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Metabolism in eco-holonic manufacturing systems based on the living systems theory

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Abstract: The industrial metabolism has been conceived on the basis of analogies about the set of biochemical reactions (anabolism and catabolism) that occur in a living being and their flows of matter, energy and substances in natural ecosystems. This conception determines forms of appropriation and consumption of substances, materials and energy, from the natural environment (natursphere) and the technical environment (technosphere) for their transformation and subsequent elimination, under the articulation of criteria of cyclicity, toxicity and efficiency. The last aim of Industrial Ecology (IE), is materialized when the variety of industrial ecosystems is eco-compatible with the variety of natural ecosystems. The naturalisation of manufacturing systems is an effort to conceive them with variety similar to natural systems in order to achieve their eco-compatibility. In addition to bionic models from natural ecosystems in the field of industrial metabolism, several attempts have been made to design technical systems using bionic models from the Living Systems Theory (LST). The formulation of manufacturing systems based on living systems can be considered as a set of dynamic systems from Bertalanffy's perspective. In this paper is postulated an Eco-Holonic Reference Architecture for its projection in the design of manufacturing systems metabolism with an adaptive, self-regulating and required variety structure and with a potential toolbox in the core knowledge of the holon throughout its life cycle.

Keywords: Holonic manufacturing systems, Living systems theory, Metabolism, Industry 4.0.

1. Introduction

Some of the features that characterize today's manufacturing systems can be synthesized in three dimensions that correspond to digital transformation, their necessary alignment with the sustainable development goals of the Agenda 2030 of the United Nations and their adaptive value chain forming integrated networks of value and suppliers geographically distributed across the planet [1].

The preceding situation identifies a set of challenges of the New Generation of manufacturing systems to which it has been intended to respond through various initiatives such as digitization, Industry 4.0, environmental integration, sustainability under the paradigm of the circular economy, among others, and with regard to operational efficiency of WCM programs (World Class Manufacturing) or Lean manufacturing with projections of the automotive, machinery , aerospace, ceramics, metallurgy, and food industries, among others. Especially relevant is the concept of the social metabolism of manufacturing systems.

The articulation of solutions to these challenges constitute opportunities to create manufacturing systems that integrate adaptive value networks, oriented to the sustainability towards sustainable development goals and supported by digitalization through the configuration of cyber-physical systems, obtaining manufacturing systems whose social metabolism is oriented to the objectives of the 2030 Agenda.

Currently, the literature on the theory of living systems applied to sustainable manufacturing systems is limited, so it is of particular interest to study the incorporation of LST into the framework of Holonic manufacturing systems for its projection into sustainable manufacturing systems through Eco-holonic architecture.

In this article, an exposition of the theory of living systems is presented, followed by the enablers of Industry 4.0, to briefly develop the model of cyber-physical Holonic manufacturing systems that integrates the three conceptual frameworks in one proposal.

2. Background literature

One of the goals to conceive manufacturing systems as second nature, determines that the required variety of the technosphere be close to the variety of the natursphere. This shows the interest of conceiving manufacturing systems bio-inspired by natural systems and obtaining sustainability metrics by the same method. The model proposed for this purpose is industrial ecology. In the present article, the Living Systems Theory (LST) is proposed in conjunction with the Holonic Framework, therefore a brief exposition, structured in the elements, its principles and synthesis rule, will be made.

2.1. Living Systems Theory

The Living System Theory (LST) can be considered as an example of Bertalanffy's theory of living beings [2]. It is a conceptual framework, developed to integrate the results of scientific and theoretical studies in biology, psychology, neurology, social sciences, economics and management [3]. LST serves as a unified theory of science that deals with the hierarchical structure of living systems [4]. This theory is also applicable to non-living entities as there are comparable analogies between living and non-living systems [5–7].

The manufacturing systems approach based on living systems tries to approach the design of products or manufacturing processes in the industrial plant as a crystal box on the basis of analogy with the metabolic processes occurring inside living beings. There is currently no publication of living systems theory applied to manufacturing systems. This makes it of special interest to study this theory and see its applicability to manufacturing systems for its projection in the Eco-holonic architecture that will be shown in later sections.

2.1.1. Living Systems Subsystems. On Miller's Theory of Living Systems [8] a whole theory is elaborated, the most interesting part of which is detailed and summarized in table 1. It is a general scheme or template in which a possible model of a living system can embody, from a cell to the global world. Each of the subsystems that make up Miller's LST [4] is shown in detail below in order to clarify their functionalities.

2.1.2. Analogy of Living Systems and Manufacturing Systems. Nature-inspired design from a general perspective proposes a set of ontological principles derived from the solutions observed in natural systems for their articulation in the configuration of product design solutions or manufacturing systems. Many are the researches on bio-inspired approaches associated with manufacturing systems among some we find the modeling of biological manufacturing systems for their dynamic reconfiguration or their autonomous and cooperative behavior by intelligent agents [9]; comparison of the main natural manufacturing paradigms such as bionics, fractals and holonics [10], and models inspired by self-organization to endow manufacturing systems with adaptive capabilities to the environment.

Biomimicry [11–13] is the basis of bio-inspired models as it tries to "imitate nature (Bio - Life, Mimicry - Imitate)". When a problem is presented, a similar situation is sought in a natural environment, analyzing the relationships between the elements involved, the feasibility of the solution expressed in that environment is analyzed and extrapolated to meet the technical or procedural requirement sought.

This allows us to establish an analogy between living systems and manufacturing systems that allows us, through Holonic modeling, the naturification of manufacturing systems.

Table 1. Millers 20 critical subsystems of living Systems and corresponding functional elements.

	Subsystems processing matter-energy and information
	Reproducer: The subsystem activating matter, energy and information to produce similar systems by following a genetic or constitutional plan.
	Boundary: The subsystem surrounding the system, keeping together its components and protecting it from the environment, allowing access only for certain forms of matter, energy and information.
	Subsystems processing matter-energy
	Ingestor: The subsystem bringing matter-energy from the environment into the system through the boundary
	Distributor: The subsystem transporting matter-energy within the system from input, via all components to the output
	Converter: The subsystem changing certain inputs into forms that can be easier processed or used by the system
	Producer: The subsystem using inputs in the system and/or outputs from the converter to produce matter and/or energy to maintain the processes of the other subsystems and/or to produce outputs from the system
	Matter-energy storage: The subsystem for storing matter-energy within the system for later use.
	Extruder. The subsystem bringing matter-energy (products and/or waste) from the system into the environment through the boundary
	Motor. The subsystem moving the whole system, and/or parts of it in relation to each other and/or the environment, and/or moves components of the environment
	Supporter: The subsystem providing the appropriate structure to maintain the functions of all subsystems
	Subsystems processing information and corresponding functional elements
	Input Transducer (Equivalent functional element-Sensor: Observing external States and translating them into internal sensor data)
	Internal Transducer (Equivalent functional element-Sensor: Observing internal States and translating them into internal sensor data)
	Channel and net (Equivalent functional element-Channel: Transporting data within the system, connecting all subsystems)
	Timer: (Equivalent functional element-Timer. Providing periodic signals within the system, to enable synchronized behavior)
	Decoder (Equivalent functional element-Coder: Changing all sensor data from different sources into an unequivocal internal code for mutual data processing)
	Associator: The subsystem, which carries out the first stages of the learning process, forming enduring associations among Items of information in the system'. Miller et al. (1990). (See main text for corresponding functional elements)
	Memory (Differently defined functional element-Memory: Transforming the internal physical States used for data processing into other internal physical States with a higher permanence for storage. See main text for details)
	Decider (Differently defined functional element: Assigns to the results of some data processing, e.g. the results of a data comparison in a comparator, a trigger for an action of an effector, i.e. has a switching function. See main text for details)
	Encoder (Equivalent functional element -Decoder. Translating the unequivocal internal code for mutual data processing into appropriate signals to trigger other subsystems/functional elements)
	Output Transducer. (Equivalent functional element-Effector. Reacts to internal triggers and translates them into changes of external States, i.e. generates data)

2.1.3. Living Systems Principles and Properties. For a living being to be considered as such, Miller identifies seven specific criteria that the system must possess [4]: (1) it must be open to organization but energetically closed [8], (2) maintain equilibrium, (3) combat entropy, (4) possess a template or pattern

[14], (5) possess subsystems [15]; (6) contain a decision-making agent and (7) possess integrated subsystems.

In conclusion, living systems theory allows the modeling of intra-individual metabolism and ecosystem metabolism, including trophic chains. This situation will be of particular relevance in order to formulate models of metabolism in the Cooperation Domain of the holon (internal to the living being) and in the Collaboration Domain throughout the value chain or trophic level.

2.1.4. Eco-Holonic framework. The holonic itself constitutes a knowledge framework for the modeling of complex self-regulated and integrated structures in harmony with the context. In the present work, the term Eco-Holonic has been established to reinterpret the interest of the integration of the activity being modelled in a sustainable way. The concept of Eco-holonical system is the union of the concept of sustainability and holonic system [16]. The central element of Eco-Holonic Architecture is the Eco-Holon. An Eco-Holon is a holon that is in stable evolutionary equilibrium with the Eco-Holarchies of the Collaboration and Cooperation domains, through a dialectical action. Its bioinspired reference would be an organism that is integrated in a harmonic and stable way in the Collaboration domains. In this domain, transforming the matter, energy and information that constitute it and give it meaning as a living being allowing its co-evolution with the environment. An Eco-Holon has properties that are clearly defined in previous publications, such as [17].

Being the holonic ontological structure as opposed to the biological or fractal ones [10], of a physical-bio-psycho-psycho-socio-cultural variety [18–21], it is justified to be proposed as the required variety architecture that through filter mechanisms and variety amplifiers, allows adaptation to changing environments.

2.1.5. Key Enabling Technologies (KETs). Digital transformation proposes that digitization affects the entire organization globally. This determines new opportunities for the business, as well as the search for efficiency with objectives of greater scope in the three dimensions of sustainability, the decrease of the complexity of manufacturing both static and dynamic and the incorporation of intelligent information technology of continuous improvement processes under the Lean approach, capitalizing and putting in value the intelligent processes, the skills of workers, flexibility and restrictions of technological equipment, conceiving intelligent factories in closed loop on the technosphere and eco-compatible, which mitigate the metabolic rift, creating economic, social and environmental value. Enabling real-time monitoring and control of the plant, and conceived from the concept of Cyber-physical systems (CPS).

Among the most widely used technologies in the field of Industry 4.0 include [22–25]: (1) Big data where massive data capture and analysis to predict the behavior of value chain and business processes; (2) Internet of Things (IoT) that providing connectivity and intelligence to different elements of the business model; (3) Cloud or single storage of all program files, facilitating access at any time and place; (4) Digital platform. Connecting different information systems through a common platform. Integrating developments from different suppliers; (5) Autonomous vehicles. Optimization of heavy, dangerous and repetitive tasks that require displacement; (6) Virtual and augmented reality. Virtual aids for operators and engineers when installing, monitoring or designing; (7) Modeling and simulation. Models for simulation of processes and systems to predict and analyze their behavior; (8) New materials. Weight reduction and increased resistance to adverse effects; (9) 3D printing. In-situ manufacturing of more complex parts to reduce lead times; (10) Cybersecurity. Protection against hacking attacks; (11) Robotics. Automation of manufacturing, increasing accuracy and decreasing lead time and cost; (12) Artificial intelligence. Decision algorithms and active prediction, through learning, data analysis and previous results; (13) Smart products or products that benefit from novel IT-based approaches to product conditioning and knowledge; (14) Augmented operators or technology at the forefront of human development and (15) Blockchain. A network that ensures the certification of transactions, eliminating intermediate agents and added documentation. All these technologies serve as a resource to design the metabolism of intelligent sustainable manufacturing systems.

3. Eco-holonic architecture proposed

Until now, the proposal for Eco-Holonic Architecture has been formulated for industry 4.0 and cyber-physical systems [26]. In order to design and implement the Eco-holonic systems, several levels of analysis are established based on the bio-inspired principles of the living systems theory and oriented on the one hand from the natural ecosystems (collaborative domain), and in another way with the required variety, from the living systems theory (cooperative domain). For this purpose, the following elements are formulated and showed in figure 1.

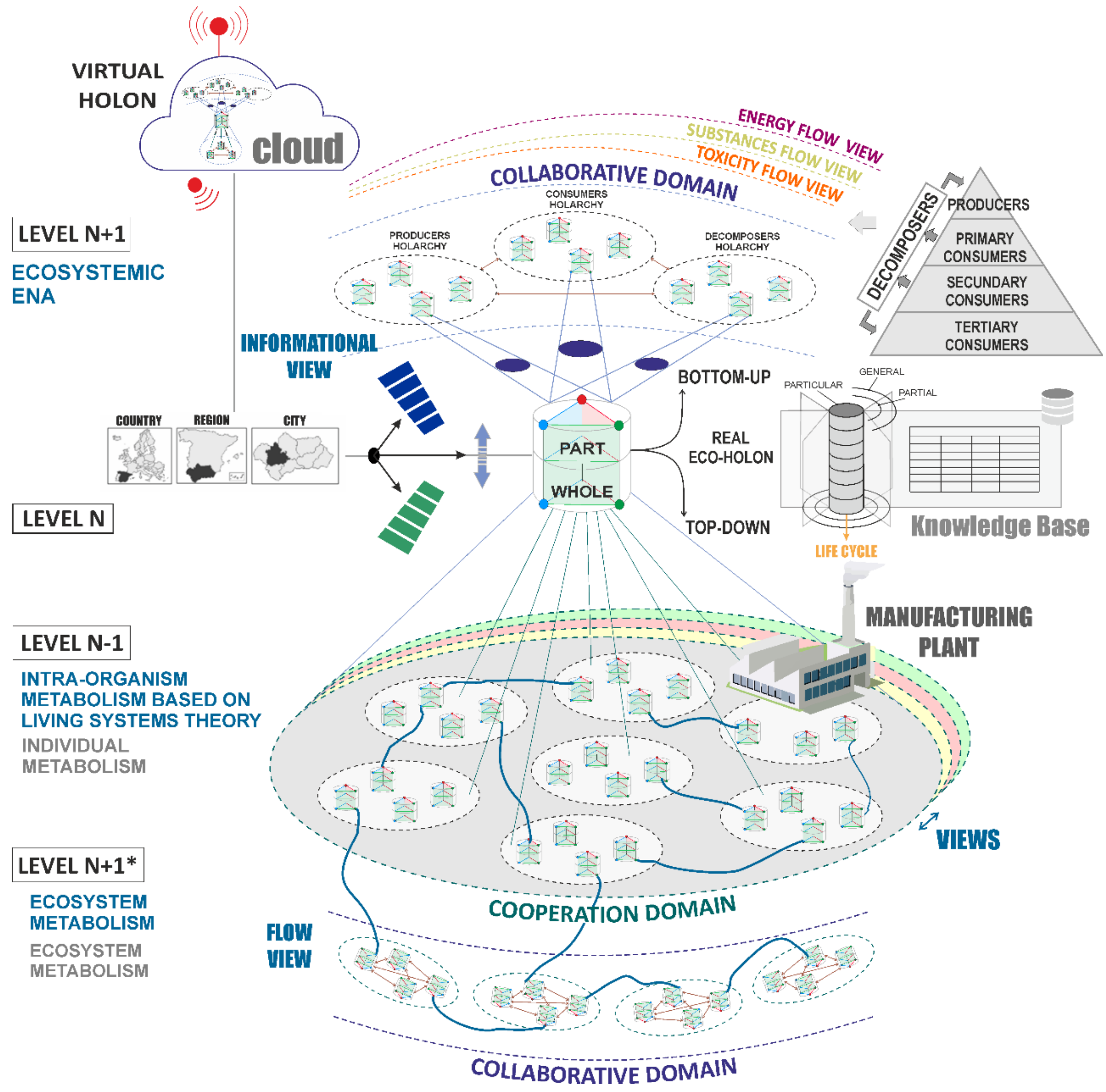

Figure 1. Metabolism in Eco-holonic Architecture based on LST.

This figure has three levels: (i) **Level N+1 Holarchy**: defines the COLLABORATIVE DOMAIN and the holonic requirements. This analysis establishes the design domains of an Eco-Holarchy for a manufacturing ecosystem with inputs and outputs of energy, water and matter, together with its interactions with other host ecosystems; (ii) **Level N Holon**: acts as an adaptive interface for the variety of manufacturing systems between levels N-1 and N+1 to ensure eco-compatibility. It defines the life cycle and self-regulatory mechanisms that establish knowledge with upward and downward control strategies. At this level, sustainability indicators are established; and, (iii) **N-1 level Holarchy**: it defines the COOPERATION DOMAIN and the holonic competence or capacities. to establish requirements of an Eco-holonic holarchy using the theory of living systems and establishing the necessary requirements of the manufacturing system that supports that living organism. These relationships are mathematically formalised by using Ecological network analysis (ENA), which allows the quantification of the ecocompatibility of Holonic Cyberphysical Manufacturing Systems based on the LST.

In order to design and implement the Eco-holarchy under the proposals made, as shown in figure 1, a macroscopic analysis of the Eco-holon collaboration domain (level N+1) and a microscopic analysis of the design and analysis of the cooperation domain (Level N-1) are carried out. Both analyses are conducted from bio-inspired principles derived from natural ecosystems in the first case and from living systems theory in the second case. In the bottom of the figure 1, the N+1* level or specific collaboration domain of the flow view to be analyzed is shown.

3.1. Macroscopic dimension analysis (Level N+1)

In the macroscopic dimension analysis [27–29] involves the analysis and design of an Eco-holarchy for an ecosystem with inputs and outputs of energy, water and matter, and interactions with other ecosystems. This situation corresponds to the supply chain.

A manufacturing system and its host system as an industrial complex, industrial park or urban ecosystem can constitute an industrial ecosystem. This can be conceived on the basis of productive entities or agents (industries) and relationships between them analogous to natural systems. The configuration of manufacturing systems can thus be established on the basis of their similarity to natural ecosystems, so that there is greater integration and compatibility between natural systems and the systems that constitute the technosphere.

3.2. Microscopic dimension analysis (Level N-1)

In the case of establishing the requirements of an Eco-holonic holarchy of the cooperation domain derived from the theory of living systems, the necessary set of requirements would be established by the holarchy that sustains said living organism.

Once the requirements of the collaboration domain have been determined, they must be transferred to the formation of a cooperation domain, forming an Eco-holarchic network of bionic inspiration, which is built by the dialectic action of the cooperation and collaboration domains.

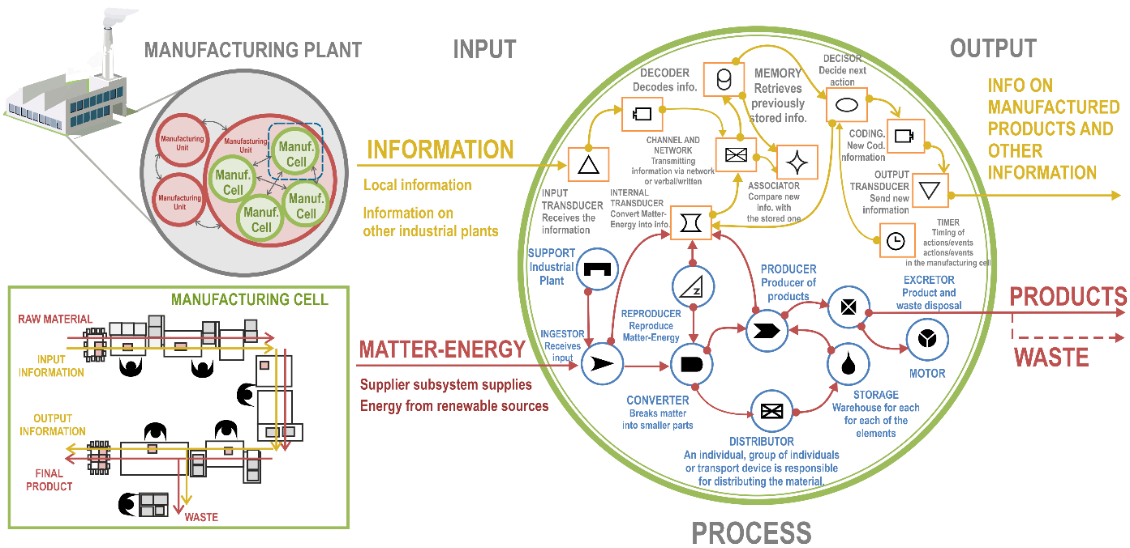

Figure 2. Manufacturing Plant modeled as a Living System.

Based on the requirements, the Eco-holonic network is identified and formulated from the Living Systems theory [30–32] or from the theory of natural ecosystems, formulating it by an Eco-holonic matrix. This procedure is applied recursively on all entities forming the Industry 4.0 Eco-holarchy. The articulation of the knowledge provided by Miller on Living Systems Theory allows modeling a manufacturing cell as shown in figure 2.

This manufacturing cell is composed of inputs of matter-energy and information necessary to carry out the processes within the manufacturing cell to obtain outputs of products, materials for reuse, reuse, or recycling and relevant information about the process carried out within the system boundaries. In addition, each of the sub-processes involved in the system can be analyzed and quantified according to the values of measurable inputs and outputs of each one of them according to criteria of economic, social and environmental sustainability. The transposition of Miller's knowledge to other levels is perfectly feasible.

4. Conclusions

The design of industrial metabolism models inspired by the LST, confirms that industrial ecosystems can imitate natural ecosystems in terms of structure, actors and interactions of the material, energy and substance flows within and outside the Holonic system. This analogy between both ecosystems provides a framework for the development of parks, industrial plants and eco-friendly manufacturing systems in which the environmental impact is almost zero. Moreover, the model would allow us to formulate proposals under industry 4.0 principles, for the engineering of the Eco-sustainable life cycle of products and manufacturing processes, associated to their living industrial metabolism.

This analogy between the two ecosystems would lead to the development of eco-sustainable parks in which the environmental impact would be null. On the other hand, the proposed model would allow us to formulate proposals for the engineering of the Eco-hydrological life cycle of sustainable products and manufacturing processes, based on the diversification, efficiency and effectiveness of the energetic processes associated with their industrial metabolism.

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