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IMPROVING THE ECO-EFFICIENCY OF MANUFACTURING PROCESSES WITH THE USE OF INDUSTRY 4.0 TECHNOLOGIES IN THE CIRCULAR ECONOMY

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Purpose: The aim of the article is to analyze the implementation of the Industry 4.0 technologies to improve eco-efficiency of manufacturing processes from the perspective of the development of innovative IT technologies in the circular economy.
Design/methodology/approach: The research methods used in the article were desk research analysis of available source data on the functioning of Industry 4.0 technologies. Additionally, the author bases on the institutional and legal method. Analysis of selected documents and existing studies have allowed to obtain answers to the research questions and to describe the eco-efficiency of manufacturing processes.
Findings: The Industry 4.0 technologies in the circular economy can contribute to improve the eco-efficiency of manufacturing processes. However, there are still some difficulties in creating the fully efficient processes in the circular economy.
Research limitations/implications: The main limitation in carrying out the research is the difficult access to data about the quantity and quality of the eco-efficiency of manufacturing processes improving by the Industry 4.0 technologies.
Practical implications: The results of analysis and the conclusions in this article can be used by managers of the different types of companies involved in the circular economy. The research impact upon the enterprise concentrating on the raising awareness of the benefits of using wide range of the Industry 4.0 technologies for improving the eco-efficiency of manufacturing processes.
Originality/value: This article describes the benefits that can be obtained from the implementation of the Industry 4.0 technologies in the circular economy. The research issues related to development of the circular economy constitute a new area of research. The newly developed focus on improving eco-efficiency of the manufacturing processes by using the innovative IT technologies in the circular economy. The eco-efficiency of the manufacturing processes in the circular economy, examined from the point of view of the use of Industry 4.0 technologies, is an innovative research approach.

Keywords: Eco-Efficiency, manufacturing processes, IT technologies, Industry 4.0, circular economy.

Category of the paper: Viewpoint.

1. Introduction

The basic assumptions of the circular economy are based on the reduction of excessive consumption of resources, while increasing the efficiency of production processes and reuse of manufactured products. The main concern is not only about increasing the potential for recycling, but also about extending the value of circularity in the supply chain, translating into both refurbishing and repairing items, selling services instead of products, eco-design, and sharing economy (Kuzior, 2013). Implementing the principles of a circular economy requires the change in the perception of the mechanisms of manufacturing processes and using innovative IT technologies in order to increase their widely understood efficiency.

The definition of the circular economy was adopted by the Polish Council of Ministers in the *Roadmap for the transition to a circular economy* and is the concept that aims to keep the quantity of products, materials and raw materials in circulation for as long as possible and to minimize waste generation, applying management methods according to the waste hierarchy (Mapa drogowa, 2019).

2. IT technologies in Industry 4.0

The introduction of IT technologies in Industry 4.0 is based on innovation in the use of information and communication technologies (ICT – Information and Communication Technologies). The use of modern IT technologies combined with the skills and experience of the employees enables the development and implementation of effective models to control the production process (Kiełtyka, 2017).

Industry 4.0 is a concept currently being implemented for the production sectors, based on the use of innovative IT-supported tools. The focal points of Industry 4.0 are: Robotization and Automation, Digitization of Manual Processes, Telepresence, Machine Learning, IoT, Communication between Machines, 3D Printing as Additive Manufacturing, Image Recognition, Autonomous Vehicles, Mobile Devices, Intelligent Sensors, Virtual and Augmented Reality, Cloud Solutions, Cybersecurity Security.

There are different approaches to the definition of Industry 4.0. Hermann (Hermann, 2016) defines Industry 4.0 as a collective term for technologies for organizing the value chain, while Industry 4.0 components are categorized as Internet of Things, Cyber Physical Systems, Internet of Services and Smart Factory. Posada (Posada, 2015) gives a comprehensive overview of new technologies and explains that visual processing can be seen as a key element of Industry 4.0. Another researcher Sommer (Sommer, 2015) believes it is important to raise awareness of Industry 4.0 and its dimensions in order to increase the competitiveness of

companies. Yin and Kaynak (Yin, 2015) believe that intelligent systems and the data they generate play an important role in business efficiency, cost efficiency, quality and error-free processes.

It's worth mentioning that another scientist Yang with his colleagues analyze the challenges and opportunities for smart solutions in the regeneration sector. These challenges include lack of standardization, life cycle design and limited information exchange. Capabilities include increased efficiency and reliability of remanufacturing processes through Industry 4.0 'smart factories', as well as technologies such as additive and hybrid manufacturing, 3D scanning, Automated Transport Systems (ATS) and AR to lower costs and improve the quality of remanufactured products (Yang, 2018).

Kerin and Pham state that technologies such as the Internet of Things (IoT), additive manufacturing, collaborative robots (cobots), virtual/augmented reality (VR/AR), and data carrier technologies such as RFID are promising for the remanufacturing sector, because the operations in this sector still consist mainly of manual processes (Kerin, 2019).

For the efficient implementation of IT technologies in Industry 4.0 it seems necessary to use calculation algorithms and to visualize the manufacturing process accordingly, as well as to design a system for capturing and processing the information obtained. This is helpful in designing a sustainable business (Kuzior, 2019).

The use of IT technologies in the area of Industry 4.0 leads to many positive utility effects, including:

- the possibility of dynamic evaluation of quantitative indicators of the production process,
- the online access to data from the production process and remote management of production,
- the calculation and determination of the parameters of the production process: maximum and minimum values for predictors, changes in the quantity of predictors, changes in the number of simulants or destimulants forming a set of predictors, changes in the eco-indicator values, changes in the weights used in mathematical models,
- the collection of data on technologies in a relational database and dissemination via the Internet,
- searching the database on the basis of custom queries,
- the preparation of reports with the results of multidimensional data analyses, the results of database browsers or calculated evaluations of the eco-efficiency of the process.

3. Improving the eco-efficiency of manufacturing sectors

The implementation of Industry 4.0 technologies can be seen as another industrial revolution, making an important contribution to the ecological effects and increasing the eco-efficiency in most manufacturing sectors.

The Eco-efficiency (EE) can be defined as an approach to managing the manufacturing process and the provision of services at competitive prices, tailored to the needs of the customers and improving their quality of life, reducing the impact on the environment throughout the life cycle of a product or service (Asem-Hiablie, 2019; Basset-Mens, 2009; Burchart-Korol, 2016; Kuzior, 2014).

Manufacturing competitively priced goods and services, while reducing environmental impacts and maintaining consumption of natural resources at a level commensurate with the Earth's capabilities, is an undeniable challenge for the economy of every country (Berkel, 2007).

It can be said that eco-efficiency is a prerequisite for competitiveness, since only innovative companies can exist on the market that are responsible to the environmental society. The benefits of improving eco-efficiency include (Kleibera, 2011):

- energy savings,
- savings in raw materials,
- reducing the amount of waste,
- improving product quality,
- simplification of processes,
- improving the health safety of workers,
- improving the image of the company,
- increasing production capacity,
- savings in environmental fees,
- increasing competitiveness thanks to the new and improved technologies, products and services,
- reducing the risk of legal sanctions related to environmental compliance.

Business managers should regularly conduct the eco-efficiency analyses to reduce material consumption, to reduce waste and emissions, to achieve material savings, reduce pollution by reducing production costs and increase competitiveness (Ekins, 2005). In addition, the organic production of "green" products provides the marketing advantages and the greater consumer acceptance. The benefits of implementing and analyzing eco-efficiency are also the increased morale of employees, the increased attractiveness for investors, the greater acceptance of the local population and the self-esteem of managers.

4. Efficiency of the manufacturing processes

When analyzing the economic potential of a company, the efficiency of production processes is crucial, i.e. an orderly set of activities aimed at the production of a particular product. Analysis of the effectiveness of the production process should focus on all technological phases, like preparatory, manufacturing and final phases, as well as operations carried out, broken down by technological, control, transport and storage. This approach applies to all types of production: single series, series (small, medium and large series) and mass production. It should be emphasized that the use of innovative IT tools in highly mechanized production with a high degree of automation of the production workstations is particularly useful.

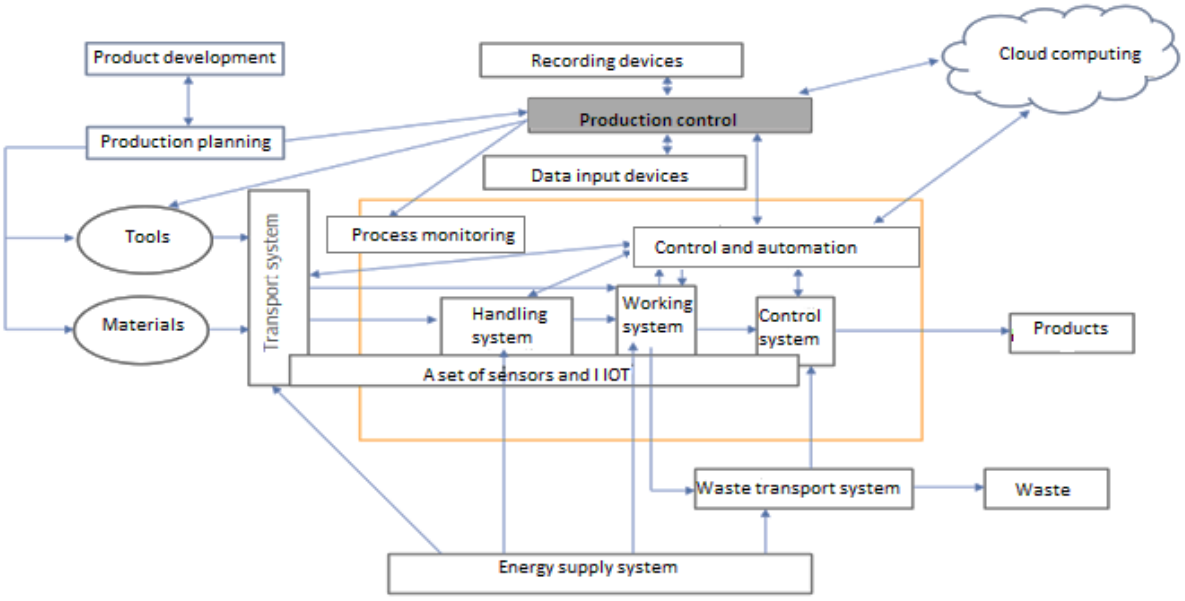

Figure 1. Manufacturing process with IT tools of Industry 4.0. Author's own elaboration.

One of the most objective and at the same time most universal indicators for assessing the efficiency of manufacturing processes and the level of use of production facilities is the OEE indicator (Overall Equipment Efficiency). This indicator can be calculated and interpreted in different ways. The quality of the data obtained in the performance analysis is decisive for its calculation. IT solutions in the area of Industry 4.0 can help in this respect.

It should be emphasised that this indicator reflects the functionality of the equipment, i.e. the machine, the plant assembly or the production line, but not the employees who use the equipment during the manufacturing process. This indicator is a key indicator for improving the production process using the Total Productive Maintenance (TPM) method. OEE requires comparing the current condition of the equipment with the ideal situation used as a reference.

This indicator is expressed in % and the maximum value it could reach is 100. If the OEE is 100%, the production plants are constantly in motion (without interruptions/stops) and work at constant speed (without any slowing down of the process) and generate only products that

fully meet the customer's needs (assumption of 100% quality). Such an ideal condition obviously does not exist, but it is a benchmark for verifying the actual condition of the plants and the entire production line.

The OEE index reflects the availability, efficiency and quality of the production facilities. The OEE can therefore be expressed as follows:

$$OEE = WS \times WW \times WJ \tag{1}$$

WS – The availability factor represents the degree of utilization of the time planned for production according to the following formula:

$$WS = \frac{actual\ equipment\ working\ time}{projected\ equipment\ working\ time} \tag{2}$$

WW – The productivity factor allows the verification of the speed of the production process, expressed as conformity with the given times of the production cycles.

$$WW = \frac{min.cycle\ time\ \times\ number\ of\ units\ produced}{actual\ operating\ time\ of\ equipment} \tag{3}$$

WJ – Quality factor represents the degree of conformity of the products with the needs of the customer, developed by the use of the existing equipment

$$WJ = \frac{number\ of\ products\ according\ to\ customer\ request}{number\ of\ all\ products\ produced} \tag{4}$$

The eco-efficiency index is used to measure progress towards cleaner production and sustainability. There are several definitions of the eco-efficiency index, of which the World Business Council for Sustianble Develepoment definition is considered to be one of the most popular. According to this definition (Verfaillie, 2000), eco-efficiency is expressed as the ratio between the value of the product and the environmental impact caused by production.

$$Eco - efficiency\ = \frac{product\ value}{environmental\ impact} \tag{5}$$

Eco-efficiency indicators should be designed to (Huppes, 2005):

- address relevant parameters affecting the environment and human health,
- focus on measurable parameters,
- be clearly formulated, readable and verifiable,
- take into account the diversity of individual business activities,
- take into account the specifics of the company's operations,
- be traceable over time,
- provide resultant information to managers on what actions should be taken to improve efficiency,
- be understandable for all participants of the process.

IT tools used in industry allow the elimination of one of the biggest technical problems in the application of efficiency indicators, namely the large amount of work involved in collecting and processing data from the process in a dynamic system in order to ensure objective representation of the actual and complete impact of the process on the environment and human health. This allows the use of fewer simplifications in the model of the analysis of the eco-efficiency of the production process, and in the broader analysis of the impact of the product or service on the environment and human health.

However, the methodological problem for researchers remains the difficult comparability of the results of the eco-efficiency analysis for different production processes or products/services due to separate specificity, environment, detailed parameters.

5. Eco-efficiency in Circular Economy

Taking into account the requirement to carry out economic changes resulting from the need to reduce natural resources by introducing the concept of the Circular Economy, the use of tools to identify and improve the eco-efficiency of production processes seems to be even a necessity.

This direction is in line with the so-called EU Package for a Circular Economy consisting of the three Communications From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions (Kuzior, 2022):

- Towards a circular economy: A zero waste programme for Europe. COM(2014)398 final of 02.07.2014.
- Closing the loop – An EU action plan for the Circular Economy. COM(2015)614 final of 02.12.2015.
- Monitoring framework for the circular economy. COM(2018)0029 final of 16.01.2018.

The implementation of the circular economy model with the application of eco-efficiency solutions in production processes undoubtedly requires multilateral cooperation and involvement of many parties – both entrepreneurs and scientific entities, institutions of the educational system, non-governmental organizations, government bodies and also consumers.

The introduction of eco-efficiency solutions in a closed loop economy can be expected to bring multi-faceted benefits: economic, raw material, environmental and social (Report, 2016).

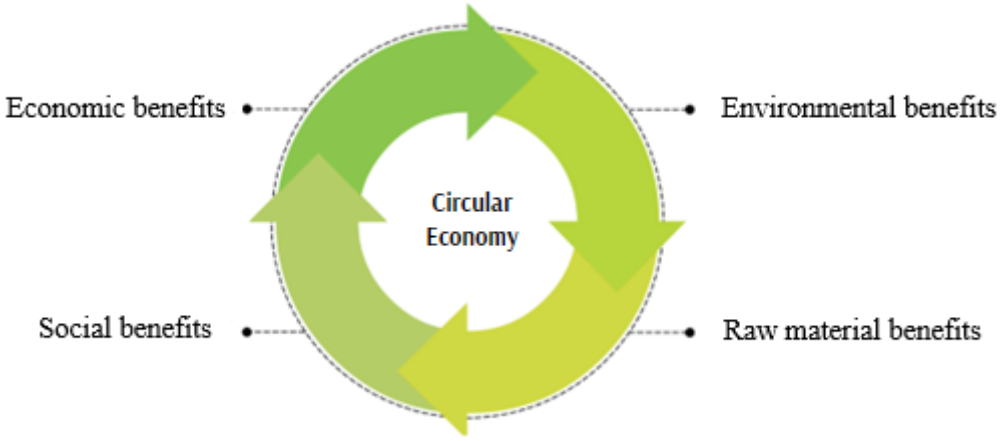

Figure 2. Benefits of Circular Economy. Adapted from: Report 2016.

Economic benefits

The essence of achieving economic benefits by applying the principles of the closed loop economy is to develop and use solutions in the production process that result in the generation of greater value, while minimizing production costs to produce products that meet consumer expectations.

Raw material benefits

With the aim of conserving natural resources, efficiency solutions contribute by design to ensure the production of high-quality products, the recovery of waste and the use of secondary raw materials.

Environmental benefits

At the core of the circular economy concept is the aim to minimize the negative impact of manufacturing on the environment and improve social welfare by making global production completely independent of resource and energy consumption. Among the objectives set by the European Commission for EU member states are: maximization of recycling of municipal waste, packaging waste with simultaneous minimization of the amount of landfilled waste and reduction of greenhouse gas emissions.

Social benefits

A wide range of social benefits based on sustainable consumption and "green" jobs are achieved through the use of the sharing economy, eco-design, reuse or recycling, among others.

6. Summary

Circular Economy, being an alternative to the traditional model of economy, includes a set of activities aimed at achieving economic, but above all ecological effects, like preventing waste of raw materials, extending the product life cycle, recovery of resources. The modern manufacturing companies increasingly use the innovative IT tools to increase the environmental

efficiency by integrating them with other production management methods in order to reduce the company's impact on the environment and increase economic performance.

Continuous improvement of products and technologies with the use of IT tools in the field of Industry 4.0 to achieve sustainable competitive advantage and improve the state of the natural environment. The feature of modern enterprise management systems is to focus on increasing the efficiency of workplaces and the entire production process, and thus to create an eco-innovative company that cares about the environment and most fully meets customer needs. Analysis of eco-efficiency in the company integrated with other methods of production management using IT tools serves to increase the level of innovation and implementation of clean technologies, contributing to sustainable development of the economy and respecting the principles of the idea of Corporate Social Responsibility (Kuzior 2022). Apart from economic rationality, ecological rationality and innovation prudence become important (Kuzior, 2019).

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