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Mind, machines and manufacturing: a philosophical essay on machining

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Abstract

Manufacturing evolution provided more and more efficient techniques to extend the anthropometric capabilities of humans. From the Neolithic Revolution to the Digital Revolution, passing through Renaissance and the Industrial Revolution, men invented new tools/systems to achieve objectives covering all the Maslow's hierarchy of needs: physiological, psychological, self-fulfillment needs.
Nowadays, the complexity of society, manufacturing and information technology as well as industry makes challenging to delineate a comprehensive framework of the machining processes that could indicate the trend of the fabrication industry.
This paper will provide an historical perspective of the manufacturing industry and its co-evolution in the actual society. In particular, a parallel between the advancement of computer science, information technologies and the machining processes will be presented by considering the description tools provided by different research areas.

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Keywords: Manufacturing, human interaction, Industry 4.0

1. Introduction

Manufacturing and human evolution are strongly related as machining capability has always influenced societies, their culture, determined military and economic power and in summary the dynamics of history. Furthermore, manufacturing capability is an index of the humans' technological and scientific advancement.

In this paper, starting from an analysis of the evolution of manufacturing, a philosophical and psychological point of view is presented in order to place into an historical perspective the latest industrial paradigm, namely Industry 4.0, and its possible development.

From the reported analysis, an unusual viewpoint of the relationship between human aptitude and the artifactual manufacturing systems is provided, by considering the role of the language theory and the advancement of the Artificial Intelligence.

2. Historical, Philosophical and Psychological Framework

2.1. Historical framework

Manufacturing and products identify the saliencies of human progress. In fact, the age system categorizes prehistory by referring to the artifacts materials: stone, bronze, copper and iron. With the first written witnesses the historical periods are classified by considering technologies. Actually, the technology route evolved through:

- the ancient Greek, with the Archimedes screw (3rd century BC), the gimbal by Philo of Byzantium (280–220 BC), the differential gears of the Antikythera mechanism (100-70 BC), shown in Figure 1;
- the Roman empire, with the watermills, the Hierapolis sawmill, the earliest known machine to combine a crank with a connecting rod, the quenching and tempering of the Gladius swords;

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Fig. 1. Antikythera mechanism (source Wikimedia, Creative Commons).

- the Medieval Europe under Christianity, with inventions such as the mechanical clock, the gunpowder, the blast furnaces, the rolling mill, the movable type printing press;
- the Renaissance, with the printing press, the linear perspective in drawing, the patent law, the rotary grindstone;
- the Industrial revolutions, initially with the use of steam power, the development of machine tools, the innovation in the iron processing, the railways, the factory system;
- the Technological revolution (second industrial revolution), with the telegraph, the use of petroleum, the electrification, new steel making processes (Bessemer, Siemens-Martin), standardization for interchangeable parts, mass production techniques, new materials such as polymers;
- the Atomic age, with the chain reaction (Chicago pile-1) led by Enrico Fermi, the military use of atomic energy, the medical treatments, the nuclear power plants;
- the Jet age, with turbine engines that permitted transcontinental and intercontinental travels faster and easier;
- the Space age, with the space race, space exploration and space technology and the fallout on materials, electronics, telecommunications;
- the Information age, with automation and computerization that makes industry les labour and capital intensive and shifts the focus towards the knowledge economy.

The main observation disclosed by the technology evolution is the time span between each age. Actually, the dynamics of the change is more and more rapid as the technologies evolve with an acceleration of the innovation that becomes structural with the revolution.

Another remark relates to the relationship between the technical problems and the principal subjects of physics. Specifically, the analysis of a technical problem is at the basis of the development of fundamental fields of physics, for example:

- Statics resulted from the study of the mechanical efficiency of the machines for weight lifting; Plutarch quoted the Archimedes words "Give me a place where I may stand and I will move the earth":
- Thermodynamics was developed after Sadi Carnot analysed the efficiency of the steam engine;
- Cybernetics and System theory were originated from the problems related to the amplification and the noise within the servomechanisms and mechanical control and information circuits.

2.2. Philosophical framework

If the analysis of the technology were limited to the inventions, to their structure and details, the deep meaning of the technological progress would be hidden into a mechanistic approach where phenomena are explained only by referring to physical or biological causes. As a consequence, by following the mechanistic philosophy, according to which natural wholes (principally living things) are like complicated machines or artifacts, composed of parts without any intrinsic relationship to each other, the behavior of natural wholes could be considered deterministically influenced by external causes acting on the parts which compose the natural whole. Accordingly, intentionality and deliberateness, distinctive of the conscious state, will be ignored by the mechanistic approach.

Actually, a sound analysis of the relationship between humans, machines and nature cannot be done by focusing only on the partial relationships between the pairs machine-nature, or human-machine, or human-nature; a holistic vision should overwise be considered (Figure 2). Human beings have been able to control their destiny and environment by building machines that essentially are a medium (mans) between men and nature. In this process the fundamental driver is the intent sought after through a mechanism, i.e. an artifact, that can obtain by nature, through an indirect route, the required goal. Particularly not every medium is a machine.

The machine, when considering its elements and behavior, is an automaton; whenever the purpose of the machine is neglected, the machine is a mechanism that can be described by the relationships between its component (dynamics). Actually, the purpose of the machine does not belong to the machine itself; the purpose belongs to the machine's builders or users, since it exists only considering their intent as the machine by itself is a mechanism without any meaning.

The machine incorporates the knowledge about the nature dynamics, and so the machine's knowledge is not only limited to the practical means to get a specific goal.

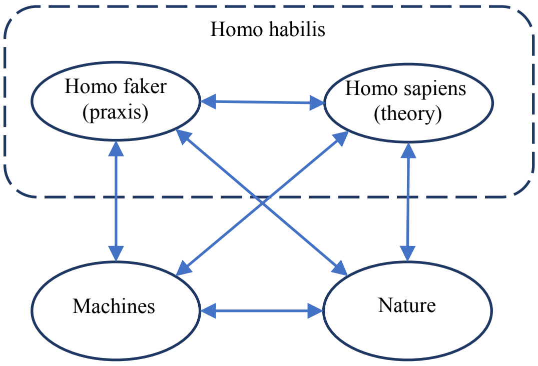

Fig. 2. Relationship between man, machines, nature.

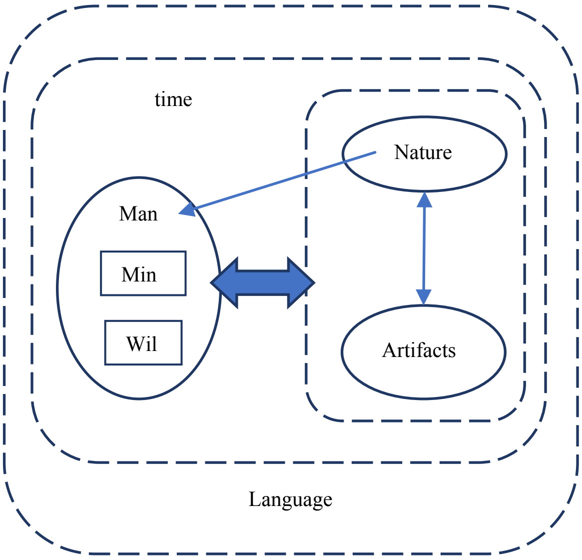

Fig. 3. Language, time, man, nature and artifacts.

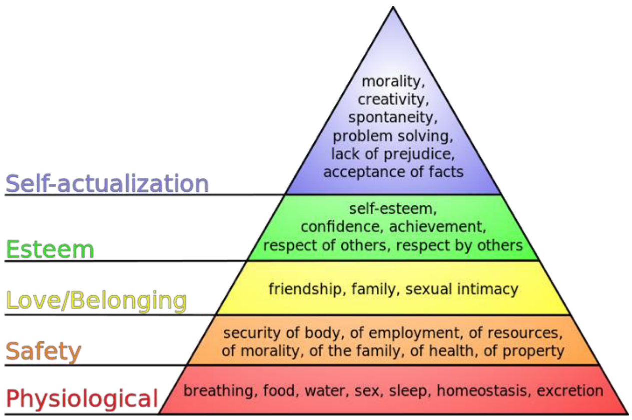

Fig. 4. Maslow hierarchy of human needs (source Wikimedia, Creative Commons).

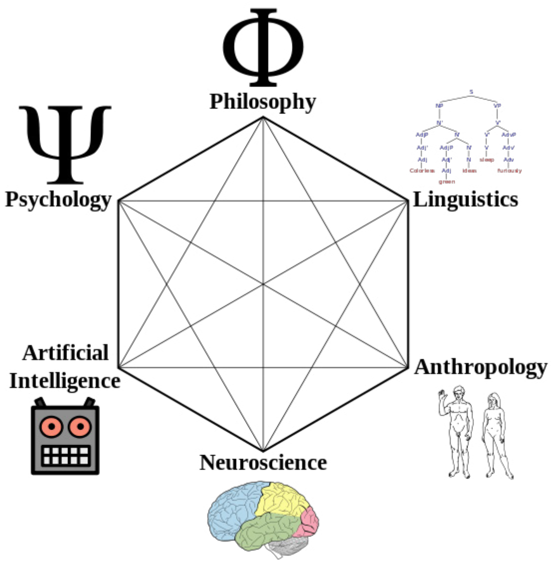

Fig. 5. Fields of cognitive science (source Wikimedia, Creative Commons).

The machine can be defined as an artificial instrumental medium between man and nature, tending towards automatism, but finalized in a heteronomous manner, which embodies a pre-theoretical decision about causality.

The solution of the practical problems connected with the development of machines, permits to the *homo faber* to establish the nature's laws and consequently to create theories distinctive of the *homo sapiens*.

At the basis of this process there is the mind, that gives through:

- *consciousness*, man's awareness of the environment,
- self*-awareness*, the ability to recognize oneself as an individual distinct from the environment of himself,
- *perception*, that permits to represent and understand the information, or the environment through the organization, identification, and interpretation of sensory information,
- *memory*, the mental faculty of retaining and recalling past experience,
- *intellect*, the ability to learn and reason, and
- *will,* the faculty to deliberately choose or decide upon a course of action,

a meaning to a specific part of the reality and, by becoming aware of the existence of entities, processes and events, eventually provides an ontological and phylogenetic representation of the world.

In this framework the language plays fundamental roles by describing reality, supporting reasoning and communicating facts, events. The cognitive functions of language permit to give a structure to reality, to relate time and experience, to express will, purpose and feelings. Figure 3 shows the relationships between human being, belonging to nature, its mind and will, time, nature and artifacts.

2.3. Psychological framework

Beside the relationships between mind-nature-artifacts, the analysis of mind, machines and manufacturing should consider the human needs that can be classified according to the Maslow hierarchy shown in Figure 4.

Maslow establishes that the basic level of needs must be satisfied before focusing motivation upon higher level needs. In particular the process to develop artifacts, such as machine tools that extend anthropometric limits, addresses two needs: the explicitly stated need related to the anthropometric limits, and the hidden, often subconscious, need, related to the creativity, to the genuine productive process necessary to develop an innovative solution, precisely the self-actualization needs.

Actually, the inventive process carried out during the design of a machine belongs to creativity and accordingly involves imagination and requires unconscious and conscious stages ranging from incubation to divergent and convergent thinking.

3. A linguistics approach to manufacturing

The recent advancements in manufacturing are taking advantage of the results provided by cognitive science, in particular of Artificial Intelligence (AI). Industry 4.0 paradigm is borrowing some of the AI ideas developed within the fields of cognitive science (Figure 5). However, the polarization of this paradigm on the technicalities could lead to failures with severe social consequences: Industry 4.0 Key Enabling Technologies (KETs) by focusing the manufacturing processes on automation, neglect the human factor that becomes subordinate and functional to production, and consequently ignore humans as the fundamental player in the artifacts making processes shown in Figures 2 and 3.

Artificial Intelligence, whose foundations were laid by Alan Turing in 1940, did not provided significant progress until 1997 when the Deep Blue computer beat the world chess champion; successively, in 2011, the Watson super computer beat humans in the 'Jeopardy!' game on television and, in 2015, AI outperformed oncologists in cancer diagnosis.

In spite of these remarkable results up today AI is limited to the development of independent systems that can face technical problems by simulating intelligence (weak AI). Particularly weak AI can be more efficient than humans in specific problems; AI is still utterly unintelligent but deep learning techniques could enable machine to learn and consequently provide a route towards a strong AI characterized by intelligent behavior, self-awareness, feelings and reasoned understanding. This goal is however far from the possibilities of the present technology.

Machine automation has been an historical trend in technology; according to Marx, "*automation is a process of absorption into the machine of the 'general productive forces of the social brain' such as 'knowledge and skills', which hence appear as an attribute of capital rather than as the product of social labor*".

In order to avoid the social consequences of automation and overcome the polarization of manufacturing on technicalities, a holistic view of manufacturing should be implemented. In particular starting from the observation that humans are *talking animals*, and language is fundamental in all the cognitive tasks peculiar to humans, a linguistics approach to manufacturing can represent a comprehensive means to integrate man, nature, artifacts as well as the inventive and manufacturing activities.

3.1. Manufacturing evolution

Manufacturing is essentially artifacts making; it basically relies on sociotechnical systems where humans conceive and use machines that exploit nature; since the industrial revolution innovation nurtured the manufacturing industry [1] to satisfy efficiency needs. Complexity and technology acceleration characterize the recent evolution of manufacturing systems [2].

Today the advancements in computer science, the capillary diffusion of internet, new manufacturing technologies, such as additive manufacturing, and AI, provide an exceptional opportunity to boost manufacturing processes and production capacity. Historically manufacturing has been driven by enabling innovations in machine tools, materials, and fabrication processes.

Considering flexibility, machine tools can be classified as:

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

In the last century the innovation trend in manufacturing has been characterized by an intense assimilation and exploitation of the advancements in electronics and computer science. In particular these advancements permitted to move from the conventional machine tools, towards CNC machine tools, Dedicated Manufacturing Line (DML), Flexible Manufacturing Systems (FMS), Computer Integrated Manufacturing (CIM), and since 1999 to Reconfigurable Machine Tool (RMT) and Reconfigurable Manufacturing System (RMS) [3].

This innovation trend was essentially driven by efficiency criteria that consider cost, time, productivity, and recently sustainability. Nowadays manufacturing is shifting from hardware toward software, pointing out the cognitive features of the production processes. The impressive potentiality provided by incorporating technologies borrowed by the information and communication technologies, requires appropriate management tools to face the resulting system complexity, to control supply networks, market globalization and guarantee manufacturing sustainability.

Industry 4.0, smart manufacturing, cognitive manufacturing, learning factories, cyber physical systems, etc. are keywords that today drive academic and industrial research. According to the Industry 4.0 paradigm, key enabling technologies, ranging from industrial internet to advanced manufacturing solutions, should be implemented [4]. The roadmap to the next industrial (r)evolution requires a comprehensive action to face:

- the cultural gap regarding the engineers' competences necessary to operate the new technologies,
- the complexity resulting from the availability of different technologies that could be globally connected.

The recent experiences stress the importance of the workers whose skills and attitude should evolve to cooperate with highly automated and globalized manufacturing systems [5].

In order to face the complexity issues by structuring manufacturing sociotechnical systems, several approaches, from heuristic to formal, have been proposed in literature [6]. Notably Ueda et al. [7] provided a rigorous roadmap for facing manufacturing systems organization by introducing the emergent synthesis theory and class I, II and III problems. Nonetheless the operative tools to implement emergent synthesis solutions for specific industrial cases should be purposely developed and depend on humans' analysis and synthesis capabilities.

3.2. Morphism: from computers to manufacturing systems

An analogy between the computer systems and the manufacturing systems can be established by considering the man-artifacts-nature model: both systems perform transformations of input into output by using resources that could be tangible (artifacts such as computer hardware, machine tools) or intangible (functional models captured by software, manufacturing processes knowhow). Furthermore, both systems, although characterized by high automation level, cannot operate without the proactive role of man, particularly his will, awareness and consciousness.

Accordingly, the evolution of computer systems can give an idea of the possible trend of manufacturing systems whenever a morphism, namely a structure-preserving mapping from one mathematical structure to another, can be established; consequently, the theoretical and practical results from one system can be transferred to the other.

In computer science, formal and semi-formal methods for the specification, development and verification of hardware and software system, anticipated by Gödel, Church and Turing, eventually achieved scientific and industrial results. Considering formal languages, the milestones were set since the 1950s with the Chomsky formal grammars hierarchy [8], successively with the Vienna Definition Language (VDL) [9] and, recently, with the concept programming language, eXtensible Language XL [10]. In manufacturing, since the 1980s many tools, such as Petri nets, graph theory, finite state automata, etc., have been used, providing benefits to software and industrial engineering [11]. It should be observed that formal languages up today fail to represent the pragmatics, i.e. the conscious will, possibly hidden, of the sentences written according to formal schemes.

However, if a morphism between the elements of the computer systems and the elements of the manufacturing systems is set, the formal tools used in one area, can be imported in the other area. A tentative correspondence between the elements a Von Neumann architecture and a manufacturing system is reported in Table 1.

Operating Systems and programming languages manage the computers' hardware and software resources (input, output, network, storage devices) through a layered structure that includes a Kernel, for the basic control of the computer hardware devices, a User Interface, and an Application Programming Interfaces, by which application developers may write modular and exchangeable code. The layered structure implements an abstraction approach and fills the semantic gap between the hardware and the user.

The same abstraction approach is adopted by the high-level computer languages whose syntax and semantics, defined according to formal generative grammars, provide the tools to express the surface structure and the deep structure of computer programs [12].

Table 1. Correspondence between Von Neumann architecture and manufacturing system

Von Neumann architecture	Manufacturing system
Processing unit	Machine tool
Control unit	CNC
Memory	Workpiece
Instructions	Part program
Mass storage	Buffers
Input/output mechanism	Pallets, AVG

Similarly, since the 1980s, manufacturing systems are moving from the hardware to the knowledge level [13] by using a layered control that includes intelligent elements for improving capacity, efficiency, quality, reliability etc. In the early 2000s' the Multi Agent Systems (MAS) emerged as a suitable tool to control flexible and lean manufacturing systems (Reza et al. 2004). These analogies could be useful to migrate the results already available in computer science to manufacturing.

3.3. A Simple Theoretical Model

A manufacturing system can be conceived as constituted by:

- The set of valid production processes (PROCESSES)
- The set of available resources (RESOURCES)
- The set possible products (PRODUCTS)

The semantics or denotation $s(p)$ of a production process $p \in PROCESSES$, is given by a function f that maps the resources into the products:

$s(p) = f$

$f: RESOURCES \rightarrow PRODUCTS$

$S: PROCESSES \rightarrow (RESOURCES \rightarrow PRODUCTS)$

Function f can be interpreted as production. The semantics of a production process can be viewed as the specification of the considered production process in terms of its production function, e.g. the semantics of turning in a given workshop is represented by the production of parts with cylindrical symmetry starting from the workpieces that can be turned by the lathes present in the workshop.

The fundamental issues in manufacturing engineering concern the following questions:

- Is it possible to establish if a given component can be manufactured with the available resources?
- In case of positive answer, what and how many different ways can be used to manufacture the component?
- Which are the economic and technological indicators to evaluate these alternatives?

Formal language theories could provide a promising framework to describe both the products and the resources. The first ones can be represented by a phrase belonging to a formal language; the last ones are specified by a sufficiently powerful grammar expressing the syntactical and semantical characteristics of the resource, i.e. of the manufacturing system. If the phrase, representing the product, belongs to the language L generated by the grammar G, describing the manufacturing system resources, including the knowhow, the manufacturing system can produce that product.

Formally, a phrase structure grammar G, according to Chomsky, is a quadruple $G = (V, T, S, P)$where:

- V is a finite nonempty set, alphabet,
- $T \subset V$ is a finite nonempty set of terminals,
- $S \in (V - T)$ is the initial symbol,
- P is a finite set of production or rewriting rules $u \rightarrow v$ with $u \in V^+$ and $v \in V^*$ where the operators + and * are respectively the positive closure (concatenation) and the closure (concatenation including the string λ of length 0), or star of Kleene, precisely:

$V^+ = \{w_1 w_2 w_3 \dots w_n | \, n \geq 1 \; and \; w_i \in V\}$ and

$V^* = V^+ \cup \{\lambda\}$

Given the grammar $G = (V, T, S, P)$, if $u \rightarrow v$ is a production of G, and $x, y \in V^*$ then $w = xuy$ directly generates $z = xvy$: $w \underset{G}{\Rightarrow} z$; the transitive and reflexive closure of $\underset{G}{\Rightarrow}$, is called a derivation or generation, i.e. if $x, z \in V^*$, y generates z, $y \overset{*}{\Rightarrow} z$, if there is a sequence $z_1, z_2, \dots, z_n \in V^*$ such that $y = z_1 \underset{G}{\Rightarrow} z_2 \underset{G}{\Rightarrow} \dots \underset{G}{\Rightarrow} z_n = z$.

The phrase-structure language $L \subset T^*$ generated by the grammar $G = (V, T, S, P)$ is defined by

$L = L(G) = \left\{ w |\ w \in T^*\ such\ that\ S \overset{*}{\Rightarrow} w \right\}$

Phrase structure grammars have the same expressive power of the Turing machine; accordingly, they can generate undecidable (not recursive) sets. Unfortunately, this feature prevents the use of the phrase structure grammars from checking if a given product, represented by a phrase, can be manufactured by a specific manufacturing system, described by a grammar. The introduction of constraints on the production rules P, makes possible to limit the grammars expressive power in order to achieve decidability. In particular the languages generated by regular grammars and context-free grammars, respectively type 3 and type 2 according to the Chomsky classification, can be recognized: the former by using Finite State Automata (FSA), the latter by LL parsers and LR parsers, respectively in $O(n)$ time and $O(n^3)$ time.

However, context-free grammars cannot express the semantics of a production process. Static semantics concerns only the features that are not involved during fabrication; e.g. the presence of a thread is possible only if there is a hole or a shaft. Dynamic semantics relates to the other properties such as the degradation of resources, tool wear, available power etc. The semantic analysis can be done on the deep structure of the phrase provided by the syntactic analysis according to Fig. 1.

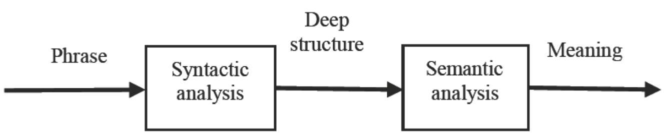

Fig. 6. Two steps process for semantic analysis.

While semantics delivers the conventional, coded meaning of a phrase, for instance a software program for computer systems, or the production function for manufacturing industry, pragmatics takes into account the implied meaning emerging from the context and the system environment. Pragmatics captures the intention of the speaker, his purpose and evaluate the message's structural and cognitive coherence; for this reason the development of a mechanistic model to capture pragmatics and human intention is nowadays not possible.

4. Conclusions

The parallel between computer systems and manufacturing systems could be a promising approach to transfer the results from one field to another. In fact, as far as the complexity of the problems could be afforded by a mechanistic method, the advantages provided by the morphism between computers and manufacturing systems could be considerable.

Unfortunately, whenever the focus of the analysis should include the human factor and the relationships between man, artifacts, and nature, the formal tools currently available show significant limits.

Indeed, creativity and real innovation involved in machine tools development and machining, demand characteristics such as awareness, consciousness, willingness that are typical of humans.

Artificial Intelligence advancement such as deep learning, could provide great improvements; however, the possible development of strong AI, characterized by intelligent behavior, self-awareness, feelings and reasoned understanding, represents a critical point for humans, due to the associated risk due to the possible overtaking of Artificial Intelligence over men.

Cognitive science should therefore give a precious contribution to the development of artifacts such as machine tools in order to guarantee the sustainability of manufacturing as well as of human society.

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