Multidimensional Vision of Sustainability in a Manufacturing Process

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***Abstract*—Sustainable manufacturing systems utilize energy-efficient and eco-friendly workflows, methodologies, and technologies. In this context, well-defined measurement methodologies and the mathematical modeling of production data play a crucial role. They are essential for consistently calculating and evaluating the indicators that characterize the sustainability of manufacturing processes. To achieve a green manufacturing process for reinforced concrete pipes, this study proposes a sustainability assessment method based on energy. This approach analyzes and evaluates resource utilization and environmental pollution within the production process. The study presents a method that utilizes indicators to assess manufacturing process sustainability from both economic and environmental perspectives. The research model uses current production data to integrate sustainability-related aspects. Requirements for information models supporting a sustainable manufacturing process were identified with the help of an energy-based reference architecture model. By means of specific indicators, this model maps out reliable pathways toward sustainable manufacturing processes. The results obtained demonstrate that this method can effectively quantify and identify the sustainability level of the manufacturing process.**

***Keywords*—technological sustainability, technological solutions, competitiveness binder, factors, green technology, multidimensional vision**

I. Introduction

Sustainability, the current requirement of an economic activity, is a complex strategy to understanding the role that people have in the ecosystem balance. At the same time, a new approach to the development concept is witnessed; it highlights multidimensionality as an integrating factor with several accessible objectives. Sustainability, quintessence of multidimensionality, is defined by the following components:

- Economic (continuous generation of development, increased utility, progress);
- Environmental (through protection and rational use of resources).

Using production processes through sustainable technologies makes the complex work cycle focus more on the environmental side and less on the technological one. The economic and social sides are minimally addressed. If these components are balanced by the company through prudent tactics and clear objectives, the results will confirm the sustainable path of technological, economic, environmental and social integration. Technological sustainability is the result showing that a manufacturing process transforms the used components into durable goods, which meet market requirements and fall within the technical, economic, environmental and social legal norms.

At present, we observe that the existence/making of a sustainable product demanded by the market, which respects and meets consumption needs, involves the participation of an economist for coordinating the sustainable route (integration). This economist must have expertise in the sustainable processing field as he will verify the economic indicators used, ensuring compliance with the production process reference standards. At the same time, he analyzes and makes sure that the technological indicators/factors maintain the correlation between the technology/ technological roadmap followed, costs, quality of the technological process and quality of the finished products. To this end, he ensures that the economic information/ components resulting from the analysis are used efficiently, to maximize quality and costs and to comply with the social and environmental requirements, according to the law. His expertise in economic processes sustainability will enable the identification, quantification, evaluation and management of the costs for material flows, energy and water consumption, taxes charged for atmospheric emissions and waste generation. Thus, there will be a maximum use of resources and a low negative environmental impact.

Analyzing the sustainable production process, the areas to be approached in the research are identified as follows:

- machinery (machines and equipment).
- technologies used.
- utilities used in the organizational process.
- products obtained and their lifecycle.
- organizational, manufacturing and supply chain contexts.
- impact on society and environment.

A sustainable production process requires, first and foremost, funding, alongside sufficient material resources and utilities. This aspect must be considered and addressed as a fundamental issue, constituting a distinct indicator—additional to the specific indicators analyzed for a sustainable manufacturing process. However, regarding the financial performance dimension of a firm as defined in the "Corporate Sustainability Assessment Criteria" of the Dow Jones Sustainability Indices, the following indicators are also proposed for defining sustainable economic activity (in addition to those concerning raw materials): cash flow, profit, the debt-to-equity ratio, and liquidity. Given these approaches regarding the diversity of indicators supporting a sustainable process, a long-term perspective on production is essential. Defining or identifying general indicators applicable to multiple manufacturing processes would enable firms to improve their market competitiveness. This approach will be analyzed in the research paper and the case study [1].

The path toward sustainable development must aim, among other things, at identifying scientific and relevant parameters/markers. It must also aim at defining a conceptual and operational sense for the existence of a transparent and responsible complex (economy, society, environment, and development). This complex should be able to provide human community with well-being, equity and responsibility (Table 1).

Table 1. Foundations of economy, environment, and society for sustainable development

Nr	Economy	Environment	Society
1	Technological process with reduced impact on the environment	circuit of resources with low impact	Equity
2	Efficient management of waste recycling	Noxious emissions in the area regulated by law	Development
3	Green assets and utilities	–	Supportability Consensus

To implement sustainable manufacturing processes, it is necessary to have management policies for combining efforts and collaborations between private sector, state and civil society. The path to a sustainable economy is a challenge for market players, who foresee an increase of investments with difficult access to financing. Therefore, government measures (clear laws) are needed to raise awareness at national level in this sense [2]. The issue of resources concerns the responsible use of renewable and non-renewable resources within production processes. Current research highlights that identifying general indicators is an essential yet challenging task. Consequently, the responsible use of diverse categories of process indicators continues to be promoted across a wide range of production activities a concept that leaves considerable room for interpretation by individual companies [3]. Against this backdrop, the present study aims to identify general indicators applicable to a sustainable production process.

II. Manufacturing Process Responsibility

Innovation is highly beneficial for the manufacturing process, being generated by research and motivated by the needs of society. Innovation helps solve tensions that arise from the clash between conservatism in technology use and the courage, backed by research, to apply new creative technologies [4].

This can be an important step toward a sustainable manufacturing process. Carefully analyzed in the light of environmental legislation too, the manufacturing process will perform economically by increasing the market share and by an easy access to bank financing [5]. In opposition to sustainable development, a process that does not comply with environmental legislation, using a manufacturing route taxed according to environmental legislation, becomes less competitive and weakens its position on the specialized market. If the strengths that define qualitative characteristics such as process flexibility (rapid adaptation to change), reduced environmental damaging and access to relevant information are used in the manufacturing process, the result will be an efficient integration toward a sustainable process.

In the specialized literature, the development of a sustainable process is called Framework for Strategic Sustainable Development (FSSD). A sustainable manufacturing process is characterized by: system, planning, strategy, control, and decision [6].

The research presented in the literature highlights that manufacturing processes are dominated by internal needs for economic efficiency, but also by governance-through environmental and social responsibilities. One can notice an openness of managers towards the absorption of solutions and instrumentation for the development of innovative manufacturing processes. These processes would address the following aspects regulated by law: environmental and social responsibility, the efficient use of raw materials (renewable and non-renewable), and the management of resulting waste. Through integration, organization, and standardization (improving the technological roadmap), the production process will evolve in a sustainable direction, enabling qualitative leaps by capitalizing on opportunities offered by a responsible approach to raw materials and utilities (based on specific indicators–I), (Fig. 1).

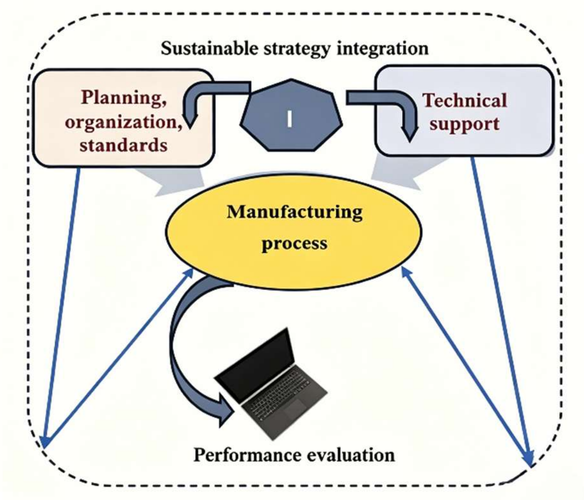


Fig. 1. Improvement cycle of a technology roadmap.

Using each branch (economic, environmental and social) of the sustainability strategy in an economic activity will bring a series of advantages to the company, namely:

- risk reduction.
- business optimization.
- development of skills of the personnel.
- improvement of process management system.
- compliance with governance requirements.

This research has emphasized that although a manufacturing process determines energy consumption and emissions, many of the evaluations performed are based on the product manufactured and the industry to which it belongs. Therefore, for a correct evaluation of process sustainability, the diversity of input and output resources must be taken into account. Much information is ignored because of the lack of measurement standards brought together in the management system of the company. Often, the attention paid to making a product in a highly competitive market has caused price and profit to overshadow the use of renewable resources (solar energy, rainwater, ambient temperature). These shortcomings regarding the inclusion of cheap resources in the manufacturing process were revealed to the company manager, following participation in the creation of past and present budgets.

The high and fluctuating costs of raw materials have often led to a decrease in profit, necessary for maintaining the company presence in the market. Therefore, the possibilities of introducing information/calculations/analyses related to the input/output flows of resources in the manufacturing process were studied.

The fact that various flows of unified components (solar energy, rainwater, waste) were included in the accounting calculations enables their assessment in the manufacturing process. It is a method presently used to evaluate the sustainability of a system (regional economy, agriculture) [7]. A set of information will be analyzed/studied in the field of manufacturing components for water supply (tubes). This information can constitute the pillar for evaluating the sustainability of a manufacturing process. Optimizing manufacturing technology and monitoring the work process will enable the efficient use of raw materials and utilities during the initial, intermediate, and final stages, resulting in a sustainable product with minimal waste and pollutant emissions (Fig. 2).

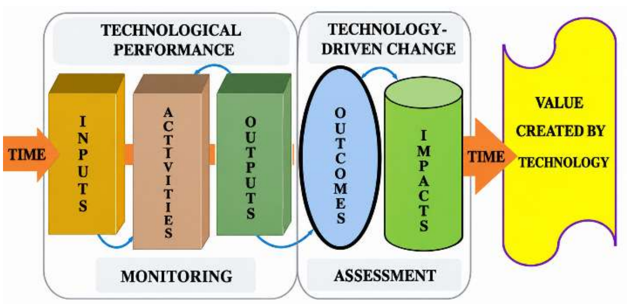


Fig. 2. Evaluating the environmental aspects of a manufacturing process.

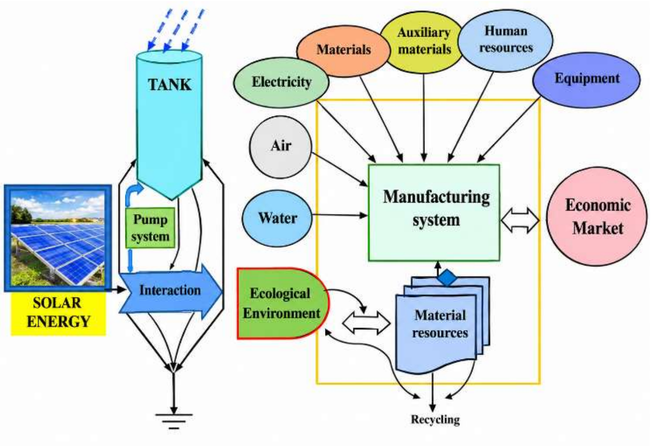
Current studies propose an analysis of manufacturing process performance. Methods have been proposed for developing energy performance certification, including specific indicators tailored to particular manufacturing processes. Additionally, various methods have been analyzed for establishing multi-objective energy indicators and benchmarks, based on energy consumption forecasting through an assessment of the entire manufacturing system [8]. Studies exist that analyze the reduction of CO_2 emissions through the partial replacement of metallic materials. However, trade-offs and limitations regarding the potential availability of these materials and their technical characteristics must be taken into account. In this context, product redesign can lead to emission reductions. Studies indicate that these reductions have been quantified only on a case-by-case basis for specific products and technologies making it difficult to generalize process indicators [9].

III. Mathematical Modeling of Sustainability Indicators

Energy theory was originally proposed by the famous American ecologist Howard T. Odum in the 1980s as a new system for measuring ecological and economic value and a method for systematically analyzing a sustainable system [9].

The benchmark of this method is solar energy; its basic unit is the Solar Emjoule (SEJ), which converts various types of energy and non-current forms of energy of the studied object (such as material flow and capital flow) into a unified solar energy.

After the analysis and processing of the data, a system energy evaluation index is constructed to evaluate the sustainable development performance of an economic process. In emerge tic analysis, the first step is to define the boundaries of the process scope, and to enumerate the main energy sources of the system. It is also necessary to clarify the basic structure of the system, the interrelationships inside and outside the system and the direction of the main ecological flow. In our case, we start from the product—1800 mm (1.80 m) diameter concrete pipe—(SC SOPMET SA). Fig. 3 shows the energy flow diagram. It can be seen that the production process utilizes renewable inputs *R* (e.g., solar energy, rainwater, wind, ambient temperature, etc., derived from nature), non-renewable resources *N* (thermal energy, diesel, and coal), and purchased resources *F* (cement, steel, auxiliary materials, labor, equipment, and management costs required for production). The output consists of finished products reinforced concrete pipes *P*-which are introduced into the market. Waste *W* generated during production is recycled [10].



(a) (b)

Fig. 3. Components that can support sustainability (a) water, (b) other components.

Various input and output data of the manufacturing system are collected via field research. The acquired data are further processed and classified. Component flows (water, material, energy, human resources, etc.) are converted into solar-energy units for energy quantification. The fundamental equation for emergy calculation is given in Eq. (1):

$$EM_i = UEV_i \times N_i \tag{1}$$

where i is the total number of resource types used in the manufacturing process; EM_i represents the solar energy of the i-th resource; UEV_i represents the conversion rate of the energy of the i-th resource; N_i is the quantity of different resource units (mass g or energy J). EM_i refers to the solar emery of the i-th resource in one day. The emergy of each input and output of the EM_N manufacturing system can be summarized to update the EM_R of resources, the EM_F of the procurement resources, the EM_P of the finished product and the EM_W of waste generated during the manufacturing process.

Based on the characteristics of the manufacturing process, several indicators are analyzed. According to these ones, the sustainability of the manufacturing system can be assessed [11]. The relevant indices identified for analysis are: economic index, social index and the environmental index. The related information enables finding the formula to determine the technological process sustainability [12].

A. Economic Index

This indicator corresponds to the Net Energy Yield Ratio (NEYR). As defined in Eq. (2), it relates the net energy generated by the production process to the initial input energy for efficient resource utilization (net output obtained after removing waste, environmental losses, and productive-context consumption):

$$NEYR = \frac{EM_P - EM_W}{EM_R + EM_N + EM_F} \tag{2}$$

B. Social index

The index denoted as EIR represents the ratio between the investments made by the economic system and the free investments from other production ecosystems.

$$EIR = \frac{EM_F}{EM_N + E\quad_R} \tag{3}$$

The *EIR* index defines the energy required to develop and use each unit of natural resources in the manufacturing process. It quantifies the complexity and cost of resource conversion within the manufacturing system. It is used as a measuring element for maintaining the path of economic development, simultaneously with sustainable development-D.

$$EIR > 1 \tag{4}$$

When $EIR > 1$, the system shows increased dependence on purchased resources, corresponding to higher economic investment and environmental load, a pattern typical of industrialized systems.

$$EIR < 1 \tag{5}$$

An EIR lower than 1 indicates higher reliance on free local natural resources and lower economic investment intensity, which is typical of primary or less industrialized systems.

C. Ecological Index

The IELR index represents the ratio of energy from all non-renewable resources (oil, coal) invested by the manufacturing system to the energy of all renewable resources (solar, wind, rainwater). Manufacturing processes generate environmentally harmful emissions. Accordingly, the improved environmental load ratio considers polluting emissions (EP). Incorporating noxious emissions into this indicator enables more accurate assessment of the environmental impacts of economic activities, as given in Eq. (6):

$$IELR = \frac{EM_N + EM_F + E\quad W + EM_{EP}}{EM_R} \tag{6}$$

$$IELR > 1 \tag{7}$$

An IELR greater than 1 indicates high dependence on non-renewable and purchased resources, together with high Pollutant Emissions (EP) and waste generation, thus indicating a heavy environmental load.

$$IELR < 1 \tag{8}$$

An IELR lower than 1 indicates reduced dependence on non-renewable and purchased resources, together with low EP and waste generation, thus reflecting a light environmental load.

Another relevant index analyzed for the manufacturing process is the Energy Waste Rate (EWR), defined as the ratio of emergy of waste emitted during the technological process to the total input emergy, as given in Eq. (9):

$$EWR = \frac{EM_W}{EM_R + EM_N + E\quad F} \tag{9}$$

The index characterizing the energy sustainability of a manufacturing process, denoted IESI, is defined as the ratio of the system's emergy production rate to its environmental loading rate, as formulated in Eq. (10):

$$IESI = \frac{NEYR}{IELR} \tag{10}$$

IV. Assessing the Sustainability of a Manufacturing Process

A. Case study

SC SOPMET SA is a privately owned company specialized in road and railway underpasses, as well as in various types of underground constructions. The company holds workshops with modern equipment and machine tools. It is a member of International Society for Trenchless Technology (ISTT). The economic sustainability of the manufacturing process of concrete tubes is assessed by combining the important ideas on the emergetic theory. The specifications of the tube shown in Fig. 4 are as follows: ø 2240 mm—Outer Diameter (OD); ø 1800 mm—Inner Diameter (ID); length of 3000 mm. The study regarding the manufacturing process was developed independently.

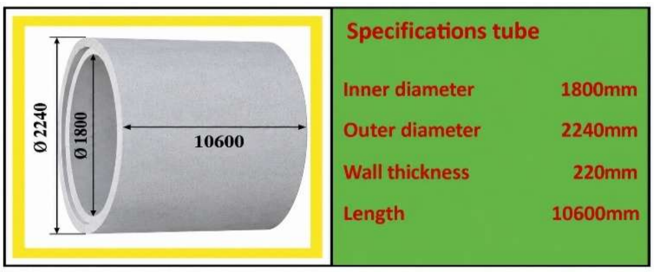


Fig. 4. Concrete tube.

The manufacturing process involves obtaining the technical drawing of the tube from the client or using an in-house design. The manufacturing workflow comprising casting, vibration, demolding, cleaning, measurement, and internal and external finishing is illustrated in Fig. 5.

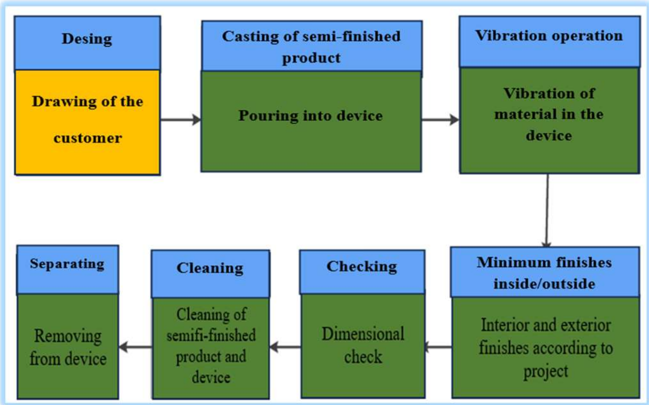


Fig. 5. Manufacturing route of the tube.

The manufacturing process presented includes quantifiable indices aligned with the objectives set out in the sustainability strategy.

D. *Analysis and Results*

The indices show that the *NEYR* of the company processing system is relatively low, with average production efficiency and economic competitiveness. The reason for the low *NEYR* is pointed out by the process analysis: the economic company has invested too much energy in equipment and labor. The tube processing time is high compared to other similar processes in the work environment of the company. Research and analysis of the process should highlight potential for efficiency in compressing execution time and reducing energy consumption. The *EIR* index analyzed in the research has a low value, namely 3.23.

To increase this value, it is possible to reduce the water consumption from the water supply network, switching to rainwater collected in the storage tanks located on the work area border. According to official data published by ANRSC, the tariffs charged by SC Apa Nova SA in October 2025 were: –6.83 RON/m^3 (14,311 Euro, without VAT) for drinking water and 3.60 Ron/m^3 (0,7068 Euro, without VAT) for sewage (VAT included) [13, 14]. That means rainwater is half the price of drinking water. If the equipment for filling with material is positioned by means of the tube-making devices, a reduction in electricity consumption will result. The excess water will be collected in a special tank and then used at the adjacent work stations (after passing through coarse filters). Therefore, this index will have an increase of 25% approximately.

The measured *EWR* and *IELR* indices have sustainable values. Filtration of excess wastewater, its use in the nearby work stations and the efficient collection of waste in specially equipped spaces will lead to an increase in ecological benefits. The *IESI* index of the process approaches the value of 0.39, pointing out a sustainable process along an average period of time, depending on future environmental legislation developments. Waste emissions from machining processes (internal and external finishes) represents 31% of the total waste emissions, mainly consisting of various residual solid materials [15]. A careful approach to finishing enables the use of the dry machining technology with particle collection, leading to an increase in efficiency up to 90%. Another included operation is the tube dry finishing. This technology achieves zero. Thus, the manufacturing process of the tube has been improved/optimized and efficient operation reduces the wastage of energy and materials, water, power, labor. Consequently, a significant amount of energy can be saved.

The results of the analysis highlight a decrease in energy costs and materials, water and labor. Fig. 6 illustrates the fluctuations in emergy evaluation indicators based on the manufacturing process inputs and outputs (raw materials and utilities). Thanks to the responsible consumption of raw materials and utilities, wastewater collection, the use of filters, and on-site electricity generation (via solar panels), the manufacturing process operates within the realm of sustainability.

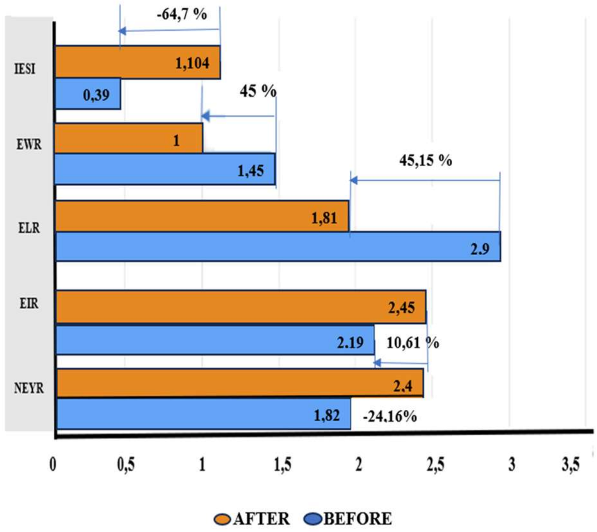


Fig. 6. Changes of energy assessment indices before and after process changes.

The figure highlights energy consumption figures following the implementation of manufacturing process optimization measures. It presents the energy savings achieved, specifically the difference (in absolute or percentage terms) between previous and new levels of consumption and the variation in the efficiency improvement indicator. It also shows the efficiency gains resulting from the new technological workflow integrated into the process and the use of eco-friendly utilities.

E. *Manufacturing Process Modeling Construction Rules*

To model and obtain sustainable value, the following information from the economic process will be taken into consideration: inputs of resource potential (P_s), manufacturing process (P_{ef}), resource consumption process (P_{cr}), start time (t_0), and processing time (t_1). The economic process is considered to be loaded with necessities (manufacturing potential) at t_0, having the inputs (P_s, P_{ef}, P_{cr}). At the same time, in the period (t_0, t_1), it will be taken into account a transformation coefficient denoted by $\alpha_{p}t_1$ (determined by the principles and laws of manufacturing), the finished product with the economic load denoted by $P_{ep}t_1$ and the losses resulting from the manufacturing process Ep^*. The following elements are included in the technological chain: resource potential (s), technology (i), management and energy (e), which, if effectively valorized, will constitute (at the end) the value potential of the product—$P_{ep}t_1$.

The product is defined by the Eq. (11):

$$P_s + E_{ef} + E_{cr} = E_{ep} + E_p^* \qquad (11)$$

The transformation coefficient $\alpha_p t_1$ (from t_0 to t_1) depends on the technological capacity and the company organization as for the integration of sustainability, thus:

$$\begin{cases} E_p^* < \alpha_p t_1 & , sustainable\ process \\ E_p^* > \alpha_p t_1 & , law\ sustainable\ process \end{cases}$$

V. Conclusions

This research paper analyzes the concrete pipe manufacturing process at SC SOPMET SA. Drawing on "emergy" theory methodology, the study examines the stages, phases, and operations of the manufacturing process, identifying key indicators that define sustainability. Data derived from the analyzed indicators (EWR, IELR, IESI) enabled the measurement and evaluation of the manufacturing process from a sustainability perspective. By developing this concept through a multidimensional approach to sustainability, the study focuses on identifying generally applicable indicators for achieving a manufacturing process that is sustainable from both economic and ecological standpoints. Based on the "energy" conceptual model, requirements were identified for information models that support process sustainability. The results demonstrate that a multidimensional approach to sustainability emphasizing a limited number of general indicators can effectively highlight the sustainability of a manufacturing process. Based on the model developed and applied in this case study, a generalized model applicable across various industrial sectors can be formulated.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Cristian Ionel Păunescu organized and structured the manuscript content, conducted content analysis, and provided the relevant research data. He also completed the first draft of the manuscript and participated in manuscript review and revision. Mihai Hagiescu responsible for the formal data analysis and research methodology design, as well as the review and editing of the manuscript. Alexandru Ștefan Velicu performed research analysis, content updating and model construction, and undertook manuscript writing, figure drawing, as well as subsequent review and revision work. All authors have read, reviewed, and approved the final submitted version of the manuscript.

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