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CHARTING THE PRINCIPLES OF THE CIRCULAR ECONOMY IN THE EVOLUTION OF CUSTOM PRODUCTION MANAGEMENT

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Abstract: Custom production is a subsector of the production industry that provides the opportunity to analyze and assess the implementation of circularity measures at every stage of the life cycle of a product, including the design phase. In most of the cases custom production is associated to engineer-to-order products concentrating the decision-making process almost entirely in-house with slight dependencies on third-party organizations, offering an open path for the circular economy principles adoption and implementation. The aim of this study is to analyze circularity measures, strategies and tools in the custom production management evolution dynamic based on a literature review. The results reveal a poor coverage in research for custom production management in the circular economy context and a focus on the production management in general around the concepts of sustainable production, Industry 4.0, Cleaner Production and sustainable job-shop production mainly from an environmental standpoint, overlooking the social and economic aspects of circularity.

Keywords: circular economy, custom production management, sustainable production, Industry 4.0, cleaner production, integrated production systems

1 INTRODUCTION

The evolution of industrial production is a major influencing factor in a country's economy. The experience of the pandemic has changed economic approaches and opened new avenues regarding the importance of risk management. Resource and production cost management is subject to change and requires strategic managerial decisions within firms. The costs of industrial production in December 2022 showed an increase of 32.8% compared to the previous year (INS, 2023a), following significant increases in the prices of energy, but also of goods of immediate use. The major contextual changes that happened in a relatively short time put the companies in front of strategic decisions of repositioning on the market, thus the production management being forced to give up the classic directions and adapt to external influences.

National economies are defined by their ability to determine the creation and efficient operation of as many manufacturing firms as possible. The development of industry is in Romania the branch that provides the biggest contribution to the achievement of the gross domestic product, having an important role in the achievement of exports. Construction together with industrial production in Romania represents approximately one third of the GDP (INS, 2023b). Economic efficiency and the degree of profitability of companies mainly depends on the production management in the context of accelerated technological advance, limited natural material resources, increased energy costs, inflation, and the continuous fluctuation of market demand.

The concept of circular economy has gained momentum in the last years among scholars, industry professionals and policy makers as an alternative for the traditional take-make-dispose linear approach. The last decades, characterized by global aspects as fast urbanization and population growth, natural resource depletion, accelerated waste generation, and pollution overlapping socio-economic and political crises led to the need to change the perspective towards a more sustainable one. Aiming to close the loop by decoupling economic prosperity and growth from raw material resource consumption and to efficiently manage waste and pollution, circular economy represents a solution that offers benefits at all levels: organizational and individual, local and global (Ellen MacArthur Foundation, n.d.)

Custom manufacturing or small batch production is a specific case where the implementation of the principles of the circular economy can be tracked and analyzed from design to end-of-life, offering solutions to closing the loop for the industrial production in general due to the in-house compression of product life cycle sequences. The engineer-to-order products in comparison to make-to-order products in the context of the circular economy can serve as a fundamental starting point to implement and assess circular strategies and measures, production units having extensive authority of decisions from the design phase to the end-of-life. Researching custom manufacturing management with the aim to delineate imprinting visions and concepts in the evolution towards circularity this study is based on a literature review highlighting the most characteristic approaches and perspectives in this field.

2 DEFINITIONS AND METHOD

Circular economy is considered in this study based on the definition refined by Kirchher *"as an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations"* (Kirchherr, Reike, & Hekkert, 2017).

Circular economy basic principles are driven by design and can be formulated succinctly in three directions (Ellen MacArthur Foundation, n.d.):

- waste and pollution elimination;
- product and material retention at their highest value in the economic circuit for as long as possible;
- regeneration of nature

According to Velenturf & Purnell (2021) a sustainable circular society is built upon:

- mutually beneficial resource flow;
- between society and nature;
- detaching natural resource consumption from prerequisites for prosperity;
- design for circularity using the R-strategies;

- creating and implementing circular business models;
- remodeling consumption by sharing or product-to-service converting;
- stakeholders' involvement;
- knowledge exchange and diversity of circular solutions and viewpoints;
- active involvement of regulatory institutions of political-economic systems;
- multi-level circular strategy implementation;
- a holistic circularity assessment approach.

Production system management is defined by its functions and objectives. Functions are defined as:

- planning;
- organizing;
- staffing;
- leading;
- controlling.

Production management objectives can be summarized in target activities as:

- cost minimization;
- productivity increasing;
- timely delivery;
- efficient capacity planning;
- warehousing and inventory optimization;
- purchase optimization;
- risk minimization.

Custom manufacturing is conditioned by:

- the universal character of the production units and enterprise;
- highly qualified staff;
- irregular manufacturing workflows;
- cell, or homogeneous machine groups due to a great variety in technological flows;
- irregular production rhythmicity;
- expanded manufacturing time;
- technological preparation does not represent a different preceding manufacturing stage.

In order to identify the circularity principles in the evolution of custom manufacturing management, a literature review was carried out on Scopus database using "circular economy" in "article title, abstract, keyword" search with the Boolean operator AND, and concepts as "custom manufacturing management", "custom production", "small batch production", "small series production", "low series production", "low series manufacturing", "job shop production", "job shop manufacturing", resulting in 20 open access articles, representing the core aspects of the research extended with complementary studies and research articles in the field of sustainable production management.

3 RESULTS

The evolution of custom production management in terms of implemented circularity principles is delineated along four basic approaches:

- sustainable production;
- Industry 4.0;
- Cleaner Production;
- sustainable job shop production.

Sustainability represents the key element in all these concepts with focus on material use and waste reduction, but not necessarily attached to R strategies or to the closed loop perspective. Reducing waste and raw materials, and recycling are sometimes considered, but reusing, rethinking, repairing, refurbishing, remanufacturing, repurposing are roughly missing notions. The environmental dimension of the circular economy is prevalent, social, and economic aspects being hardly mentioned.

3.1 Sustainable production

Sustainable production is a concept widely explored by many scholars and industry professionals since the 1970s when the unsustainability of the production management and process was recognized and settled the demand for a better solution. Perception and translation of the sustainable production manifested in a great variety, to the extent that many authors claim that there is no uniformly or sufficiently accepted understanding of the concept and its associated sub-concepts (Moldavska & Welo, 2017; Sartal, Bellas, Mejías, & García-Collado, 2020).

For the industry, sustainability must fulfill not only the requirements of the economic ends, but also to ensure socially and environmentally responsible processes. Sustainable production can refer to the enterprise as a whole or it can refer to certain components, such as product, process, technology, organization, supply, employees, or customers (for example a product designed with the minimization of required resources; an internal regulation implemented for safety and employee integrity, etc.). The most comprehensive and used definition of sustainable manufacturing is formulated as the production of goods with least possible impact on the environment and social accountability assumption for employees, the community and consumers throughout the life cycle of a product, while achieving economic benefits (Zhang & Haapala, 2015).

Sustainable production is closely related to the LCA (Life Cycle Assessment) method, which as a management and environmental impact assessment method considers all aspects of resource use associated with an industrial system throughout the life cycle of a product.

Another concept associated with sustainable production is the TBL (Tipple Bottom Line) which refers to the pillars of sustainability: the economic, social, and environmental dimensions. The TBL offers the framework in which the sustainability of production systems is assessed but does not imply the cyclicality imposed by the circular economy.

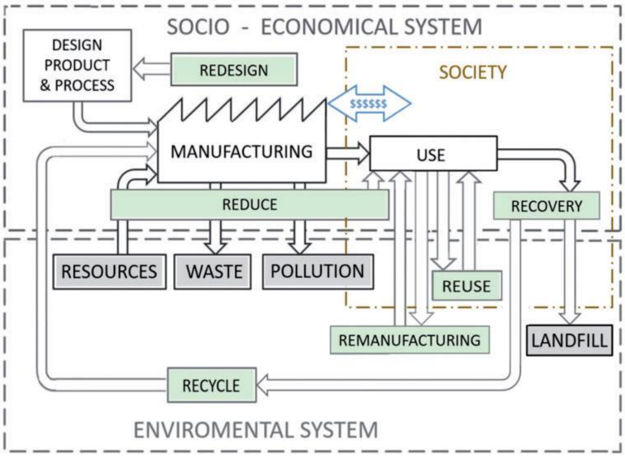

Figure 1. Sequence of sustainable manufacturing (SM) process within 6R and TBL dimensions (Sartal et al., 2020)

Sustainable manufacturing as a research domain is analyzed also as a conceptual and methodological framework being linked to principles of the lean environmental performance, the sustainable supply chain, the adjustment to the Sustainable Development Goals, social dimensions of inclusion and stakeholder involvement, newer technologies and generalizability (Bhatt, Ghuman, & Dhir, 2020).

3.2 *Industry 4.0*

The fourth industrial revolution is changing production by digitizing processes and monitoring them in real time, eliminating human errors and optimizing the necessary available resources. The precise and continuous monitoring of the production processes offers the advantage of accurately evaluating the results thus making it possible to increase productivity. Industry 4.0 relies on the connection to the concepts of the Internet of Things (IoT) and product to service in manufacturing companies, creating vertically and horizontally integrated production systems. The actively changing customer demands can be met in the resulting smart factories where the high variability of small batches, the human skills and automation are interspersed (Thoben et al., 2017). The characteristic tools for Industry 4.0 are IoT (Internet of Things), cloud computing, additive manufacturing, BigData, AI (artificial intelligence), cobots (collaborative robots), VR (Virtual Reality), cyber-physical systems. To implement the defining elements for the fourth industrial revolution in a manufacturing enterprise, the existence of CNC machines and an ERP (Enterprise Resource Planning) or MES (Manufacturing Execution System) is assumed.

Industry 4.0 as a result of the accelerated advancement of technology and the mass customization tendency is closely linked to concepts as smart products, sustainability, R strategies, lean manufacturing, flexible manufacturing, agile manufacturing, innovation management, knowledge management, collaborative networks and digital transformation (Suleiman, Shaikholla, Dikhanbayeva, Shehab, & Turkyilmaz, 2022). It is important to highlight that not the implementation of technology as such is the booster for performance in the production systems, but the optimal synergy between the individuals, tasks and technology (Yue, Wang, Fang, & Han, 2020).

3.3 Cleaner production

Cleaner production (CP) is a term introduced by the United Nations Environment Program (UNEP) as a guidance for environmental performance improvement for organizations, a term conversely used with concepts as cleaner technologies, waste minimization and pollution prevention (Yusup, Wan Mahmood, Salleh, & Ab Rahman, 2015). “CP is a continuous, integrated and preventive environmental strategy for products, services and processes that aims to increase overall efficiency and reduce risk to both humans and the environment “ (UNEP, 2006) .

CP strategy means increasing process efficiency by optimizing key parameters for quality production with minimal by-products/waste. For significant diminution in energy, water and utilities, process integration and process intensification are in operation largely in the manufacturing industry. Process integration is in accordance with the concept of circular economy and industrial symbiosis where resource consumption is optimized within the system (Fan, Chin, Klemeš, Varbanov, & Liu, 2020).

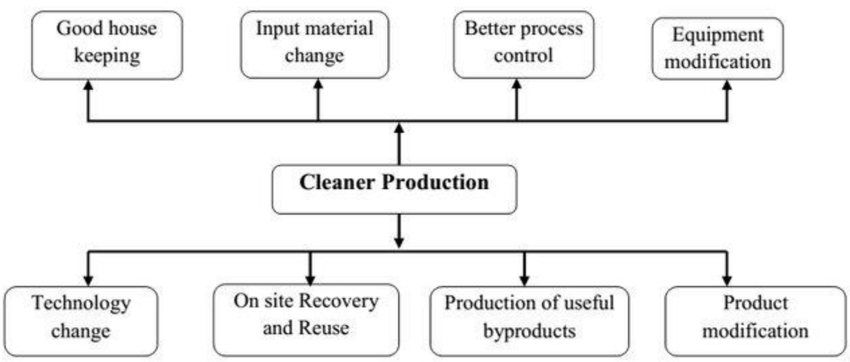

Figure 2. Schematic representation: elements of Cleaner Production system (Terefe, Gashaw, & Warkineh, 2015).

CP measures could be grouped into three major categories: waste reduction at source, recycling, and product modification.

Options for reducing waste at source are subdivided into good housekeeping and process modification options. Good housekeeping usually means changing existing practices or introducing new ways of operating and maintaining equipment. Process modification refers to the options for raw material modification, better process control, equipment modification, and technology change. Changing raw material options includes the use of less hazardous materials or higher quality raw materials aimed at reducing the amount or the toxicity of process waste. Better process control aims to optimize process parameters and conditions such as pH, temperature, pressure, residence time, etc., to ensure that existing processes operate at higher efficiency and with less waste generation and emissions. Equipment modification includes small modifications to existing equipment such as installation of drip trays, installation of fluid coupling in mixers, activation of pumps by level control mechanisms, etc., which aims to reduce the generation of waste caused by poor equipment design. Technological change is the replacement of technology, or the processing cycle to reduce the generation of waste and emissions during the production process.

Recycling represents the on-site recovery and reuse of materials and energy. Recovered materials can either be reused in the same process or used for another objective (for example, in the production of useful by-products).

Product modification involves changing the product with the aim to minimize waste during production, use and disposal, i.e. throughout the entire life cycle of the product.

3.4 Sustainable job-shop production

To produce small batches, the general and operational management adapts from the perspective of the circular economy to the general rules regarding production. Studies show that the specific interest in the optimization of small series production activity is channeled towards the search for solutions by which the level and effect of uncertainty related to disruptive factors can be reduced. Custom production does not allow repeated observation of deviations and identification of patterns or probabilities, thus technological process interruptions and reproduction or reprocessing activities disrupt planned activities and involve costs. Most such solutions relate to digitalized monitoring and activity control.

In the actual custom manufacturing process, uncertainty plays the role of a stringent impediment for an effective enterprise. To cease this barrier, intelligent manufacturing scheduling models integrated with uncertainty generators are proposed, linking the sources of uncertainty and the types of interrelations between them along the process itinerary (Serrano-Ruiz, Mula, & Poler, 2022).

The various production disturbances that occur in the flexible production process of the workshop may affect the production process, some of which may lead to the extension of the production completion time. As an exit guide from this drawback, a flexible dynamic workshop scheduling method based on DT (digital twin) is proposed in a dynamic scheduling framework (Wang, Leng, Liu, Wang, & Meng, 2022).

Identifying the problem of reaction time to uncertainties and disturbances of the custom production system, another method also based on DT and tested in an aerospace manufacturing plant based on the theory of vector neural

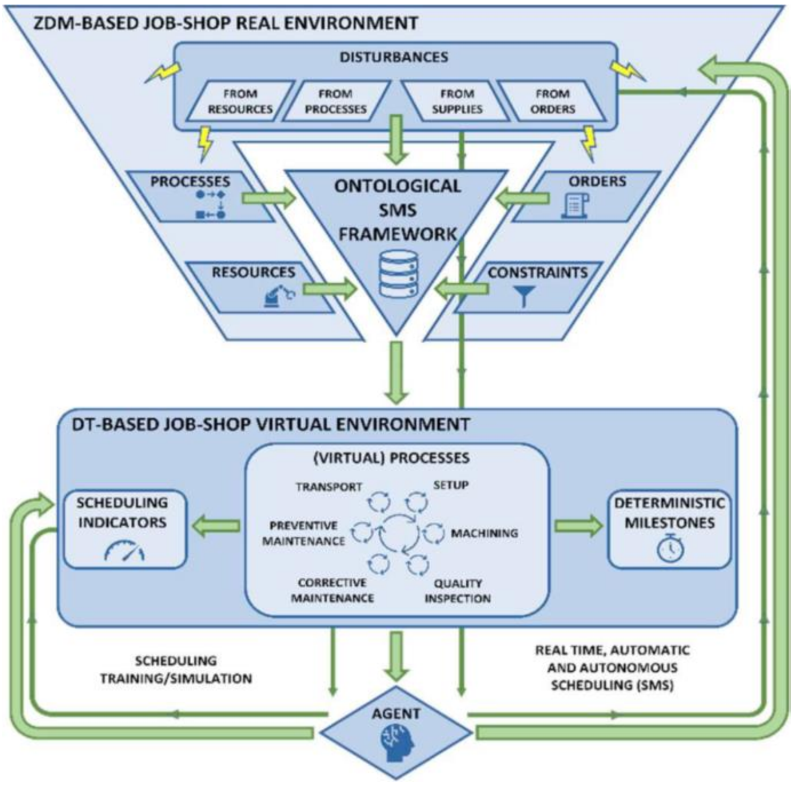

Figure 3. SMS domain setup based on digital twinning in a zero disturbance model (ZDM) (Serrano-Ruiz, Mula, & Poler, 2022).

networks effectively identifies and corrects the effects of disturbances providing increased productivity (Ding, Guo, & Wu, 2022).

A proactive approach was identified, being generated by using genetic algorithm for contingencies in the production of very large items when it is necessary to undergo some rework or reprocessing. The solution consisted in a system that produces different scenarios for the disruption factors to reduce delivery times or overtime costs required for corrective measures (Morinaga et al., 2023).

Also by using the genetic algorithm production scheduling models were developed to improve collaborative production management, by integrating MES (Manufacturing Execution System) and ERP (Enterprise Resource Planning) in discrete collaborative production (T. Xu, Li, & Feng, 2022).

An approach to improve resource consumption in the custom manufacturing process is to integrate IoT to identify the level of uncertainty related to machine operation and to identify carbon emissions (Su, Dong, Lu, Chen, & Ji, 2022).

4 DISCUSSIONS AND CONCLUSIONS

Custom production management analysis in relation to the circular economy principles is a scattered field, lacking representation, and structure, although it offers the possibility for generating successful management models by researching throughout the whole life cycle of a product in the pursuit of natural resource consumption and pollution reduction in a cost-effective, economically rewarding, sustainable way. All phases of custom production are carried out in most cases in-house, granting the opportunity to support and promote circularity and resource waste management from design to end-of life of a product.

Limitations consist firstly in identifying small batch and custom manufacturing economic units as no official catalog or register of such units exists, thus sampling for research is very difficult and only seldom case studies focus on the topic. Secondly, rarely a production system is distinctly entirely custom or low batch manufacturer, entangling the research if there is no clear-cut tracking and evidence of the effects of circularity within the company.

However, studies about integrated production systems, collaborative strategies for circular economy in manufacturing, and engineer to order products could serve as pathways in the research of circular economy principles in the custom production management.

The integrated positive impact of circular economy, Industry 4.0 and lean manufacturing on sustainability performance of manufacturing firms is endorsed by studies concluding the beneficial influence of Industry 4.0 and lean manufacturing as mediating enablers (Ghaithan, Alshammakhi, Mohammed, & Mazher, 2023). Industry 4.0 is analyzed also in relation with Cleaner Production strategies resulting in a classification of ten clusters of the mentioned association (strategy, waste, recycling, life cycle, resources, energy, production, work, performance and environment), confirming the requirements of the circular economy (Satyro et al., 2023). Environmental footprint, recyclability of materials and post-use material assessment are analyzed in the process of integrating circular economy principles in additive manufacturing, stating the benefits and advantages of a new, sustainable production process (Chowdhury, 2023). Enabling technologies of Industry 4.0 (IoT, BigData, additive manufacturing, cloud computing, blockchain, AI, simulation, automation and robots, cyber-physical systems, autonomous vehicles, radio frequency identification) are identified in studies for the improvement of green supply chain adoption (green manufacturing, reverse logistic, green design, carbon management and green warehousing) (Morella, Lambán, Royo, Sánchez, & Latapia, 2023). Digital Twins being a Industry 4.0 tool are identified as lacking environmental-related functions in resemblance to the circular economy requirements and regulations for a better sustainability performance of production entities (Popescu, Dragomir, Popescu, & Dragomir, 2022).

Barriers in implementing resource efficiency measures are analyzed in framing by supply side, demand side and life cycle measures related to the business model changes (in supply chain, internal process, customer interface, financial model and value proposition) in 143 cases (Diaz Lopez, Bastein, & Tukker, 2019). Three manufacturing configurations (product value extension, resource value extension and processing) that enable success are identified in a study conducted on 96 circular start-ups analyzing circular manufacturing activities in relation to the supply characteristics. (Prosman & Cagliano, 2022).

The specific characteristics of custom production could provide successful management models for implementing the principles of the circular economy by bearing the authority of decisions at all stages of the life cycle of a product. Studies are scantly depicting the management process in the implementation of circularity elements in the custom production activities. Further research is needed, not only to create feasible management models, but also to sustain and boost the process of closing the loop for the existing custom manufacturing entities in an economically, socially, and environmentally safe and beneficial manner.

Circular economy today is not only a fancy theoretical concept. Global, national, regional, and even local regulations are conferring a compulsory bundle of environmental requirements simultaneously with the fluctuation of the market dynamic and the resource limitations. A proactive approach for a better future, but also for present economic benefits relies on the perspective change from linear to circular. Education, formal and informal, is crucial in internalizing the essence of the circularity principles and adopting them for generating value for individuals and communities. But for a manufacturing firm or any economic unit the transition to a new way of thinking and acting is necessary to be also profitable in monetary terms.

This study structured the concepts related to the custom manufacturing in the context of the circular economy. Sustainable manufacturing, Industry 4.0, Cleaner Production, and sustainable job-shop production were identified as concentrators of circularity and sustainability visions. Although research on implementation of circular practices in custom or small batch manufacturing is scarce, the leading directions can be concluded from the research field of the sustainable production.

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