Considerations Regarding the Holonic System of Manufacturing Systems

DASCHIEVICI LUIZA, GHELASE DANIELA
Faculty of Engineering and Agronomy, Braila,
"Dunarea de Jos" University of Galati,
47, Domneasca St., Galati,
ROMANIA

Abstract: - Traditional manufacturing systems provide efficient production optimization but exhibit limited adaptability to changes, mainly due to their rigid structure and centralized control architecture. In this context, holonic manufacturing systems represent a promising approach, based on the integration of autonomous and cooperative units capable of dynamically responding to variations in the production environment. This paper proposes a structured approach to holonic manufacturing systems, highlighting the defining characteristics of holons and their organization within a holarchy. A prototype holonic system for vehicle body equipment manufacturing is analyzed, including the description of technological processes and the identification of corresponding holons. Furthermore, the relationships between state variables and performance indicators are discussed, together with an interpretation of holon interactions within the system. The proposed approach provides a conceptual framework for the modeling and development of flexible, adaptive, and robust manufacturing systems.

Key-Words: - holonic manufacturing system, holarchy, manufacturing system, prototype holonic manufacturing system, workshops, holonic configuration.

Received: March 16, 2026. Revised: May 19, 2026. Accepted: June 13, 2026. Published: July 27, 2026.

1 Introduction

Traditional manufacturing systems provide good optimization of production, but have a low capacity to adapt to changes, due to the rigidity and centralized architecture of the control structures. In the current context, characterized by a high dynamics of requirements and an increased complexity of industrial processes, it is necessary to develop flexible, adaptive, and autonomous decision-making manufacturing systems, while maintaining robustness in the presence of disturbances.

The concept of holon, introduced by Koestler, provides an appropriate framework for structuring these systems. A holon represents an identifiable entity that functions simultaneously as an autonomous unit and as an integral part of a more complex system. In holonic manufacturing systems, people, technological equipment, and computational resources are integrated into autonomous and cooperative units, forming a holarchy that allows both local autonomy and global coordination.

Holonic approaches have been intensively studied as solutions for increasing the flexibility, reconfigurability, and robustness of manufacturing systems. However, integrating these concepts into structured representations that correlate system variables, operational behavior, and process organization remains a current research direction, especially in the case of complex manufacturing processes.

In this context, this paper proposes a structured approach for the description of holonic manufacturing systems, with a focus on the identification and characterization of holons in a concrete industrial application. A prototype holonic system for the manufacturing of automotive bodywork equipment is analyzed, describing the relationships between state quantities, performance indicators, and the organization of the manufacturing process. Also, the interactions between holons are interpreted in a distributed framework, in accordance with the principles of multi-agent systems.

The objective of the paper is to provide a coherent framework for conceptual modeling and structuring of holonic manufacturing systems, as well as an application-oriented perspective.

The structure of the paper is as follows: section 2 presents the main characteristics of manufacturing systems; section 3 is about the holon concept applied to manufacturing systems, in section 4 are established the defining characteristics of holons in manufacturing systems, section 5 presents a prototype holonic manufacturing system, in section 6 is presented holonic modeling approach to manufacturing systems, in section 7 is presented the generic holon model and section 8 contains the main conclusions of this paper.

2 Characteristic Aspects of Manufacturing Systems

A manufacturing system can be defined as a structured set of interconnected activities and resources involved in the transformation of raw materials into finished products. These systems include not only technological processes, but also activities related to product design, planning, production, inspection, management, and marketing.

From an organizational perspective, a manufacturing system is composed of multiple entities, such as production units or workshops, each characterized by a certain degree of technical and organizational coherence. In addition to these internal components, manufacturing systems are influenced by external activities, including supply, cost calculation, production planning, and overall enterprise management.

The core of a manufacturing system is represented by technological subsystems, such as machine tools, cutting tools, operators, and workpieces, which constitute the primary elements involved in the production process. These are complemented by auxiliary equipment, including fixtures, measuring devices, and safety systems, which ensure the proper functioning and reliability of the manufacturing process.

For the purpose of analysis and modeling, several fundamental concepts are required. The state of a manufacturing system at a given moment is described by a set of state variables, which characterize its dynamic behavior. Certain state variables can be influenced through control actions and are referred to as control variables. Control represents the process of guiding the system evolution toward desired objectives, while maintaining system parameters within imposed limits, despite the presence of disturbances.

In more advanced configurations, adaptive control mechanisms can be employed, where the system model evolves in time to reflect changes in system behavior. This enables improved responsiveness and robustness, particularly in complex and variable manufacturing environments.

These concepts form the basis for the structured description and further development of holonic manufacturing systems, where autonomy, interaction, and adaptability play a central role.

3 The Holon Concept Applied to Manufacturing Systems

Currently, the industrial application of holonic systems is relatively low. There are a few implementations of holonic systems. The holonic shot-blasting system presented in work [1] is a demonstration of how separate robots can act autonomously and cooperate with each other to perform tasks.

A holon, as defined by Koestler, is an identifiable part of a system that has a unique identity, but at the same time is composed of subordinate parts and in turn is a component of a larger whole, [2], [3].

A holonic manufacturing system is a way of organizing based on the integration of people, technological equipment, and computers into autonomous and cooperative units in order to increase the flexibility, configurability, and robustness of the system to internal and external disturbances and variations, [4].

A holonic manufacturing system (HMS) does not represent a new technology, but rather an attempt to combine and use existing technologies (computer-based communications, decentralized control, intelligent agents, model-based diagnostics), [5].

The information part of the holon, strictly referring to holonic manufacturing systems, is represented by an agent, [2], [6]. A multi-agent system is represented by a collection of independent agents, each of which has a certain degree of autonomy regarding its actions and perception of the environment, [7], [8].

The field of multi-agent systems is part of the branch of distributed artificial intelligence, which means that this system solves the problem by dividing it into several tasks, which are to be performed by several agents, Figure 1.

Fig. 1: The interaction of an agent with the environment
Source: Created by the authors

The holonic manufacturing system, Figure 2, is made up of multiple holons (holarchy) that cooperate with each other to achieve a common goal and that integrate all manufacturing activities, from order management to design, production and marketing. By cooperation, we mean the process in which a set of entities develops and executes plans to achieve a predetermined goal.

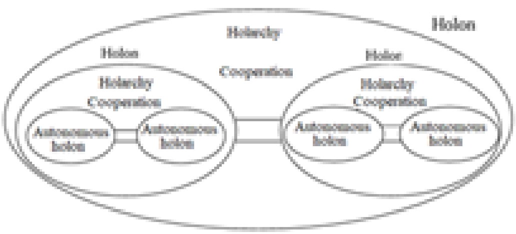

Fig. 2: Representation of a holarchy
Source: [7]

Thus, complex systems can be built which are efficient in the use of resources, resistant to internal and external disturbances, and adaptable to changes in the environment. Each production unit (production capacity, technological resource) can be a holon. Holonic behavior can be expressed through two complementary tendencies, self-affirmation and integration. The stability of holons results from their ability to act autonomously, without continuous assistance from a higher level, in unforeseen situations.

An important term to keep in mind is the term "holarchy." Holarchy is a mode of management based on the autonomy and cooperativity of holons that are subject to a set of rules/regulations. In this way, it can be said that the holonic manufacturing system is a holarchy that integrates the entire range of manufacturing activities, including order acceptance, design, production, and marketing activities, in order to achieve a rapid manufacturing enterprise.

The autonomy of holons to perform given tasks is an inherited property and expresses their "self-affirmation tendency". It refers to: local control and operation of machines, the optimization at the local level, self-ordering, self-configuration, self-diagnosis, self-learning, self-repair, etc. Autonomy allows holons to decide the necessary actions they need to take, such as individual objectives to execute without consulting another overseeing entity, [2], [9], [10].

Co-operation through negotiation between holons expresses the "integrative tendency", which is due to the need for survival and evolution in the environment and refers to properties such as: flexibility, goal-orientation, self-organization, and extensibility. Each production unit (technological resource, production capacity) can be a holon. These units cooperate with each other, from planning and ordering to direct physical processing for the manufacture of a product.

The structure of holonic manufacturing systems is based on a functional hierarchy and self-similar units (a repeatable structure at all levels), Figure 2, and as an information support object-oriented design, [2], [11].

Cooperation is the characteristic that allows holons to agree on common plans and execute them reciprocally. It also helps holons seek help in the event of a malfunction, which occurs after the execution of a common plan has begun.

4 Establishing the Defining Characteristics of Holons in Manufacturing Systems

Holons have 4 fundamental capacities:
-self-preservation: the capacity of holons to preserve their individuality, to preserve their particular integrity or autonomy;
-self-adaptation: a holon functions not only as a whole that has the capacity for self-preservation but also as a part of a larger whole, and in its capacity as a part, it must adapt or accommodate itself to other holons;
-self-transcendence (self-transformation): through interaction with other holons, any holon transforms into a new whole (self-transformation) and will have its own forms of relative autonomy and communion with other holons;
-self-dissolution: through its holarchic structure, each holon is developed vertically based on other holons, and when it disappears, it is subject to self-dissolution into its constituent holons, following the path to the initial state from which it started.

Holonic structuring is achieved under the conditions of respecting certain attributes, as follows:
1. Holonic structuring means identifying in the system elements that have holonic characteristics, which are; [12], [13]:
a) autonomy: the holon is able to make its own plan, a program, to regulate its work regime, depending on the targets it has and the conditions at a given time; its mode of operation is not influenced by the operation of another holon;
b) the cooperation: holons are able to operate together, that is, to carry out a plan together under the conditions that each one executes part of it independently; following the realization of part of a

product by each holon, the finished product should ultimately result according to the requirements.
2. The holon considered is a closed structure that functions autonomously, has connections with the rest of the holons, and is characterized by cooperativity (negotiation) with the environment, [13], [14].

Structuring the system consists of breaking it down into holons that have attributes of autonomy and interaction with the environment. The manufacturing system itself is an autonomous holon that interacts with the environment. The environment does not directly influence it in terms of its way of working.
The identification of holons in the case of the manufacture of automotive bodywork equipment is presented below.

5 Prototype Holonic Manufacturing System

The manufacture of equipment for vehicle bodywork involves several components and stages:
1. additional chassis fabrication with the operations: marking; cutting; welding; adjustment for tension relief;
2. body fabrication with the operations: marking; cutting; welding components; welding the entire body; adjustment for removal of stress;
3. accessories manufacturing with the operations: marking; cutting; turning; milling; welding; mechanical assembly;
4. separate painting of the additional chassis and the body with the operations: surface preparation, priming, and painting.

The following steps are taken for the final equipment of the vehicle:
1. assembly of additional chassis and chassis accessories with the following operations: welding; mechanical assembly, and painting;
2. Installation of hydraulic equipment with the following operations: installation of pipes; installation of actuation equipment; installation of the tank; installation of the hydraulic cylinder; painting;
3. assembly of the body accessories: welding, mechanical assembly; painting.
4. Filling the installation with hydraulic oil.
5. equipping the vehicle with mechanical safety accessories;
6. equipping the vehicle with electrical safety accessories.

From the sequence of operations presented, we find jobs that involve the same operation and we will initially consider that there will be one holon for each operation, in the logical order of the operations, as follows: 01 holon for marking; 02 holon for cutting; 03 holon for welding of components; 04 holon for welding assembly; 05 holon for adjusting for removal of stress; 06 holon for turning; 07holon for milling; 08 holon for surface preparation; 09 holon for priming; 10 holon for painting; 11 holon for mechanical assembly; 12 holon for equipment and accessories assembly; 13 holon for equipping with safety accessories.

It should not be forgotten that each holon can act alone and at the same time constitutes part of the holonic manufacturing system. As such, each must be characterized by input quantities and output quantities, but at the same time, there must be one or more quantities that allow the holons to be controlled in terms of the sequence of operations and the type of product that results in the end.

The matrix of state variables (MS) and performance state (MP) will be established for each holon, as follows:

01 MS: material type, initial size, final size, marking speed, number of pieces; MP: marking time, cost per operation;

02 MS: material type, cutting size, cutting length, cutting speed, number of pieces; MP: cutting time, cost per operation, energy consumption, waste quantity;

03 MS: material type, weld type, weld bead length, electrode type, number of passes, current intensity, welding speed, quantity of electrodes, number of pieces; MP: welding time, energy consumption, cost per operation, quantity of waste;

04 MS: material type, weld type, weld bead length, electrode type, number of passes, current intensity, welding speed, quantity of electrodes, number of pieces; MP: welding time, energy consumption, cost per operation, quantity of waste;

05 MS: material type, adjustment length, adjustment speed, number of passes, number of adjustment places; MP: adjustment time, energy consumption, cost per operation, amount of waste;

06 MS: material type, turning tool type, final dimension, turning length, feed, turning speed, number of pieces; MP: turning time, energy consumption, cost per operation, amount of waste;

07 MS: material type, milling cutter type, final dimension, milling length, feed, milling speed, number of pieces; MP: milling time, energy consumption, cost per operation, amount of waste;

08 MS: material type, surface size, number of passes, number of pieces; MP: surface preparation time, cost per operation, amount of waste;

09 MS: material type, primer type, layer thickness, number of layers, surface size, primer quantity, drying speed, number of pieces; MP: priming time, cost per operation, amount of waste;

10 MS: material type, paint type, layer thickness, number of layers, surface size, paint quantity, drying speed, number of pieces; MP: painting time, cost per operation, amount of waste;

11 MS: number of parts to be assembled, assembly order, type of assembly wrench, number of rotations for tightening, number of pieces to be assembled; MP: assembly time, cost per operation;

12 MS: number of equipment/accessories to be assembled, assembly order, type of wrench for assembly, number of rotations for tightening, number of pieces to be assembled; MP: assembly time, cost per operation;

13 MS: number of safety accessories to be equipped, order to be fitted, type of wrench to be equipped, number of rotations to tighten, number of pieces to be equipped; MP: time to be equipped, cost per operation.

The manufacturing of bodywork equipment involves several components and stages, and consequently several types of holons, of which we will consider 3 types of holons: the cutting holon, the drilling holon, and the welding holon. These are described by the state quantities, as follows:

-holon for cutting with state quantities: material type, length to be cut, width to be cut (size to be cut), cutting speed, number of pieces; and performance quantities: cutting time, cost per operation, energy consumption, amount of waste;

-holon for drilling with state quantities: material type, hole diameter, drilling speed, number of holes, number of pieces; and performance quantities: drilling time, energy consumption, cost per operation, amount of waste;

-holon for welding with state variables: material type, weld type, weld bead length, number of passes, current intensity, welding speed, quantity of electrodes, number of pieces; and performance variables: welding time, energy consumption, cost per operation, quantity of waste.

Denoting with h1f, h2f, …, h13f, the 13 holons that make up the holonic manufacturing system for manufacturing and bodywork of automobile chassis, this system can be represented as a union of such holons located on the same hierarchical level, Figure 3, where "f" represents the number of holons of the same type that enter the holonic manufacturing system at the time of executing an order.

Extrapolating, we can represent the holonic system of a department, Figure 4, of an enterprise, Figure 5, but also of a group of enterprises associated to carry out a joint activity, such as the manufacture and assembly of bodies on vehicle chassis.

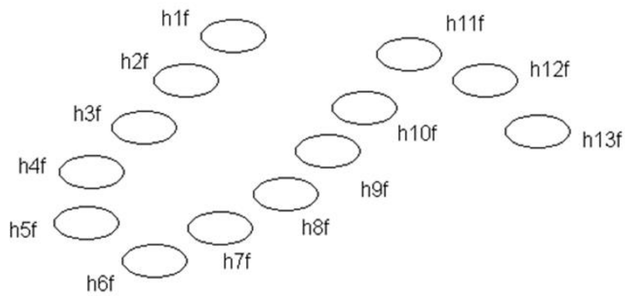

Fig. 3: Holonic System for manufacturing and equipping vehicle chassis
Source: Created by the authors

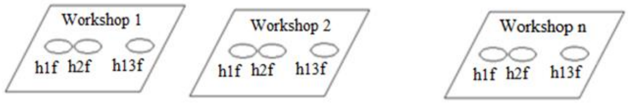

Fig. 4: The holonic configuration of a department consisting of n workshops
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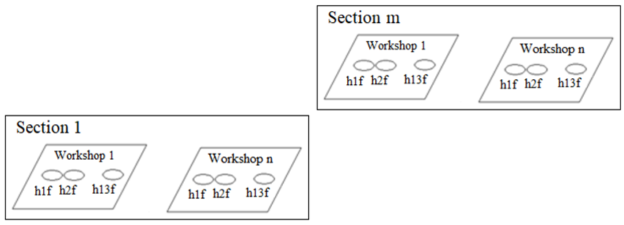

Fig. 5: The holonic configuration of an enterprise consisting of m departments with n workshops each
Source: Created by the authors

6 Holonic Modeling Approach to Manufacturing Systems

Manufacturing systems modeling can be done in four stages, classified as follows:

-structural modeling, which has as its theoretical counterpart supervised learning, which assumes that the environment provides both the problems that the holon has to solve and the correct answers to these problems; In this modeling, the man-equipment-technology ensemble will be considered as a holon, and the behavior of the holon will be described by a model. At the input, the state quantities of the holon can be: size, speed, stability measurement quantities, and time. Some of these will be considered control quantities. At the output, the holon will have as quantities technical-economic indicators that measure performance, such as: surface precision/quality, material consumption, energy consumption, labor consumption, productivity.

- Canonical modeling; it involves identifying the rules proposed by management that govern the environment in which technological holons operate. Each technological system of holon type has a certain environment at its level. The environment in which it operates/works is governed by a series of laws, rules, or situations. The laws of the environment form a structure called the canon. Canonical modeling means determining the laws that govern the environment in which a holon-type technological system operates, such as commercial policy, procurement policy, human resources policy, or pricing policy. Canonical modeling is the modeling of a policy, a fact characterized as subjective, in the sense that it is the result of a modeling of managerial policy decisions. The canon of the environment in which a manufacturing/technological system operates is given by internal regulations, operating regulations, job descriptions, and other regulations.

- functional modeling, which has as its theoretical counterpart reinforcement learning, which assumes that the environment provides data about the correctness of the actions taken by the holon, but does not say what the correct actions should be. This type of modeling refers to a structure that interacts with the environment. Basically, the holon receives targets/objectives to achieve and returns to the environment the conditions and consumptions for achieving the tasks.

Functional modeling consists of establishing the connection between the targets received and what the holonic structure returns to the environment in which it works. For example, for a target of “n” pieces with certain dimensions, the holon's response will be given by the material consumption for these pieces, the specific working parameters or the amount of waste.

However, we must note that we can have different answers for the same targets. We can state that we do not have a single solution but a range of solution values.

Following the interaction with the environment, a learning process takes place, which is a process by which the learning holon improves its capacity for action so that, during subsequent requests, the holon takes actions with increased efficiency. Through reinforcement learning, the environment provides data about the correctness of the actions taken by the holon, but does not say which actions are correct. Thus, the relationship between the holon and the environment is modeled, the behavior of this relationship is described and the holon is taught to interact with the environment so that bonuses are maximized and penalties are minimized over a certain period of time. In this case, the holon must discover for itself which actions lead to obtaining a greater reward.

To increase the scientific rigor of holonic modeling, the relationships between state quantities and performance quantities can be expressed in a general mathematical form.

Thus, the relationship between state quantities and performance quantities can be written as:

$$E = f(MS, t) \tag{1}$$

where:
• E represents the vector of performance quantities;
• MS represents the vector of state quantities;
• t represents time.

This relationship describes how the evolution of state quantities over time influences the performance of the holonic system.

The problem of controlling the holonic system can be formulated as an optimization problem, where the objective is to minimize the function:

$$J=f(C,T,Ec,D), \tag{2}$$

Respecting technological and resource constraints, where:
• C represents the cost of the process;
• T represents the execution time;
• Ec represents the energy consumption;
• D represents the amount of waste generated.

The interaction between holons within the holarchy can be modeled using a graph representation:

$$G = (H, R) \tag{3}$$

where:
• H represents the set of holons;
• R represents the cooperation and coordination relationships between them.

This representation allows highlighting the distributed structure of the system and the collaboration mechanisms between autonomous entities.

In this context, the learning process of holons can be interpreted as an adaptation of the function (f), so that the performance of the system is improved over time, based on the interaction with the environment.

-causal modeling, which has as its theoretical counterpart unsupervised learning, which assumes that the environment does not provide information about the correctness of the actions taken by the holon. Causal modeling is a modeling of an objective reality, which includes the internal environment of the firm from an economic, technical, and organizational perspective. This type of modeling includes both targets, independent variables, given by work parameters, and dependent variables, given by state variables.

7 Generic Holon Model

The basic model consists of the following:

-a technical component consisting of the work equipment for each process;

-a technological component that includes data and information about the process;

-a human component that performs the respective process;

-a component regarding the work environment and utilities for each process.

We can describe the holonic model in the form of a closed box, Figure 6, into which a series of parameters necessary for the process enter and are resulted, based on dependency relationships, the performance quantities that allow us to measure the effectiveness and efficiency of the manufacturing system. This leads to the determination of the optimum of the objective function established for the process under consideration.

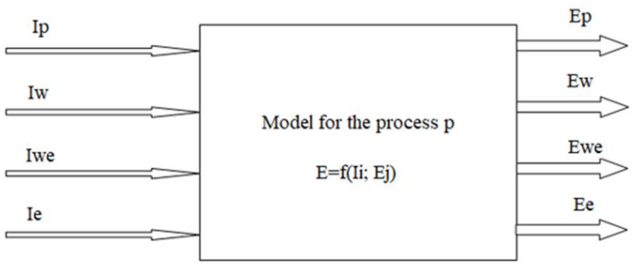

Fig. 6: Generic model holon
Source: Created by the authors

Inputs

Ip = process data: material type, dimensions, process type, work parameters;

Iw = data regarding the worker: qualification, work level, number of work norms;

Iwe=data regarding the work equipment: type, technical parameters;

Ie=data regarding the work environment and utilities: environmental restrictions, noise level, noxious level, types of utilities provided.

Outputs

Ep = product data: dimensions, quality level;

Ew = data regarding the worker: working times; workload;

Ewe = work equipment data: operating times; technical condition; equipment utilization rate;

Ee = work environment and utilities data: waste quantities, technological consumption.

The objective function model for transforming input data into output data is of the form:

$$E = f\,(Ii\,;\,Ej) \tag{4}$$

with i=1...n and j=1...m; where n=number of input data; m=number of output data.

A relationship can be written between the performance quantities and the state quantities, which constitutes the state equation that characterizes the state of the holon at a given moment. The equation is of the form:

performance quantity = f(state variable 1, state variable 2, …, time). (5)

The research will involve determining the state variable and performance metric by direct measurement and creating databases for each type of holon.

8 Conclusion

Currently, the industrial application of holonic manufacturing systems is relatively limited, although some demonstrative implementations exist, such as the “shot-blasting” holonic system presented in work [1], which illustrates how autonomous robots can cooperate to accomplish tasks.

This paper introduces and details a prototype holonic system for vehicle body manufacturing, highlighting the classification of holons, their defining characteristics, and their interactions within a manufacturing holarchy. The proposed system preserves the stability of pure hierarchies while exploiting the dynamic flexibility of heterarchical systems, demonstrating how holon autonomy and cooperation can be leveraged to integrate all manufacturing activities, from order acceptance and design to production and marketing.

The main contribution of this paper lies in conceptualizing an original methodological framework that defines the relationships between holon state and performance variables and provides a conceptual representation of holon interactions. This framework offers a foundation for future research, including simulations, optimizations, and experimental validations of holonic system performance.

The study also demonstrates the applicability of holonic principles in industrial environments, emphasizing the potential for rapid adaptation to changes, reduced vulnerability to disturbances, and holon self-organization. Therefore, the proposed system can be extended to other types of modular and complex manufacturing processes, contributing to the development of flexible and intelligent enterprises.

In conclusion, the results of this study open the way for future implementations, including:

- detailed mathematical formalization of the relationships between state and performance variables;
- integration of adaptive control and multi-agent systems;
- evaluation of system performance under real production conditions;
- extension of the methodology to other manufacturing processes and related industries.

Thus, this paper provides a solid framework for the design and development of agile and modular holonic manufacturing systems, representing an original contribution to the literature and a foundation for future research and applications.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.