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TOWARDS GLOBAL DIGITAL MODELING OF MANUFACTURING

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Abstract: *Manufacturing performance is limited by the large variety of models that are used for information processing and by their continuous modification. Research opportunity is brought by manufacturing digitalization, enabling to capitalize on the capabilities of digital technologies, needed for mass personalization in the cloud technology era. Paper addresses the development of a new vision concerning manufacturing modeling, to increase is the manufacturing performance by implementing a global digital model, built on the basis of the manufacturing holonic digitalization. In this purpose, manufacturing is here modeled as decisional, instead of physical process, and as holarchy of decisions, instead of succession of actions. Moreover, the manufacturing model is formalized as open data and not as a data processing algorithm.*

Key words: *Manufacturing control, Global modelling, Decision making, Holistic monitoring, Comparative assessment.*

1. INTRODUCTION

As the human needs for goods have diversified in time, together to the modalities available for create these goods, the word *manufacturing* has also taken a more and more comprehensive meaning and the manufacturing modeling techniques comply with this understanding.

Manufacturing is defined as the process of turning raw materials or parts into finished goods using tools, human labor, machinery, and chemical processing [1].

Manufacturing is the creation or production of goods with the help of equipment, labor, machines, tools, and chemical or biological processing or formulation. It is the essence of secondary sector of the economy. The term may refer to a range of human activity, from handicraft to high-tech, but it is most commonly applied to industrial design, in which raw materials from the primary sector are transformed into finished goods on a large scale [1].

Manufacturing may be seen as a physical process based on product transforming through natural phenomena (physical, chemical, or biological), artificially provoked [2].

A large variety of *natural phenomena*, known and modeled in the fundamental sciences (e.g., Physics, Chemistry, Biology, Economy science, Ecology) are artificially activated and represent the basis of *industrial processes*. This is why the industrial processes, in general, are much more complex than the underlying natural phenomena. Moreover, manufacturing means a set of different industrial processes, which must be correlated in order to enable the obtaining of the needed product. This correlation makes the manufacturing to be even more complex. For these reasons, manufacturing modeling by composing basic models of the natural phenomena, delivered by the fundamental sciences, is very rarely feasible.

In recent years, the needs in manufacturing modeling have been tried to be satisfied by developing other kinds of basic models, which, describe industrial processes, instead of the natural phenomena on which the processes are based, and then by composing some of these basic models. However, the obtained results are modest, while manufacturing modeling still remains difficult, because the basic models of industrial processes are excessively variated and complex and their support changes its behavior and, as consequence, the models built at a given time lose their validity. In other words, while the natural phenomena models are simple and perennial, the ones of the industrial processes are complex and have limited lifespan.

Starting from here, the challenge is the development of a new vision concerning manufacturing modeling, in order to reduce the variety and complexity of manufacturing models, as well as to make them permanent. In our vision, the solution for this challenge is the global digital modeling of manufacturing, newly developed and introduced in this paper. Next section presents a futuristic scenario, the third section deals with manufacturing modeling in the future, the fourth section includes a discussion about the impact of global digital modeling, while the last is for conclusion.

2. FUTURISTIC SCENARIO

Regarding the global manufacturing trends, during recent years products complexity and variety continue to increase, their life cycles are becoming shorter, markets have become multinational and global, competition having to be faced is fierce with every passing day, market conditions fluctuate widely, and customers are all demanding high-quality, low-cost products and on-time delivery [3].

Under these circumstances, 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 [4]. Mass customization is directly related to “make to order” (MTO) strategy when product manufacture follows customer specifications and manufacturing does not start until the receiving of customer order [5]. Related to this, the relevant features of manufacturing are: *i)* high variety of orders, *ii)* large diversity of manufactured products, generating a great number of manufacturing tasks, and *iii)* strict terms of delivery [6,7].

The great number of manufacturing tasks lead to making at least as many decisions concerning them. The frequent modifications occurring in the manufacturing environment state, as well as the perturbations generated by exogenous factors, determine very short decisional horizons (down to the level of a single task). There is a permanent need for quickly making many and diverse decisions, in a high number of decisional points. Therefore, a big decisional effort sustained by numerous and highly qualified personnel is needed.

Let us consider that in a manufacturing environment of the above-described type, a digital model is generated and incorporated into a new asset, generically entitled *Automatic Decision-Maker* (ADM). If so, each needed decision will be automatically made by entering to ADM input the manufacturing task to be accomplished, the ADM being expected to deliver the best decision. This action could be possibly followed by decision invalidation, in the case of an unexpected conflict, and by the automatic making of another, newly generated decision. Hereby, the decisional cycles afferent to the accomplishment of manufacturing tasks are automatized with ADM help, while the human effort remains to be dedicated only to invalidate decisions in the cases of conflicts generated by perturbations.

3. VISION INTO THE FUTURE

3.1 Defining of the Global Modelling

Here, manufacturing is seen as an activity, similar to those that take place in other fields. It is distinguished by the fact that the object of the activity is the obtaining of *industrial products*, and its subject is the *management and control* of this process, based on the *manufacturing model*.

The process is seen as successive changes in the *morphological form* of the product (Fig. 1) and/or in the *state* of the product. For a given morphological form, described by features, the state is described by variables that concern the physical state and also by the degree of compliance to the imposed conditionalities e.g., the accumulated expenses, timespan, carbon footprint, or product quality. A change in the product state is called *task*, its accomplishment representing a *manufacturing sequence*.

The difference between *global* and *conventional* modeling of manufacturing is made by the answers to the following questions.

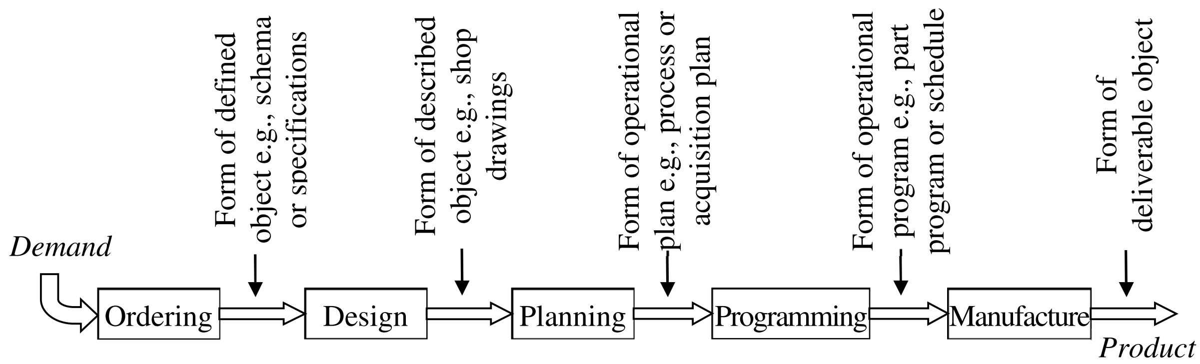

Fig.1. Typical morphological forms of the product along the manufacturing chain

A. *How does modeling cover the domain to be modeled?*

The domain to be modeled is the causal relationship between product and process, along the entire manufacturing chain, for a given product and a given manufacturing environment.

Conventionally, this domain is covered by dividing it into several successive processes, after that each such process being independently modeled.Global modeling involves a unique model for all tasks.

B. *How is manufacturing approached to be modeled?*

One may notice that the manufacturing process actually has a dual character. On one side, there is a physical process, through which product state changes, on the other side we have a decisional process, according to which the physical process takes place. Unlike the current approach of manufacturing as a physical process, we here propose to see it as an ensemble of two intercorrelated processes (decisional and physical processes), simultaneously deployed. For a better understanding, let us take a look at the manufacturing diagram, corresponding to the accomplishment of a generic manufacturing task T_1, as depicted in Fig. 2. The horizontal axis is associated with decisional process evolution, while the vertical axis shows the physical process ongoing. At the beginning, there is the task T_1 having to be accomplished, the product being in PS_1 state.

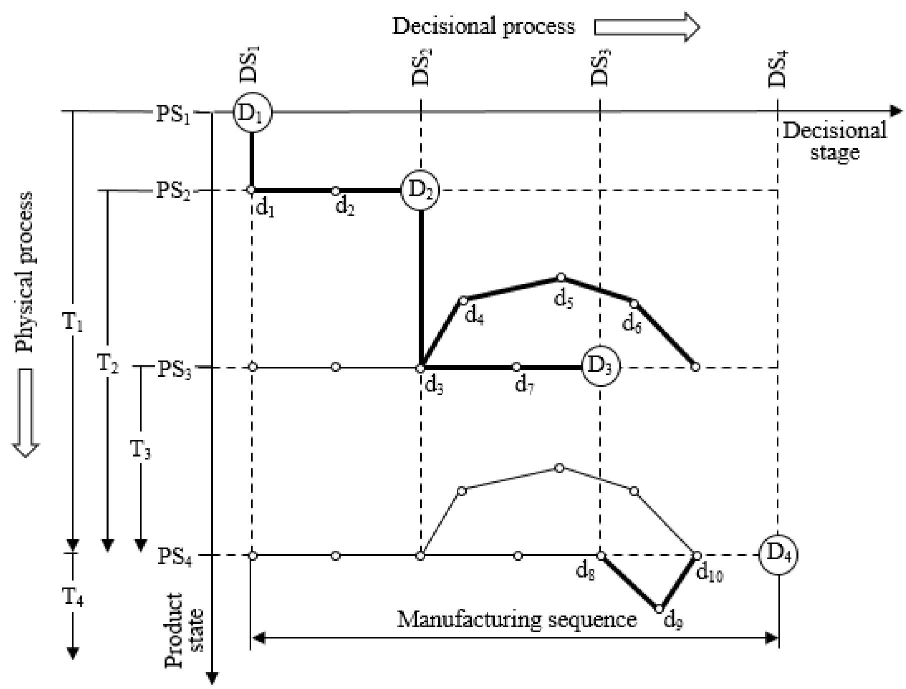

Fig. 2. Manufacturing diagram in global modeling

At this moment, in the DS_1 decisional stage, all the decisions needed to bring the product to the final state (here, PS_4) are made, no matter if they are structural decisions (issued from D_i decision-cycles) or functional decisions (issued from d_j decision-cycles).

After executing the process sequence under the incidence of d_1 and d_2 decision-cycles, the product reaches PS_2 state, when a new decisional stage DS_2 was planned. Because it is quite sure that the product real state, which is found at this moment, differs from the planned one (because of the inherent perturbations of any kind), the continuation of T_1 task accomplishment is replaced by the accomplishment of the T_2 task, meaning the bringing of the product from current state PS_2 to final state PS_4, and a new set of decision-cycles D_i and d_j is generated.

After executing the process sequence under the incidence of d_3 … d_7 decision-cycles, the product reaches PS_3 state, when the decisional stage DS_3 was planned. The things repeat in the same manner until the product reaches PS_4 state, and in the DS_4 decisional stage this state is evaluated and the T_4 task is released towards somewhere else.

Conventionally, the manufacturing is approached as a *multiple physical process* and is only *functionally* modeled. Such a process consists of natural phenomena, taking place simultaneously or in correlation. Model variables are those that describe the natural phenomena that make up the physical process.

Global modeling approaches the manufacturing as a *structured decisional process* and models it both *structurally* and *functionally* by equation (1) describing each decision-cycle,

$$F(Task, Decision, Result) = 0. \qquad (1)$$

A decisional cycle means covering the two steps from below.

1. <u>The decision-making step</u> consists in the processing of the values of certain manufacturing variables that define the *hypothesis*, to obtain the values of other manufacturing variables, meaning the *conclusion*, which is relevant because if the conclusion were to materialize, then the hypothesis would be confirmed. Currently, the hypothesis is described by *Task* vector, T, variables, while the conclusion – by *Decision* vector, D, variables.

2. <u>The decision-implementation step</u> consists in the materialization of the decision variables values, in the form of a minor intervention in the manufacturing environment, whose effect is a major evolution, called outcome, as well as in monitoring the *actual* values of the variables composing T and D, which are the *Result* vector, R, variables.

The following actions must be deployed during the first step:

- Identification and evaluation of the potential sequences to go further from the current state, considered as starting point, and
- Making a decision regarding the way to follow in order to accomplish the hypothesis-task. The decision means a set of solutions of equation (1), which have to answer the questions from Table 1, and it may contain structural decisions, released by structural decision-cycles D_i, and functional decisions, released by functional decision-cycles d_j.

The *structural decision* consists in replacing the hypothesis-task by some conclusion-tasks, such as their accomplishment is equivalent to hypothesis-task accomplishment. The structural decision can be seen as a structural solution of equation (1) that means its transformation into an equivalent system of equations of the same type. The structural decision related to a manufacturing sequence is formalized as a holarchy of decisional cycles, where the belonging relation is the relation between the decision afferent to conclusion-task and the one afferent to hypothesis-task (Fig. 3).

Table 1

Decision content.

Decision	Question	Action
Structural decision	***Which*** *is the target?*	*Piloting*
	When *will the target be reached?*	*Scheduling*
	Which *is the level of performance?*	*Optimization*
Functional decision	***Who*** *reaches the target?*	*Tooling*
	How *will the target be hunted?*	*Setting*
	Which *is the level of performance?*	*Optimization*

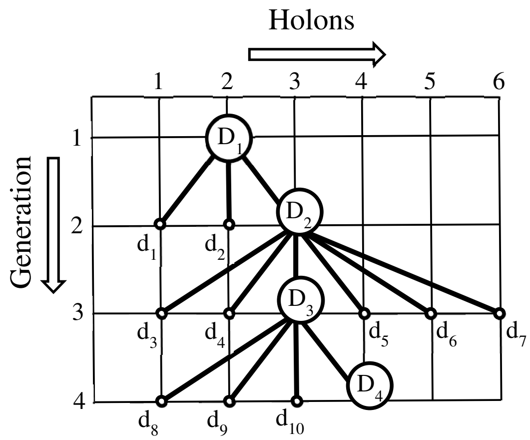

Fig. 3. Holarchy of decision-cycles representing a structural decision

Here the line between two decisional cycles represents a task, which is both conclusion (for the upper cycle) and hypothesis (for the lower cycle).

In the beginning, the holon 2, from the first generation, performs the D_1 decision-cycle, releasing all the decisions needed to bring the product to the final state, and the holons 1 and 2 implement the decisions resulting from d_1 and d_2 decision-cycles. Then, at the level of the second generation, the holon 3 evaluates the actual situation, performs the D_2 decision-cycle, and the holons 1, 2, 4, 5 and 6 implement the decisions resulting from d_3 … d_7 decision-cycles. After that, at the level of third generation, the holon 3 evaluates the current situation and performs another decision-cycle, D_3, while the holons 1, 2 and 3 implement the decisions resulting from d_8, d_9 and d_{10} decision-cycles. Finally, the concluding D_4 decision-cycle is performed by holon 4.

The *functional decision* consists in executing the hypothesis-task and represents a functional solution of equation (1), which is formalized as a set of values of the variables describing the tooling, setting and performance.

For a manufacturing sequence, the functional decision consists of the functional solutions of equations (1), related to all decision cycles d_j.

C. *How are the causal relationships among model variables modeled?*

Let us consider the modeling of a generic manufacturing sequence (Fig. 4).

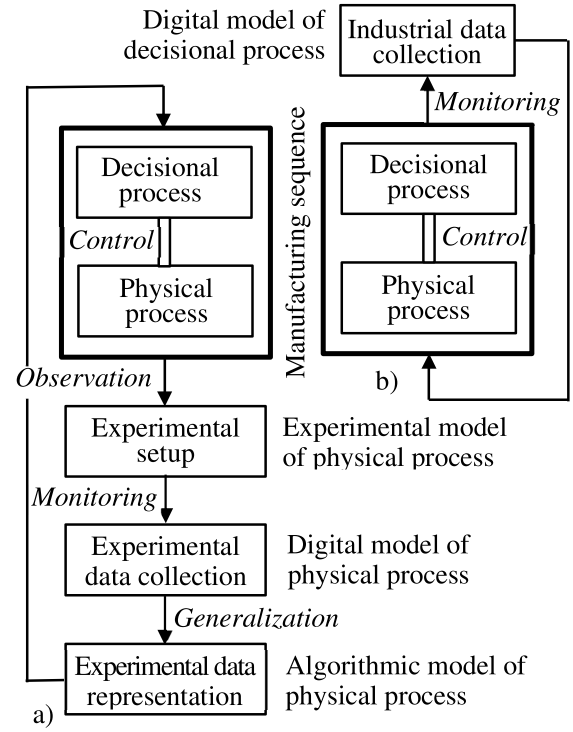

Fig. 4. Causal relationship modeling:
a) Algorithmic modeling of experimental physical process (conventional approach); b) Digital modeling of industrial decisional process (proposed approach).

The sequence includes a decisional and a physical process, leading to a certain task accomplishment.

Conventionally, an experimental setup is firstly built, meaning the *experimental* model of the physical process or of the industrial process. An experimental instances database, representing the process digital model, is then obtained by monitoring the experimental setup. The algorithmic model of the process is finally generated on the basis of collected data.

Global modeling means that the digital model results by monitoring the industrial decisional process and consists in an *industrial* instances database. This model actually means a digital model of the decisional process, which is directly used to support current decision-cycles.

3.2 Design of the Model

The global model building means to create the manufacturing facilities from below.

- The *Holistic Monitoring System*, which is a monitoring system able to reveal and evaluate the manufacturing system state & dynamics [8]. The "holistic" attribute derives from two issues:

- The monitoring action concerns all the values of the variables composing *Task*, *Decision*, and *Result* vectors, these describing the system state, and
- The clusters formed by selecting from above-mentioned variables the ones that could be used for building the causal model of the system [9], may be found according to different *Result* variables.

• As it can be noticed from Fig. 2, 3 and 5, an information exchange must take place among the different decision-cycles. Thus, the sender decision that becomes the receiver task, is transmitted in one direction, while the result obtained after accomplishing the received task is transmitted in the opposite direction.

The *Global Communication Network* facility enables this exchange of information, its structure being illustrated by the ADM operation diagram in Fig. 3. It supports the information flow from below.

At first, there is the flow of structural decisions along the manufacturing path, from order input to deliverable output. Then we have the communication of information about the tasks between the different points where physical processes take place, in one direction, and the information about results, between the same points, in opposite direction. There is also an exchange of information regarding tasks, decisions and results between the decisional points of each decisional stage and the ADM operating the current manufacturing process. Finally, all information must be communicated to both human decision maker and ADM. The exchange of information among the different ADM-s operating in the cyber-space is also necessary.

• As already mentioned in the previous section, the ADM is an informatic tool, which at interrogation (made by the input of a given task) delivers the best response, meaning the ensemble of decisions required to completely accomplish the manufacturing task.

The *Comparative Assessment Algorithm* facility is needed by ADM to find this response by applying the comparative assessment technique [10]. It actually concerns the dialogue between the manufacturing area and the ADM and means, in principle, to compare the current task to similar, already accomplished tasks, with known decisions and results.

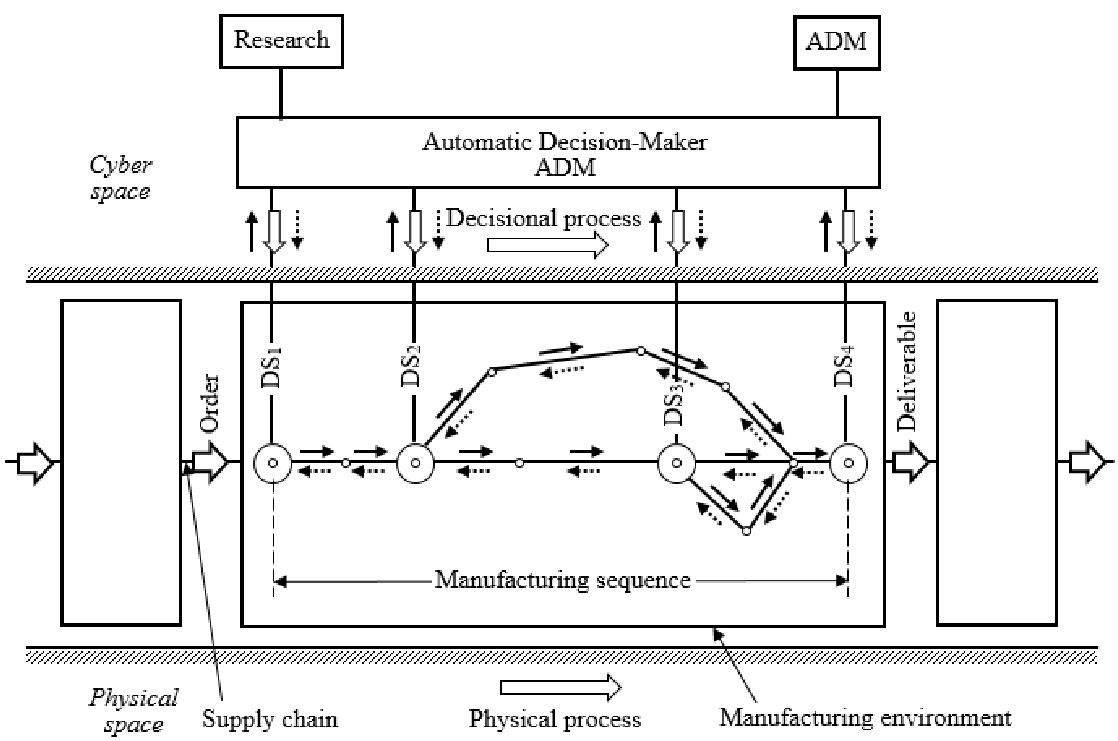

Fig. 5. ADM operation diagram

The relevance, coherence and comparability of the (1) equation represent the basis of the Comparative Assessment Algorithm, its superstructure being the Machine Learning Technique.

3.3 Applying of the Model

The typology of the global model application regards all the manufacturing stages: quotation, order acceptance, design, planning, programmig, and process control. A given global model is actually applied by constructing a corresponding ADM, which will further use it for operating at three levels: quotation, simulation [11], and decisional update The first issue concerns the capacity of giving rapid answers to potential orders from market, the second – the finding of hypothetical results for the manufacturing of a certain product, while the third – the needed adjustments of the decisions following to be applied, due to the perturbations that inherently affect the manufacturing environment.

The variables of the global model must meet an essential requirement, for making feasible the model application: the variability. More clearly, the value of such a variable should have a domain of variation, where it can be adjusted.

3.4 Risks Mitigation

The following risks can be anticipated now.

- Decision-making degenerates into decision-"cloning" due to the reduced variety of manufactured products of a certain type up to the present time. Mitigation can be done by importing data from research.
- Decisions are inadequate due to major and/or rapid modification of the manufactured products. Mitigation is done by importing data from other interconnected ADM-s.

3.5 Requirements

As already highlighted, the manufacturing cycle involves decision-making. While low-level decisions will be made at the level of individual assets, a manufacturing environment-level coordination will be enabled to ADM on the base of the global model. Hereby, the availability of a basic communication capacity among these assets is a necessary condition. Each manufacturing asset must communicate with previous and next assets, as they are working according to the manufacturing procedure. The number of algorithms needed in the decision-making process will be minimized up to the remaining of a unique, global algorithm, which will have to self-adapt to the evolution of the manufacturing environment, mainly by self-updating its associated instances database. Because the ADM will have to deal with large amounts of data, the existence of high-capacity servers for open-data storage will also be a basic requirement.

3.6 Technological challenges

As the above-presented vision looks, two main technological challenges have to be answered in order to enable the ADM implementation. The first is the development of a complex monitoring system, able to holistic monitor [9] the manufacturing environment. The second regards the creation of a communication network of IoT (Internet of Things) type, which will interconnect the ADM with its associated instances database, but also with the other ADM-s operating in cyber-space

4. IMPACT

The impact is revealed by the output, outcome, and implications of the global digital modeling of manufacturing.

<u>The output</u> is a new asset inside the manufacturing environment, ADM, which will be able to supply an accurate and reliable description of environment state (here included the component assets, but also the product) at the current moment, in the past (the decisions from previously accomplished tasks), and in the future (prediction of decisions to be taken up to the delivery of currently manufactured product).

The outcome consists in: *i)* online optimization of the manufacturing process, which further leads to diminishing of the effort dedicated to manufacturing process driving, *ii)* increasing of efficiency in manufacturing assets exploitation, and *iii)* reduction of expenses and timespan for manufacturing management and control.

The implications are: *i)* managerial skills will be mainly required to personnel, instead of the skills regarding the deployment of physical processes enabling the manufacturing, *ii)* Standardization in manufacturing will be accelerated, in order to ensure the coherence in ADM application, and *iii)* Research results will be applied in a shorter way, by formalizing it as a data set included in ADM, instead of analyzing different natural and industrial processes.

5. CONCLUDING REMARKS

The decisional process model, as defined through relation (1), includes, in implicit form, the physical process model. Hereby, similar to manufacturing, many other activities could be seen as decisional processes, afferent to physical or other nature of processes (e.g., administrative or economical). This is why this vision is coherent with other visions, from other fields.

The new paradigm of global digital modeling proposed here is expected to generate a market for holistic monitoring data. The actors of the new market could be manufacturers, research units and intermediaries. The market might stimulate the regulation of the format in which these data will be formalized.

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MODELAREA GLOBAL-DIGITALĂ A FABRICAŢIEI

Performanţa în domeniul fabricaţiei este limitată de marea varietate de modele utilizate în procesarea informaţiei şi de continua lor modificare. Oportunitatea cercetării de faţă este data de digitalizarea fabricaţiei, care permite valorificarea capabilităţilor tehnologiilor digitale necesare particularizării în masă din era tehnologiei "cloud". Lucrarea priveşte elaborarea unei noi viziuni asupra modelării fabricaţiei, pentru a creşte performanţa acesteia prin implementarea unui model global-digital creat pe baza digitalizării holonice. În acest scop, fabricaţia este modelată ca un proces decizional şi nu ca unul fizic, ca o holarhie de decizii şi nu ca un şir de acţiuni.Mai mult, modelul fabricaţiei este formalizat ca o bază de date deschisă şi nu ca un algoritm de procesare a datelor.

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