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Sustainable Fractal Manufacturing: a new approach to sustainability in machining processes

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Abstract

Over the last decades manufacturing industry alongside installations and activities have caused damage to the planet, society and ecosystem. This impact is characterized by spending energy and material resources, environmental degradation, destruction of ecosystems, loss on biodiversity, effects on public health, welfare and life quality. Actions [1] that have been carried out to mitigate this situation have increased the complexity in manufacturing processes. It is necessary to establish new models that reduce this complexity in design and management stage, and allow the development of task's manufacturing to promote sustainability in the processes involved, maintaining the technical, economic and quality feasibility. The aim of this work is to develop a manufacture model based on the Fractal Paradigm to manage and structure the manufacturing processes, including the sustainability as minimal complexity (or required complexity) in manufacturing systems and incorporating the new paradigms Green Manufacturing and Cleaner Production, taking into account the principles of Cradle to Cradle (C2C).

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1. Introduction

The progress in sustainable development is growing in all industrial sectors. Within the integrated strategy of life cycle management, the manufacture stage is one of the key phases of performance because of the consumption of

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resources, emissions and the rest of negative impact. Although the current objective is to minimize the environmental, ecological and social damages [2, 3] there are initiatives focused on the perspective that the Industrial Ecology called III Generation of activity. They are not focused on the reduction of impacts but in the elimination (zero impact and positive or creation of environmental value), using strategies of cyclicity, efficiency and eco-compatibility of manufacture, as the natural ecosystems do. In this way, the sustainable manufacturing projects must take into account the three dimensions of sustainability: environmental, economic and equity, which should be considered in a balanced way to achieve the more efficient results with which carry out a better use of resources and reduction of impacts on the environment and its elements [1, 4, 5]. These dimensions need to be integrated into the set of parameters and requirements that require the features of current manufacturing systems (design and development of products, technology, manufacturing system management, governmental regulations, new techniques available outside the scope of standards or recent patterns of clean production and responsible consumption, all of them considering parallel the needs of users, customers and technical - economic feasibility of quality solutions). This dual objective implies high complexity, which is not always possible to manage or assume for companies and organizations. Therefore, in this research a manufacture system restructuration is proposed; the model links the fractal paradigm in manufacture with the new paradigms for sustainable manufacturing (Clean Production, Green manufacturing and Cradle to Cradle), with the objective of minimizing the complexity in the manufacture stage and maximizing efficiency in results.

2. Evolution of the manufacturing paradigms toward sustainable integration

The evolution of modes of organization and automation in manufacturing systems has been focused on the moment demand, take to account costs, quality, variety or responsibility. There are a set of manufacture approaches and paradigms to optimize each requirement from the efficiency, quality and safety [6–8]: this includes "just in time" production, flexible, agile, concurrent, "done for" MTO, MTS, ATO and ETO (Make-To -Order, make-to-stock, Assembly-To-Order and Engineer-To-Order), Global Mnfg, Reconfigurable or Total Quality. In recent decades, the intelligent manufacturing systems have required, by the large volume of information and operations, new paradigms such as the fractal, bionic or holonic manufacturing to address the complexity; these paradigms provide to manufacture: autonomy, self-regulation and auto-optimization. In addition, over the past few years, a set of paradigms has emerged that facilitate the development of sustainable manufacturing projects: Clean Production, Green Manufacturing and Lean Manufacturing [9]. In this work a model is proposed taking as reference the triple bottom line perspective and the Fractal Paradigm; the Fractal Model for Required Sustainable Manufacturing allows to integrate the whole range of aspects of sustainable development and don't forget all the results in cost, quality, feasibility or efficiency that the conventional manufacturing has achieved over the last few centuries.

3. The Fractal paradigm for the sustainable manufacturing

The intelligent manufacturing systems make up the next generation of manufacturing systems (SGSF) which sets out the theoretical foundations of distributed, virtual and extended manufacturing (it is characterized by its autonomy and self-regulating). In this field, the scope of knowledge about the fractal manufacturing is developed. The first fractal manufacturing systems appeared as a solution to minimized the intelligent manufacturing systems complexity in organizations, which incorporate a set of very high information and manage a large number of units in order to be successfully developed. The fractal research projects arise from both around the framework of intelligent manufacturing systems, in order to obtain greater efficiency of incorporation of value in products under minimum variety. The first contribution was made by Warnecke (1993) with his work "The Fractal Company", in which he describes the configuration of the new manufacturing companies; Warnecke proposes this concept from the analogy organization - natural fractal system: fractal object = organization, company and manufacturing plant; ecosystem = market; natural competition = globalization. Warnecke establishes the analogy take to account an inspiration in fractal objects forms and its characteristics. In this work the ideas of Warnecke and other researchers are taken to develop the sustainable manufacture model proposed [10–13]. In [14] a set of reasons about the benefits of the fractal manufacturing as paradigm are highlighted and why they allow incorporate in machining engineering a comprehensive orientation by autonomous groups aimed at excellence and open innovation sought to obtain the sustainable manufacturing under the criteria of minimum complexity.

3.1. Evaluation of the Fractal Paradigm for design the Fractal Sustainable Manufacturing System

The objective of fractal manufacturing [14, 15] is to develop a framework for the planning, design, modelling, simulation, optimization, management and assessment of processes in analogy with the forms of organization of fractal natural entities; natural fractal objects adjust their functions, features or principles according to the context demands (environment pressure). Before designing a fractal system of manufacture, it is necessary to know the fundamentals of the fractal entities. It is necessary to examine the Fractal Paradigm and the philosophical and theoretical principles of natural objects, to establish a process of transposition of their characteristics into manufacturing systems, i.e. to define the analogy. With that purpose, the principles underlying the fractal objects, their solutions and its dynamics are defined below.

3.1.1. Evaluation of the Fractal Paradigm for design the Fractal Sustainable Manufacturing System

The concept of fractal was developed by the mathematician Benoit Mandelbrot in the years 70 [16]; fractal was described as a fixed point of a set of contractive applications. From the same time, some definitions was developed, being the most suitable for this case study: (D1) Fractal: final product that is obtained through the infinite iteration of a geometric process (elemental, minimum variety). (D2) Fractal as formal object: it is the set of forms typically generated by mathematical repetitive processes and is characterised for the same aspect in any scale of observation, has infinite length, is not distinguishable and has fractional dimension or “fractal”. That is to say: fractal is composed of an entity elementary (minimum of variety) whose infinite recursion will determine the final structure but at the same time, a structure of variety.

The knowledge area of fractal geometry determines the characteristics or aspects to projection in design of manufacturing systems such as: (A) generative dimension (possibility of generation of very complex structures (multi-variety) through processes and simple objects), (B) constructive dimension (complex geometric sets in appearance but for its description, construction and exploration, require very little information (integrate minimum complexity), to be performed on objects the property of self-similarity) and (C) informational dimension (the infinite iteration of the process information (the simple form) is entered in a gradual way until the desired level, through processes of invariability scale). These properties allow objects to have a fractal structure: self-similarity (its construction is obtained by a function applied on an object, which generates another similar object) and has a process of growth based on simple objects with the possibility of infinite iteration. The above properties allow us to deal with the transposition process only in the formal part. But there are other properties of the natural fractal entities that the formal mathematical fractals do not have. These properties have been developed to be in interaction with the natural ecosystem, thank to evolutionary process and with the aim to adapt to the conditions of the environment, i.e. all the properties associated with the improvement and optimization process. Below some descriptions of fractals as natural objects are described.

(D3) Fractal as natural object: these are natural objects and entities whose internal or external operation interactions can be described as a geometry fractalized (structure or function). Natural fractals entities organize their molecules in the most efficient possible way to survive in the ecosystem; they develop high effective forms of behaviour (expansion, growth, structure), where the body increases its potential in an "exponential" way through simple instructions. The properties can be summarised as: (1) Goal orientation: they live only for they goal, functions or activity, (2) Auto-Optimization, Self-Organization, Self-Perfection: they optimize their characteristic of theirs operation and objective (geometric, energetic, informational, surface, etc.) that enable them to adapt to any change of the environment to survival (pressure context situation), (3) Dynamism-Vitality: their interaction with the environment (temporal and spatial evolution) are carried out through a set of endogenous flow of forces, which reflect how the fractal entities activates the processes of generation and integrates the required variety to goal orientation, (4) Open Systems: they exchange information, mass and energy with the environment, (5) Non-Linear Systems: their interaction with the environment and their survival is based on a radical and incremental innovation,

(6) Phenomenology Popup: to continuous from discrete process, with deterministic behaviour or not, that is, they have a set of characteristic that allow adapter to the environment demands.

Therefore, the two levels described allow us to establish the analogy and the process of transposition from the fractal entities (both mathematical and natural objects) so that the sustainable manufacturing can be achieved. The characteristics of the natural entities are similar to manufacturing systems: organization, optimization, adaptation to the environment… and although its mathematical formalization is not always available in analytical terms, it is necessary be taken into account in the transposition process for the analogy fractal natural- fractal manufacturing system.

4. Fractal Model for Sustainable Manufacturing

This work proposes a model for the sustainable fractal manufacturing with "required fractalization" as new concept. Taking into account the characteristics described in the previous paragraph, we define below the sustainable fractal manufacturing and the design principles that should be used for designing systems of sustainable fractal manufacturing (figure 1). This is followed by a description of the principles of design that includes the requirements of the model for the fractal manufacturing; then we expose the fractal architecture for the machining engineering. The proposal is not closed and future research will be extended and expanded to the different levels of manufacturing; in this work we only development the machining process in the informational level.

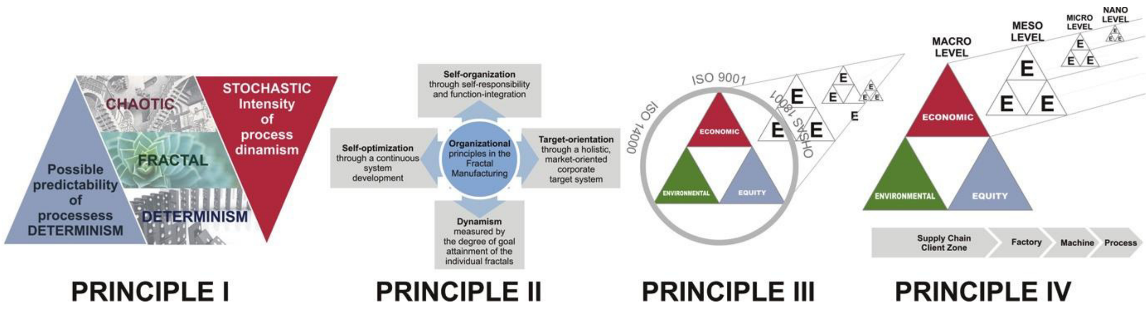

Fig. 1. Principles of Fractal Sustainable Manufacture

I. Principle of manufacturing organization fractal: This principle establishes the requirements to organize all procedures as deterministic fractal processes to adapt to the chaotic dynamics of the market. It allows the manufacture system to adapt to the environment through self-organization: the fractal manufacturing processes (such as open and innovative organizations) are stable in its evolution under the environmental pressure or in a turbulent context; in the case of the sustainable manufacturing, this situation will be possible thanks to a set of metrics and criteria to serve as an active and pro-active way to be adapted all moment to the market variability (internal characteristic restructuration depending on needs).

II. Principle of organization derived from the variety or fractalicity required: This principle establishes a set of organizational properties of the Fractal Manufacturing System. It provides to the manufacturing system of self-similarity (whose elements are characterized by dynamism), guidance to the objective, self-organization and self-optimization; fractals of manufacture shall be designed and configured for similar structures and recursive forms, which reduces the complexity of the system and facilitates the incorporation of the three dimensions of sustainability.

III. Principle of fractalization of sustainable product's life cycle: This principle develops the co-evolution between the fractal organization and the environment or ecosystem, to achieve a sustainable behaviour in the machining process. It proposes the integration of the social, economic and environmental perspective in the fractals of manufacturing in whole life cycle from the perspective of the variety required (minimum complexity). This principle will enable the goal orientation of the fractal system: in this case, the objective is the sustainability. An organization that controls a Fractal Manufacturing Process with sustainable approach will be oriented to the sustainable results.

IV. Principle of fractal levels of sustainable manufacturing: This principle sets the level of fractalicity. All fractal of manufacturing will be structured in different fractal levels with the goal of moving and to achieve sustainable development in a similar way, like a natural fractal object does. The hierarchical structure is composed of (1) the macro-level (that integrates supply chain and customers), (2) meso-level (industrial plant, factory and organization of the manufacturing process) and (3) Micro and nano-level (process, machine and working strategy). The division in levels will provide the manufacturing system of multidimensionality, self-similarity and dynamic management at any level or scale. This structure reduces the complexity, promotes the sustainability of the system and allows achieving the self-optimization, self-regulation and self-control with independence and effectiveness (without interference, unnecessary expenditure of resources or duplicate information).

5. Case of study: Fractal implementation to sustainable machining processes

In this part we apply the principles proposed into the micro level of the engineering sustainable machining. The model developed for the Fractal Sustainable Manufacturing System is explained by figures 2, 3, 4 and 5. The model in this work only describes the informational architecture that the Fractal manufacturing system; it organizes the sustainable performance and minimizes the complexity. The following paragraphs explain the basis of the fractal organization of a sustainable system; the objective of this work is the fractalization of machining processes, but the model is opened for future research. To analyze the system of sustainable manufacturing fractal is necessary take into account that the manufacturing phase belongs to a set of stages of the product life cycle (system or service); in this phase, some information flows, matter and results are created, which contribute to the final result of sustainability of the system (in figure 2, first fractal triangle is formed by the product life cycle: 1) genotype, which will include the design and development of the product and system, 2) Manufacture, 3) phenotype or system associated with its life cycle, which includes the stages of market, use and end-of-life. Once located, the Fractal Manufacturing System is divided into three levels: MACRO-level (supply chain), meso-level (organization, factory or manufacturing plant) and micro-level (manufacturing processes).

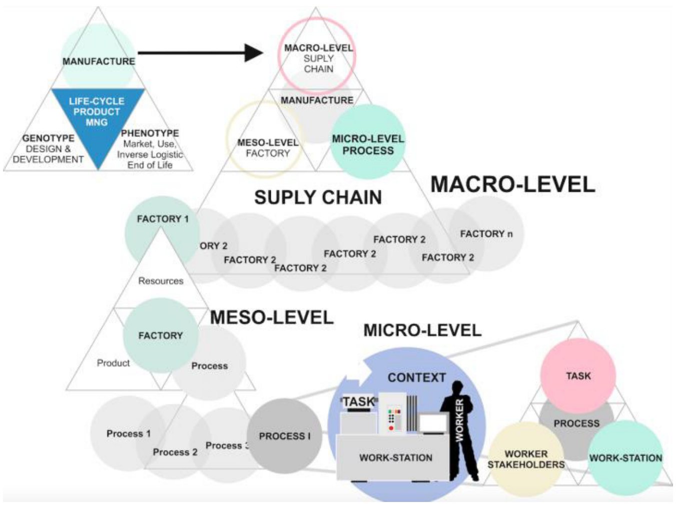

Fig. 2. Product management: Fractal of life-cycle product and system

This is possible to understand in the second triangle fractal of figure 2 named "MANUFACTURE. This fractal deploys the stage of manufacture to the same way; it is composed of a set of factories and organization that exchange material flows and products (or any other resource material), services or informational resources, and all of them in interaction form the supply chain. Focusing on the detailed view within the supply chain, but in response to some of the manufacturing plants that make up, it is always the same structure in other levels: product, process and resources define the meso-level of Fractal Manufacturing System.

As the objective of this work is the development of sustainability fractal for the machining processes, the model focuses within the meso-level, that is to say, the PROCESS (i.e. the micro-level of the stage of manufacture); the fractal process consists of three other elements: work-station, stakeholder and task. From this situation, in figures 3 and 4, informational architecture for the sustainable machining is detailed. Each of these fractals is made up of another set of three fractals to be deployed at the same time in macro, meso and micro levels. In addition, each fractal will have results at the same time of environmental, social and economic efficiency or impact, that will be included in each figure and embodied as results of the sustainability of the process in figure 5 ("database").

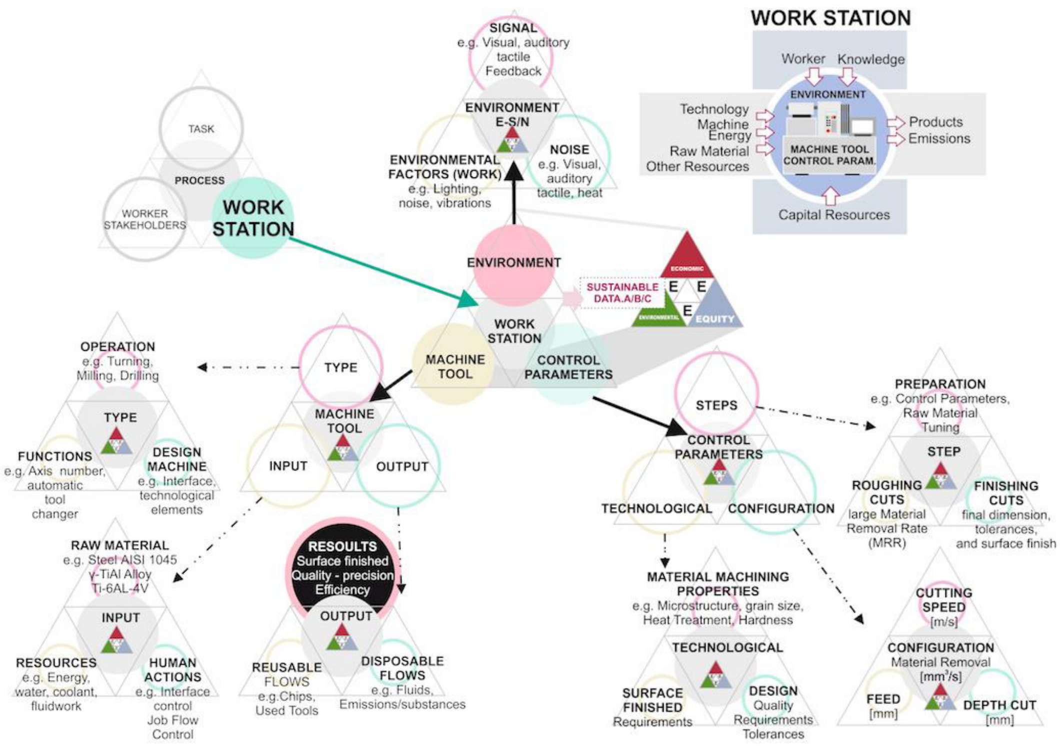

Fig. 3. Micro-process level fractalized: Fractal for workstation

The fractal process is composed of the workstation, the task and a set of workers who contribute and make possible the results of the process. If all information necessary to accomplish this is analysed, the data set increases the complexity of the sustainability control; these data could be grouped together in the conventional way, according to (1) inputs (technology, machine tool, energy, material resources, capital resources, etc.), (2) outputs (the product - parts and the flows of emissions and waste, etc.) and (3) the support of the tasks, workers and knowledge. In this case, the fractalization of sustainability has been carried out following the pattern of macro, meso and micro fractals to organize and manage the process, and according to the triple bottom line (3E) (economic, environmental and equity). It is possible to analyse in detail the fractals formed from each element in the fractal of the workstation. In this way, figure 3 shows the architecture of the informational fractal workstation. The same is divided into three levels: (1) machine tool (all information related to the type of operation, - milling, turning, etc. -, the input streams - raw material, energy, cutting fluids, etc. -, and the outputs - flows of emissions, waste and the resulting product or part; (2) context or environment (all the information regarding environmental factors -such as noise, lighting, vibration, smell, etc.-, information relevant for the task (signals) and interference or not relevant information from the environment of adjoining work, machine, or any other source); (3) control parameters of the process, that are the phases of the manufacturing, finishing properties and configuration of the machine. These three elements interact with the workers of a direct or indirect way, and they will have to be taken into account to increase the efficiency and ultimate productivity. All the interactions and results of the elements included in the fractal are evaluated (environmental, social and economic impact) that will be picked up at the end of the process by the fractal of efficiency (it is represented in figure 5). The second element of the *fractalization* of machining process corresponds to the workers (figure 4, left).

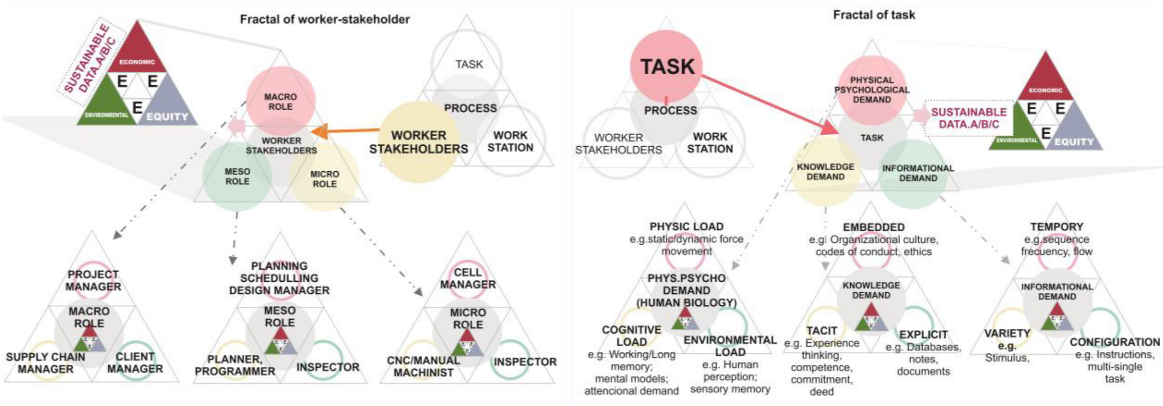

Figure 4. Micro-process level fractalized: Fractal for worker stakeholder (left) and Fractal of task (right)

In this case, the fractal is divided in three roles in compliance with the principle: macro, meso and micro levels. Within the macro-level are all workers who are involved in the process management, i.e. , activities related to supply chain management, customer interaction and project management. At the meso level, the workers are responsible for the design process of the products/parts to be processed (including CAD) and planning of the machining processes. Finally, the micro level will be direct responsibility of the people in charge of processing, starting with the incorporation of the design in the process (CAM) and controlling or running the machining tool, i.e. workers dedicate to control and use of machining cell. All levels have an agent (an inspector) that is responsible for the management of the quality results of each activity: management, planning and design, machining. In each of the roles are adheres to the structure that indicates the bottom of figure 4. The tag <LEVEL-ROLE-X> lists all of the features (fractalized too) that should be taken into account for the sustainable design of the process from a social point of view, i.e. skills, experience, training, job quality, motivation, attitude, etc., that will be sufficient for the design and evaluation of the results of a sustainable machining process (social sustainability assessments contribute indirectly to the enhancement of economic efficiency, for example, by increasing the productivity of the process).

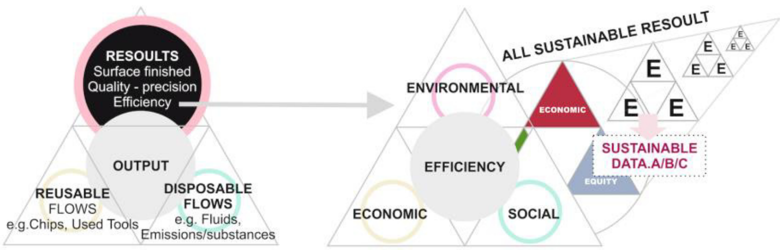

Fig. 5. Micro-process level fractalized: fractal of results

The fractal of task (figure 4) collects the informational architecture relating to the implementation of the process on the part of the employee. The task is closely related to the efficiency of the final results, workers; it is divided into demand physio-psychological, demand for knowledge and informational demand. It is necessary take to account these dates to improve the worker performance in the machining process (relevance results for their welfare in the workplace as efficiency and productivity).

Each fractal previously analysed generates the information about sustainable 3E, that is to say, the results of each one of the fractals in figures 2, 3 and 4 will be integrated in the fractal of sustainability that shown in figure 5: fractal of results.

6. Conclusions

At the time of planning, managing and implementing sustainable manufacturing projects, it is necessary to integrate a set of specific parameters which are related to the design and development stage of products, technology, manufacturing system as governmental regulations, new techniques available outside field of standards, limits of the planet and its ecosystems, recent patterns of cleaner production and responsible consumption, considering simultaneously needs of users or clients and the technical and economic solutions feasibility. Therefore the three dimensions of sustainability (environmental, economic and equity) must be taken into account in a balanced way to achieve the most efficient results, which perform better use of resources and reducing impacts on the environment and its components. This means a high complexity in the organization of the manufacturing stage, which should be managed from new models like the one developed in this paper: model of sustainable fractal manufacturing.

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