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HOLONIC DIGITALIZATION OF MANUFACTURING – THE TOOL OF 4-TH MANUFACTURING REVOLUTION

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Abstract: Nowadays increased expectations regarding the industrial processes combined with the outstanding progress in the field of computers and information technology have led to the occurrence and development of the Industry 4.0 concept. The currently accepted meaning of digitalization is the use of digital technologies to transform an object/process in order to provide new revenue and value-producing opportunities. Industry 4.0 means the entrance of industrial manufacturing into the digitalization era. This paper intends to be a contribution to the implementation of Europe's strategy for digitalization and proposes the holonic digitalization concept introduced in manufacturing and tailored for supporting the development of the 4th industrial revolution. The implementation of manufacturing holonic digitalization consists of the accomplishment of the following four steps: sampling, holonization, digital representation of the holons, and building of holon dataset. Holonization of the manufacturing activity means its deep multi-level configuration into several stand-alone components, each component being a holon of manufacturing i.e., a sequence of manufacturing seen as a holon. The digital description of a holon refers to both holon attributes and causality, and it is obtained by holistic monitoring of the holon operation. The building of holonic cyber-tooling means to design both the flow of information and the decision-making procedure, and to build perennial cyber-tools needed to support the flow and procedure. This building lays on approaching the information processing as a decision-making process, and on the implementation of appropriate performant digital technologies.
Key words: manufacturing holon, holonic digitalization, holistic monitoring, decision making, manufacturing activity, cyber-physical system.

1. INTRODUCTION

Nowadays increased expectations regarding manufacturing combined with the outstanding progress in the field of computers and information technology have led to the occurrence and development of the Industry 4.0 concept. Its goal is to achieve a higher level of operational efficiency and productivity by a higher level of automatization. Industry 4.0 means the entrance of industrial manufacturing into the digitalization era, where everything is digital: business models, environments, production systems, machines, operators, products and services (Alcacer and Cruz-Machado, 2019).

The currently accepted meaning of digitalization is "the use of digital technologies to transform an object/process in order to provide new revenue and value-producing opportunities" [2]. Digitalization embraces the ability of digital technology to collect data, establish trends and make better decisions. Quite synonymous to "digitalization", the term of "digital transformation" can also be met in literature. For example, Vial, 2019, defines it as "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies".

For the EU, digitalization has become a major target. In March 2021, the EU Commission presented a vision and avenues for Europe's digital transformation by 2030, here including the EU manufacturing industry [4].

Advanced digital technologies are a critical element of digitalization/digital transformation (Jones et al., 2021). Among these, one can mention: additive manufacturing (Matos and Godină, 2020), cloud computing (Wu et al., 2013), connectivity, robotics and automation (Lu et al., 2020), big data and manufacturing analytics (Tao et al., 2018), artificial intelligence (Hansen and Bøgh, 2021), digital twins (Cimino et al., 2019), and Model-Based Enterprise (MBE) environments (Camba et al., 2017).

Manufacturing digitalization is changing how products are designed, produced, used and maintained as well as transforming the operations, processes and energy footprint of factories and supply chains. One of the key drivers for digitalization is the ability for manufacturers to be able to improve their responsiveness and agility through changing market conditions and customer demands. In addition,

transitioning from manual operations and implementing automated solutions can enhance processes and improve performance monitoring and decision making [13]. Moreover, Tokody, 2018, argued that it is possible to create a generic holonic agent, which can be further used to develop a generic Cyber Physical System (CPS), which further gives the opportunity to build a Smart Factory.

Digital manufacturing is an integrated approach to manufacturing that is centered around a computer system [15]. More specific, the digital manufacturing consists in the application of digital information (from multiple sources, formats, owners) for the enhancement of manufacturing products, processes, supply chains and services [16].

The first step and, at the same time, the grounding pillar for implementing the digital manufacturing, i.e., for manufacturing digitalization, is information digitization. Digitization means, in general, the process of taking non-digital formats of information and turning them into digital formats [17]. Many processes from manufacturing field have already been digitized: designs are completed in 3D CAD files, drawings are being sent to tablets built specifically for that purpose, digital twins exist to mirror the objects they're building, while more and more things are connected via the internet of things.

Related to digitalization, there is also the concept of informatization. A system, which crucially relies on digital objects (described through files), is considered as informatized. Informatization refers to the culture of engineering systems, which are informatized by design (Paulin, 2018).

Both digitalization and informatization of an object (be it a system or an activity) make necessary to deal with data concerning that object, represented in digital format. Reaching the digitalization / informatization purpose involves to acquire, store and analyze large amounts of data. The acquisition of data defining a given manufacturing object is realized by monitoring. An example illustrating the integration between digitalization and monitoring in the case of a CNC machine tool is presented in Figure 1.

Fig. 1. Architecture of CNC machine tool equipped with control system of precision state (Xing et al., 2021).

Some shortcomings, below presented, can be revealed by critically analyzing the literature that addresses the manufacturing digitalization subject.

- A certain degree of confusion between "digitalization" and "digitization" is persisting, e.g. (Ugido Lozano et al., 2018) refers to 3D scanning as digitalization (instead of digitization) technique.
- In what concerns digitalization techniques, there is very little information in literature, e.g. [21] only defines a three-steps strategy for digitalization an activity. Furthermore, the mechanisms of increasing the activity performance by digitalization are not clearly defined and analysed.
- A conceptual clarifying regarding the specific aspects of digitalization, when it comes to be implemented in manufacturing, is missing.
- Digitalization is superficially approached, because it refers only to information processing. The causality existing inside the digitalized object is not considered, hereby it is not taken into account when making decisions concerning this object.

The challenge to be faced in this paper is the conceptual development of digitalization, based on an integrated-holonic approach, aiming to mitigate the above-mentioned shortcomings. This conceptual development is introduced in manufacturing digitalization. It is important to mention that manufacturing environment dynamics (currently ignored) is here considered. Concrete aspects regarding digitalization implementation are also analyzed. Last but not least, the digitalization development being presented at conceptual level, it

has the potential to extend its application area from manufacturing towards other activities.

2. THE APPROACH

Here, digitalization is approached at vision level, where this concept means: appropriate rebuilding of a subject + digital representation of the subject + applying of digital technologies into subject operation algorithm.
Although it has general application, we here present the digitalization concept by considering the case when manufacturing is the subject of digitalization.
Manufacturing is approached by referring to both manufacturing environment and manufacturing activity.

2.1 The manufacturing environment

- **Is approached** as a space where the demands of industrial products meet a set of manufacturing assets (be it information, material, or human nature), enabling thus the obtaining of industrial products by triggering, maintaining, and sustaining certain physical processes.
- **Is based** on the manufacturing procedure, which supposes the product to pass through a succession of typical states (Figure 2):

- State of defined object (looking as technical specifications, site plan, conceptual schema etc.);
- State of described object (e.g., shop drawings);
- State of deliverable object (manufactured product).

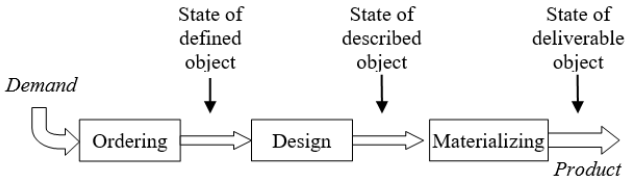

Fig. 2. The succession of product typical states according to the manufacturing procedure.

Here, the changing of product state becomes a task, while the triggering of the procedure for accomplishing a manufacturing task becomes a decision.
According to the manufacturing procedure,
- The task accomplishment is done by passing through three stages: configuring, programming, and execution (including the result evaluation), and
- The task triggering consists in making distinct decisions concerning the execution of each stage.

- **Is embodied** by the potential tasks, **is operated** by decisions that lead to the accomplishment of current manufacturing task and **is described** by the set of manufacturing variables, as well as by the causal relationships between these variables.
- **Its state** is constantly changing,

- Because at a given time, only some of the potential tasks that could be activated are available, as well as
- Because its causality is changing in time.

The current operation of specific manufacturing environment means manufacturing activity.

2.2The manufacturing activity

- **Is approached as** a process of making & implementation of decisions, further referred as *d-process*. These decisions concern the handling of the manufacturing environment, in order to appropriately accomplish the current task.
- **Concerns** a succession of d-process sequences, each sequence having the following stages:

1. The preparing stage that consists of analyzing the task and selection of those assets which may support the making & implementation of the d-process,
2. The decision-making stage that consists of the analysis of a set of manufacturing variables, as hypothesis, in order to establish another set of manufacturing variables, as conclusion, which are relevant because if the conclusion were to materialize, then the hypothesis would be confirmed,
3. The decision-implementation stage that consists of the materialization of the decision, in the form of a certain minor intervention in reality, called setting, which has as effect a major evolution in reality, called result,
4. The decision-evaluation stage that consists of measuring the actual values of the variables, and
5. The closing stage, which consists of preparing the "invoice" for the received task and sending it to the one who has generated the task.

- **Is embodied** in the running of all d-process sequences related to the product.

2.3 The manufacturing digitalization

- **Has as subject** both manufacturing environment and activity,
- **Aims** to improve the manufacturing performance by implementing digital technologies, and
- **Consists** of building a digital manufacturing environment, able to describe the causality of the real manufacturing environment, as well as of the using of the first-one in the operation of the second, on such a way as to capitalize on the benefits offered by the digital technologies.

3. THE CONCEPT OF MANUFACTURING HOLONIC DIGITALIZATION

We here introduce the holonic digitalization concept, which we have approached at a general level because it could be applied in various domains of activity (e. g., administration, businesses, industry). For a better understanding, the concept will be further explained by considering its application in a specific field, namely in manufacturing.

3.1 Architectural diagram

The proposed architecture of holonic digitalized manufacturing is presented in Figure 3. The changing of product state actually takes place into the physical module ϕ of the dedicated manufacturing environment, configured by putting together the needed materials *MT*, tools *TL* and energy *EN*, brought from the physical site.

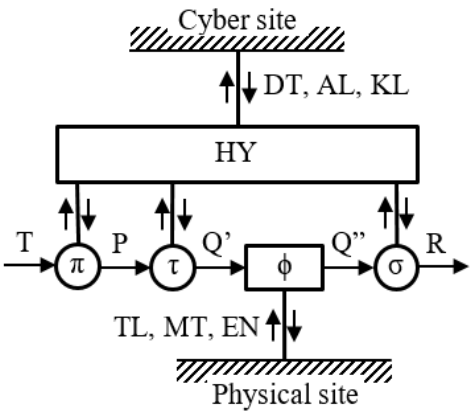

Fig. 3. Architectural diagram of holonic digitalized manufacturing.

The afferent d-process is performed, at its turn, by the cyber-modules π, τ and σ, which deal with the set of manufacturing variables *T*, *P*, *Q* (*Q* = *Q'* ∪ *Q"*) and *R*, according to the holonic sequence described in section 3.2 from below. The digital manufacturing environment is here seen as "holony" *HY* (that is a Holons colonY), as set of elements provided with one or more aggregation operations among them, which generate other elements from the same set (similarly to an algebraic structure). Hereby, the holonic d-process is controlled by the holony *HY*, where one can find two types of holons, corresponding to two basic configurations: *T-P-R*-holons, playing a configuring role, and *P-Q-R*-holons, with execution role. The functioning of both types of holons is described below. They operate with the help of the data *DT*, algorithms *AL* and knowledge *KL* that may be taken, when needed, from cyber site. The main informational resource for holonic process control is supposed to be the recorded set of *HY* previous own decisions.

3.2 Holonic sequence

It must be noticed, from the beginning, that by manufacturing task *T* we mean, in general, the action of bringing the product from the initial state to the final state, no matter of the manufacturing stage (ordering, design, materializing) that is concerned.

The manufacturing tasks can be grouped after their specificities, on classes $n = 1, 2, \ldots$ (e.g., a certain class may refer to the design of a screw-pump or to the machining of a crankshaft). A holonic modeling of the tasks performed by industrial robots is presented in [22].

Manufacturing takes place by successively running holonic sequences. During each such sequence, a given task is accomplished, according to a decisional flow, which involves the making of several partial decisions (Figure 4).

Here, the word "decision" has the most general meaning, namely the choice of a way to follow in a certain point of a given activity.

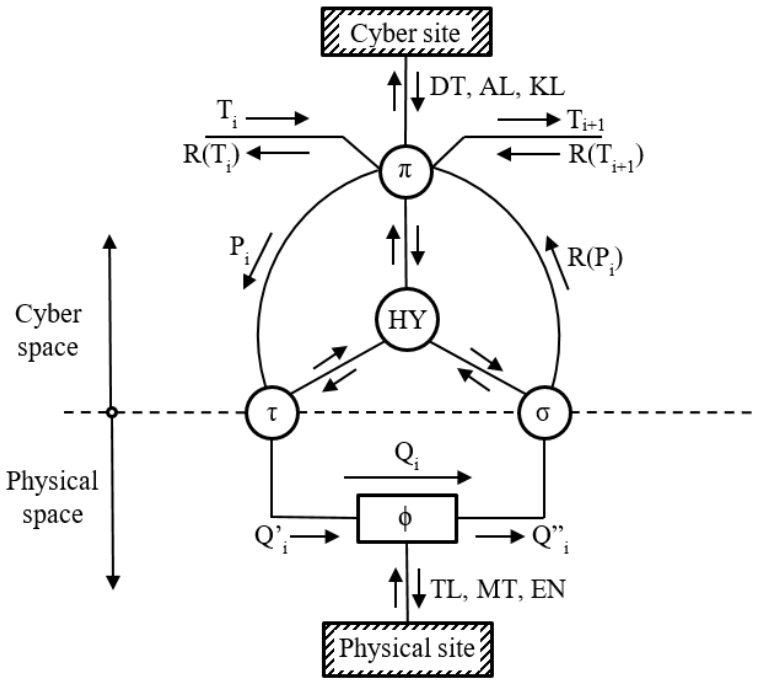

Fig. 4. Holonic sequence diagram

The holonic sequence (*HS*) is initiated when the piloting cyber-module π receives the task T_i and makes the first partial decision, which is of *managerial type* and refers to task configuring by a *T-P-R*-holon. Thus, π decomposes T_i and concomitantly generates the new task P_i, which will be executed during the current sequence by a *P-Q-R*-holon, and the new task T_{i+1}, which will be released. Each task, no matter of its type, is described by a vector of values for a certain number of variables. At the same time, π takes from cyber-site existing knowledge *KL*, algorithms *AL* and data *DT* that are necessary for T_i accomplishment.

The programming cyber-module τ receives from π module the information about the executed task P_i. After simulating the results of its potential decisions, it makes a second partial decision, of *control type*, for establishing the values of the variables composing Q_i' data-vector that describes the way on which P_i will be actually accomplished. Then, Q_i' is communicated to the product transformation physical-module ϕ, which takes from the physical space the tools *TL*, materials *MT*, and energy *EN* required for P_i task accomplishment and proceeds to this. As consequence, another data-vector Q_i'' is obtained by monitoring the operation of ϕ module. The ensemble formed by reuniting Q_i' and Q_i'' gives Q_i data-vector.

The measuring cyber-module σ collects information coming from monitoring sensors and makes a third partial decision, of *evaluation type*, regarding the result of P_i accomplishment, $R(P_i)$. The vector $R(P_i)$ gives the values for the same variables as P_i, but as they have actually resulted (being, in general, different from the intended ones).

The results vectors $R(P_i)$ and $R(T_{i+1})$ of executed and released tasks, respectively, are transmitted to the piloting cyber-module, which aggregates them and finally finds $R(T_i)$ - the result of T_i accomplishment.

For each manufacturing task T_i, $i = 1, 2, \ldots$ a decisions-set including all the decisions concerning every task accomplishment up to the current moment can be created and used as Decision Support System (DSS) for future accomplishments of T_i. The decisions-set line corresponding to a T-P-R-holon should result by putting together the vectors T_i, P_i, and $R(T_i)$, while in the case of a P-Q-R-holon, the decisions-set line will be composed of P_i, Q_i, and $R(P_i)$.

3.3 Holonic d-process

Let us consider a generic task of *n* class, $T = T(n)$, meaning to bring a given product from the initial to the final state. This is achieved by going through several successive holonic sequences, as illustrated in Figure 5.

At the level of the first holonic sequence, HS_0, the task, re-denoted by T_0, is configured in order to establish the intermediary states through which the product must pass. As a consequence, more *product reference states* are identified among the intermediary states (here, for simplicity, only a single reference state S_{ref} is considered). A product state is considered as a reference state if *i)* the product passes through that state no matter the task accomplishing solution, and *ii)* there are no causal relations between the previous and the following intermediary states of the product. The consequence of the D_0 decision is the decomposition of T_0 into a certain number of components - lower rank tasks.

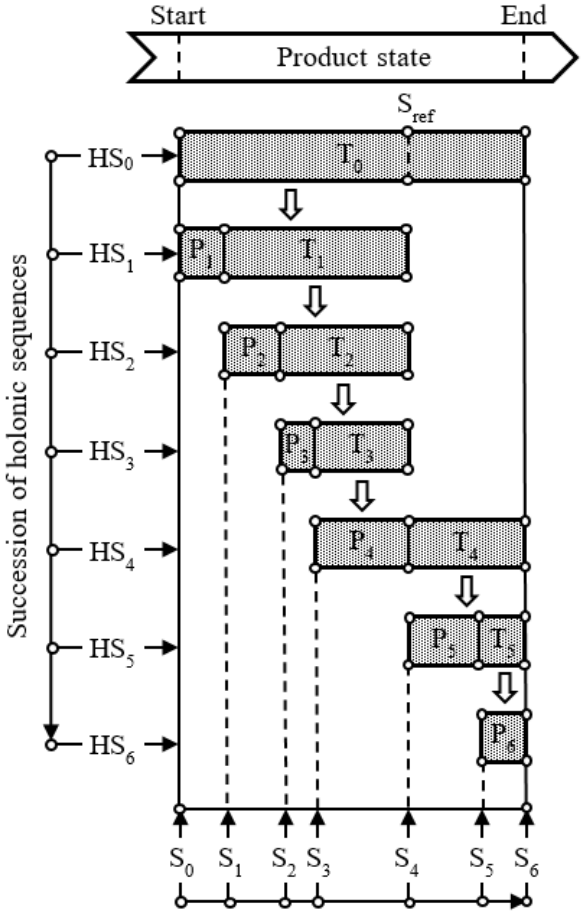

Fig. 5. Holonic d-process flow

The next holonic sequence, HS_1, regards the first component task and consists in establishing which part of it, P_1, will be executed at this level, to bring the product to S_1 state, and which part will be released, as T_1.

The following holonic sequence, HS_2 regards T_1, and consists in establishing which part of it, P_2, will be executed at this level, to bring the product to S_2 state, and which part will be released, as T_2.

The holonic sequences continue to succeed one after another until S_{ref} (actually S_4) is reached and then, after the same algorithm, until the product is brought to the final state (here – S_6).

4. IMPLEMENTATION OF THE HOLONIC MANUFACTURING DIGITALIZATION

The holonic digitalization of manufacturing means, in the here-presented approach, the building of a holonic digital environment (*HY*) that learns the causality of the changing real manufacturing environment and it is subsequently used as decision support system, *DSS*. In other words, it means the replacement of the "seeing and doing" paradigm with "learning and doing" paradigm.

The implementation of manufacturing holonic digitalization consists of the accomplishment of the following four steps:

- Sampling,
- Holonization,
- Digital representation of the holons, and
- Building of holon dataset.

Sampling refers to the manufacturing activity that took place into the manufacturing environment, during a given time period, and consists of *i)* dividing the manufacturing activity into several holonic sequences, and *ii)* digitally describing each holonic sequence by the values of its task and decision variables.

Holonization consists of aggregating the holonic sequences obtained from sampling into several holons, as well as of aggregating the holons into a holarchy.

The holons are generated through the multi-level partitioning of the decisions obtained from sampling, the partitioning criterion being the task variables. Each holon is defined as a set of holonic sequences that have the same variables, and belongs to a "holarchy", i.e., a hierarchy based on the relationship of belonging. Here this relationship is "the holon A includes the holon B", in the sense that each holon B sequence has as a task the decision from a sequence of holon A, and, consequently, B belongs to A. The holons are seen as *autonomous* and *cooperative* entities, and also as *perennial*, meaning that once defined, they remain available for the future. The deeper is the partitioning level, the narrower are the holons. The less deep levels refer to management, while the deeper levels refer to control.

Digital representation refers to the variables of both task and decision of the holon, hereinafter referred as "holon variables", as well as to the causal relationship between them. The digital representation consists in the "*industrial identification*" of the holon, and it is performed by holon variables monitoring and by comparative assessment of the obtained data.

Here, by "*industrial identification*" of an object is meant the continuous monitoring of the object during a given time period, finalized with the current digital dataset, and continuous comparative assessment of this dataset, finalized with the causal model. The digital dataset associated with the causal model represent the object representation.

Building of holon dataset, which includes the entire information coming from previous accomplishments of a given class of tasks by the considered holon, is further presented in a synthetic manner. For sampling, in Table 1 there is presented the dataset of a hypothetical holon.

The first section of the dataset (in yellow) defines the holon identity, by mentioning the class of the task to the accomplishment of which the holon is dedicated (here - *n*), the type of the holon (here - execution), and the set of variables having any significance in the operation of the holon (here - 9 generic variables).

The second section (in pink) is dedicated to establishing the variables through which the current task, the decisions for its accomplishment and the result of this (*P*, *Q* and *R* vectors, respectively) will be described. It should be noticed that, in principle, more variables among the nine considered in the example from Table 1 could be taken into account for each of the three vectors; furthermore, one and the same variable may be included in two or all three vectors. The structure of *P*, *Q* and *R* vectors is actually decided according to the managerial approach of the current task and in the table, it is highlighted in blue. Thus, *P* is currently described through variables 1 and 2, *Q* - through variables 3, 4, 5 and 9, while *R* – through variables 6, 7 and 8.

The third section (in blue) stores the information gathered from holon previous operation and has two subsections. The first-one (entitled *Data*), contains the recorded values of the variables that have been measured for each task previous accomplishment through a holonic sequence. As one can see, not all variables were measured for every sequence, this depending on the manner in which the manufacturing process took place and on the available measuring capabilities. The second subsection (entitled *Causal cluster*) shows causal relations among the variables describing the holon operation. Each causal cluster [23] gives the variables that can be used in order to define the neighborhood (comprised as set of similar cases, selected after a given criterion) of the current manufacturing process. One or another of these clusters may be chosen for predicting the result of current task accomplishment, in order to support the decisions making, depending on the variables chosen to describe this result.

The fourth section (in green) deals with the tooling (algorithms & technologies) available to be used for task accomplishment, and it also has two sub-sections. The first subsection refers to information processing, while the second - to material processing. In what concerns information processing, the choice for a given algorithm or technology is made depending on the causal cluster dimension and on the database extension.

5. CONCLUSION

The manufacturing digitalization can be considered a tool enabling the manufacturing performance increase, which is reached by improving the process control (brought closer to optimal) and also by a more efficient processing of the information needed in this purpose.

The implementation of manufacturing holonic digitalization requires, in principle: *i)* Holistic monitoring of the manufacturing process [24], the performing of which is conditioned, at its turn, by the development of the manufacturing equipment architecture, and *ii)* Integrated configuration of the informational system, for enabling the appropriate management of the information coming from monitoring (recording / processing / storing).

Under the conditions from above, the implementation of the holonic concept for manufacturing digitalization naturally flows in time, becoming deeper and deeper due to information accumulation.

A notable benefit of the proposed concept is that, once implemented, it automatically self-adapts to manufacturing environment dynamics as well as to the evolution of the requirements concerning the product, as they are imposed by the market.

Table 1. Holon dataset

Holon identity	Task class		n								
	Holon type		P-Q-R								
	Variables		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Upload and Download	Task (P)		x	x			x	x	x		
	Decision (Q)				x	x	x		x	x	x
	Result (R)							x	x	x	
Control	Operational data	(1)	x	x	x	x	x	x	x	x	x
		(2)	x	x	x	x	x			x	x
		(3)	x		x	x	x	x	x	x	
		(4)		x	x	x	x	x	x		
		(5)	x	x	x	x	x	x	x	x	x
	Causal cluster	(1)	a		b	c	d				e
		(2)		a	b	c		d	e		
		(3)	a	b	c		d	e		f	
Tooling	**Process**		**Algorithm**			**Technology**					
	Information processing	(1)	Comparative			Cloud computing, 5G					
		(2)	Analytical			Real-time analytics					
		(3)	Neural			Artificial intelligence					
		(4)	Numerical			Machine learning					
		(5)	Genetic			Quantum computing					
	Material processing	(1)	Multi tool			Dedicated architecture, DNC Embedded programs					
		(2)	Multi stage			Open architecture, CNC In-process metrology					

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