain number of released tasks.

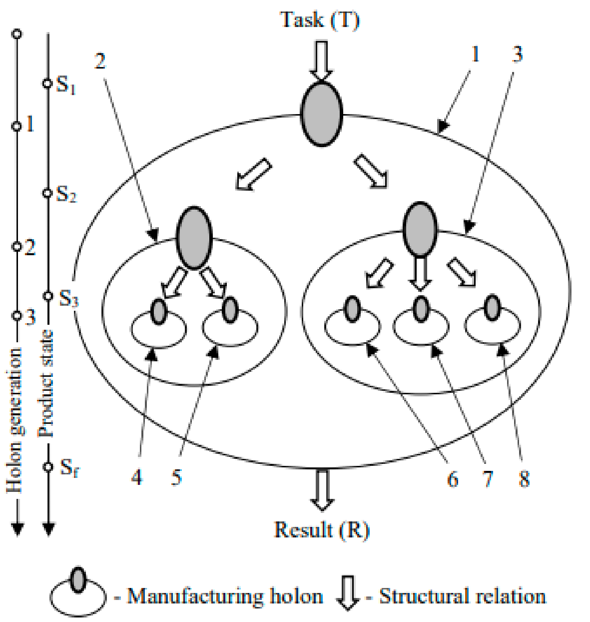

Fig. 8. Structural dimension.

The Fig. 8 illustrates the structural dimension. The task T is communicated to Holon 1, of first generation, product state being S_1. Holon 1 configures T, as result, the product being brought in state S_2, while two new tasks issued after this are transmitted to Holons 2 and 3, from second generation. Each of these holons configures its received task, the product reaching the state S_3. Both Holons 2 and 3 generate further tasks for Holons 4 and 5, respective Holons 6, 7 and 8, all five from third generation. After the last generation of holons accomplish their task, product state becomes the final one, S_f, and the manufacturing process is ended.

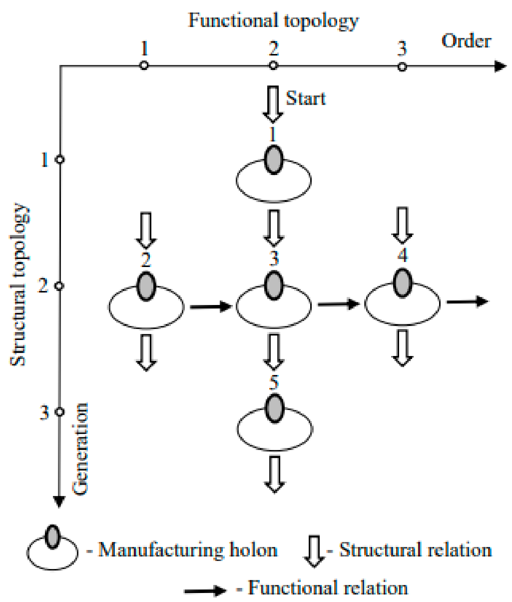

Fig. 9. The two dimensions of architectural holarchy.

D. Architectural Holarchy

The two dimensions of the architectural holarchy are presented in Fig. 9. Each architectural holon is intended to accomplish a manufacturing task, seen as manufacturing process component, and, at the same time, it must provide the tooling for this. As consequence, the manufacturing holons from all configuring levels, as well as the system in its wholeness, have dual character – hard (concerning the functional part) and soft (concerning the structural part). Starting from here, it should be noticed that between the manufacturing holons there is actually a crossed holarchy, involving both functional and structural relations.

IV. System Operation

Manufacturing system operation consists in the operation of the component holons. No matter of their position in the architectural holarchy of the system to which they belong, the manufacturing holon operation supposes to cyclically run manufacturing work-cycles by covering, for every such cycle, several successive steps (Fig. 10).

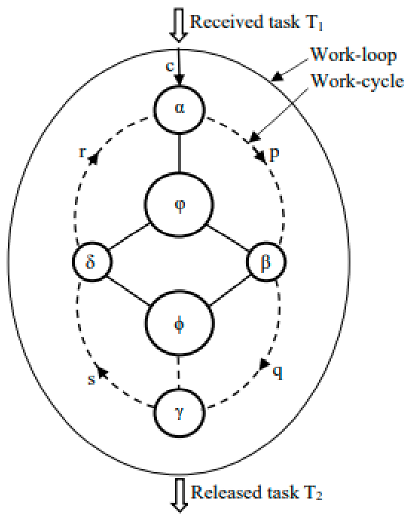

Fig. 10. Holon work-cycle.

The first step is *piloting*, which means to establish, depending on the results r of previous cycle, the task variables vector c for the current cycle. The piloting module, denoted by α, delivers the piloting variables through p vector.

The second step is *analysis* (for workstations from design and planning stages), respective *programming* (for workstations from processing stage). The dedicated module is β and the result of its operating is the setting vector, q.

The third step is *modelling* (for workstations from design stage), *simulation* (for workstations from planning stage), respective *processing* (for workstations from processing stage). The module in charge to perform this step is ϕ, with the help of module γ, which drives ϕ. The γ module receives the vector q from module β and provides the output vector, s. The γ module enables the communication with both physical space and commercial environment.

The fourth and last step is *synthesis* (for workstations from design and planning stages) respective *measuring* (for the workstations from processing stage). The specific module is δ and it delivers the results vector r, which, at its turn, is considered for the next, work-cycle.

The informational exchange between the modules α, β, γ and δ is controlled by the monitoring module, φ, which receives, respectively delivers the required information when this is needed.

V. Conclusion

This paper answers to the challenge of a more efficient adaptation of the manufacturing system when changing the product, when working in MTO strategy of manufacturing. In this purpose, the paper proposes a conceptual rebuilding of the manufacturing system, based on modularization and holonization of both manufacturing task and tooling of the system. The next generation manufacturing system, rebuilt, is modelled as architectural holarchy. If this model is implemented, then, during system operation, new generations of holons will be created by successively reconfiguring both manufacturing task and tooling, until the product reaches its final state. As consequence, an aggregation of task modules and tooling modules could be realized for reusing them in new forms of the manufacturing system, built on the base of the same concept, for realizing other products. This way, the manufacturing systems of all types will restructure by themselves and last as long as needed, and, at the same time, they will naturally accord to the demanded products at the highest possible degree of appropriateness. It should be noticed that, after manufacturing a given product, new task information occurs, because the entire manufacturing process is supposed to be monitored, evaluated and recorded. Hereby, one can speak about a heritage consisting in both new task information and newly aggregated modules, which represent the forms through which the system becomes increasingly adapted to the manufactured product.

Conflict of Interests

The authors declare no conflict of interests.

Authors Contribution

Alexandru Epureanu developed the paper main concepts, while Gabriel Frumuşanu did the rest of the work.

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