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CIRCULAR WASTE MANAGEMENT TO SUPPORT THE SUSTAINABILITY OF NONCONVENTIONAL MANUFACTURING COMPANIES

Elena-Bianca NEGOMIREANU, Mirela MANCIU-SIMIJDEAN, Oana IUȘAN, Mihai DRAGOMIR

Abstract: *The transition to a circular economy requires continuous improvement in manufacturing processes, the identification of new and more durable materials, and the reduction of waste through innovation and ecological design. This paper identifies and analyzes potential waste generated by a manufacturing company that employs classical manufacturing processes (i.e., machining) in conjunction with nonconventional processes (i.e., electro-erosion and additive manufacturing), as well as a final assembly stage where parts come together to form the final product. The paper details those wastes that, through recycling and recovery, can reduce raw material costs and the quantity of waste generated, as well as those that require special attention due to their environmental unfriendliness.*

Keywords*: circular economy, manufacturing process, recycling, sustainable, waste, environmental*

1. INTRODUCTION

The circular economy and environmental concern demand active involvement from manufacturing companies through innovation in finding environmentally friendly and durable inputs (recyclable materials) and continuous improvement in manufacturing processes. The goal is creating sustainable products that adhere to circularity principles and generate less waste.

The reliance on virgin raw materials, diversification of industrial demand, the growth of the manufacturing sector, and increasing environmental awareness, prompt both the academic and private sectors to seek solutions for developing new manufacturing technologies. Thus, in their development, consideration must be given to reducing electricity consumption and greenhouse gas emissions, as traditional manufacturing technologies are known for their high energy requirements and environmental impact.

From the emergence of nonconventional manufacturing technologies to the present, they were viewed as alternatives to machining, but they still require continuous improvement and adaptation to achieve sustainable production. As these methods rely on different energy sources (e.g., electrical, or chemical) and employ atypical consumables, this task is not a simple one, and requires innovative approaches.

Recent technological advancements open the door to innovative materials with new properties and "smart" materials. The path forward is represented by a combination of new technologies and new materials, which aims to make production more sustainable by using fewer inputs and less energy, generating less environmentally harmful waste in the early stages and fewer pollutants. These technologies increase the speed of processes while reducing the number of technological phases, with positive, but also negative, implications for a company's economic and financial results.

To implement these technologies in production, innovation, eco-design, collaboration between product designers and recyclers/resource providers to identify environmentally friendly and sustainable raw materials become essential for success.

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2. LITERATURE REVIEW

The current work investigates waste generated, in the context of the circular economy, by manufacturing companies that use both classical manufacturing processes (e.g., machining) and nonconventional processes (e.g., electro-erosion and additive manufacturing), along with a final assembly stage of the product.

The relevant literature is primarily focused on the treatment of waste generated by the use of these manufacturing processes (classical and nonconventional), emphasizing the importance of correctly identifying the waste generated, its nature (hazardous or non-hazardous), and choosing the best treatment method based on priorities established taking into account national legislation, the availability of recycling capacities, and internal waste management policies.

One major obstacle is the small quantity of waste generated, which can result in high transportation costs to recycling or recovery facilities. As a result, the waste generator may choose a less environmentally friendly and non-circular waste treatment method, primarily based on operating costs with an impact on profit. The lack of traceability in waste reporting and the mismatch of information regarding the quantity and types of raw materials used, resulting production, and waste generated by production are known issues in all types of manufacturing.

Regarding the use of metal powder in additive manufacturing from an environmental perspective, some authors consider this manufacturing method more ecologically friendly than traditional ones, although there is not enough research on Life Cycle Assessment. To be environmentally friendly, it is essential to use raw materials as efficiently as possible without negatively affecting the employees [1].

Additive manufacturing is promoted in the literature because it generates less waste and can reduce energy costs, thus for companies in the metal and plastic-based production industry, this technique has become a standard in the past decade [2].

Other authors have also studied the details of using 3D printing to replace conventional manufacturing methods. Even if this technology is generally seen as especially useful for prototyping and small-scale production, there are many operational, environmental and financial aspects where it can’t measure up to cutting technologies (e.g., process stability and capability, fast ramp-up times, the learning curve for operators, etc.). These challenges require innovations related to the materials used, and the maturity and acceptability of the machines that employ them, along with novel approaches to cost control and post-processing [3]. Achieving these advancements will make additive manufacturing the preferred choice for mass production by adding economic advantages to the environmental benefits associated with the field.

However, further investigations and studies are still necessary regarding additive manufacturing, as this is a relatively new technology whose environmental impact is both difficult and too early to properly assess on a large scale. A comparative analysis conducted in the aerospace industry compared to the industrial machinery industry, using life cycle assessment and life cycle costing methodology, resulted in the following conclusions [4]:

- the costs of manufacturing in the aerospace sector can be reduced by a significant percentage of 33.2%;
- the costs of manufacturing in the machine building sector are increased by 79.3% due to the complexity of the necessary materials and operations;
- the environmental footprint is positively impacted in both domains, mostly on account of reduced material consumption.

Regarding the electro-discharge machining process, it offers superior economic advantages, explaining the continuous annual growth rate of 3-5% in the production of machining tools in specialized factories [5]. When employing this manufacturing process, companies can achieve important time and cost savings, while reducing the quantity of metallic waste and refocusing their environmental efforts with the help of specialized service providers that can process and salvage valuable materials.

Modern technologies are recommended for parts with difficult machinability and high complexity [5]. In the specialized literature, there is limited information available on the quantity and origin of waste generated in nonconventional manufacturing [1].

All these studies require further analysis and process improvements to achieve positive outcomes for the environment, waste management, product quality, sustainability, and favorable economic and financial results.

3. METHODOLOGY AND RESULTS

By promoting the circular economy and creating innovative solutions, a new framework is proposed for addressing waste issues in the manufacturing industry. Manufacturers are taking a serious look at how production can be carried out in a more efficient and environmentally sustainable manner. Sustainable production is crucial in heavy industries. In these cases, nonconventional manufacturing technologies appear, at first glance, to reduce waste compared to traditional manufacturing methods.

In these combined manufacturing processes, the following types of waste are generally created (Figure 1):

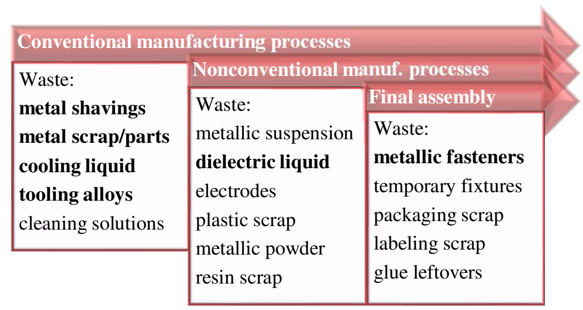

Figure 1. Waste generated by a generic manufacturing process

The above diagram shows the typical production flow of a manufacturing company. The main categories of waste are identified (and written in bold font), excluding waste related to the factory equipment, transportation and personnel, and the analysis below investigates the ability of the firms to manage them within a circular economy approach.

Table 1 and Table 2, below, summarize the valuable and less valuable uses of waste generated under these typical conditions, based on current manufacturing practices.

Table 1.

Valuable waste management to support circular economy reuse of materials

Waste type	Treatment/processing technologies	Results / Possible uses
Metal shavings Metal scrap/parts Metallic fasteners Tooling alloys	• Separate collection of materials • Inputs for steelmaking factories • Recovery of alloying components through chemical reactions • Recycling through separation into individual elements (tooling alloys)	• Steel and other alloys that can be reused for new metallic components • Metallic materials are well suited for circularity reuse
Cooling liquid Dielectric liquid (based on [6])	• Separate collection of materials • Separation of water and impurities • Recovery of metallic materials and processing as above • Recovery of organic and inorganic materials and chemical purification • Wastewater treatment, verification and discharge	• Cleaned industrial water is returned to the municipal systems • Metallic materials are used for steelmaking, as above • Chemical compounds are reused for the production of new cooling or dielectric liquid, or other applications
Electrodes (based on [7], [8])	• Separate collection of materials • Waste handling, separation, storage • Recycling depending on the type of material (without foreign impurities, it is an excellent material for processing)	• Melting to create new consumables with the same composition and different initial parameters • Used as a base or raw material for other alloys or composites

Waste type	Treatment/processing technologies	Results / Possible uses
		• Used on a large scale in steel foundries, carbon sticks and other applications (e.g., catalysts, moderators, etc.)
Metallic powder	• Separate collection of materials • Recycling to a limited extent, depending on the type of material used • Disposal if contaminated with oils	• Reuse after the preparation process (sifting stage), for the same purpose • Reuse of unused powder, provided that the environment (e.g., air) is clean • Repurposing of used powder for secondary applications (e.g., reinforcement or thickening) usually by third parties
Resin scrap	• Waste handling, separation, storage • Recyclable: eco-resin, silicone resin, and epoxy resin (chemical recycling - dissolution or mechanical recycling - melting or processing into reusable granules) • Not recyclable: polyester/fiberglass resin, polyurethane resin, must be disposed of properly and safely • Reprocessing and filtration when it is necessary and possible, for liquid components	• Transformation into post-consumer recycled resin (PCR resin) that has similar applications to any recycled plastic • Compacting, and ecological storage or use as fuel for thermal energy generation

For ensuring efficient waste management, the technical safety data sheet and product label are important, especially for products containing chemical agents. This is necessary to understand the correct information about them and the waste management procedures, considering the hazardous nature of the substance, if applicable.

All the waste generated in nonconventional manufacturing technologies must be analyzed within the framework of sustainability, with increased attention to contaminated waste, which is considered hazardous. To ensure a sustainable framework, the following elements must be developed:

a) The existence of recycling facilities to ensure efficient recycling, allowing for reintegration into the economy;

b) Continuous innovation of these facilities, considering the specificities and types of waste generated in these technologies;

c) Ensuring the improvement of production sustainability;

d) Economic feasibility of recycling in relation to overall costs;

e) Recycling of metal alloys as a priority, but addressing the other materials in a comprehensive approach;

f) Definition of standards and certifications for certain nonconventional technologies for industry acceptance;

g) Improvement of existing technologies for the use of recyclable materials (3D printing with recyclable materials such as rPET, recyclable metal powders, etc.).

The chosen treatment method for each type of waste depends on the existing local recycling facilities and collaborations with specialized collection/recycling companies to choose the best method, considering the material's specificities, its quality, and the costs associated with recycling/recovery. In this case, the application of an ecologically and economically sound approach is necessary.

Thus, among these valuable wastes, recycling metals and metal alloys represent a milestone towards environmental sustainability, considering their recyclable nature and the costs involved in extracting virgin material, as well as the concern for the limited natural resources. For these, recycling facilities are quite widespread, providing the most viable solution for recovery.

The recovery of metal powders prevents the depletion of natural resources, adhering to the fundamental idea of sustainability, especially since their manufacturing involves complex processes. Metal powder recovery can be more challenging than metallic materials and possible mixing must be taken into account. The recovery of metal powders can enhance production efficiency and improve the quality of the final product, avoiding cross-contamination between different production cycles or materials. The sustainability level of powder recovery depends on the industry and application [1], with some industries facing restrictions due to certifications. However, reusing metal powders requires a careful evaluation of the changes that occur through their usage. When necessary, a process like screening is employed while maintaining the quality of the final product [9], which leads to the reduction of costs in terms of raw materials and the overall waste generated.

In cases where the powder becomes contaminated, it can be recycled through remanufacturing and reatomization to obtain new powder after adjusting the composition. In this context, Gorji et al. concluded in their study on the mechanical behaviour of parts using new powder versus reused powder that up to ten cycles of recycle and reuse can be employed without significant losses in their characteristics [10]. Recycling metal powders is a crucial part of the manufacturing process for many industries. This ensures the recycling of metal powders, the conservation of resources and the reduction of environmental pollution while bringing a highly profitable income stream. The disposal of unusable powder is carried out in accordance with national legislation, aiming to reduce or negate its impact on the natural environment.

Regarding the properties of the dielectric fluid, used in many nonconventional technology applications, it deteriorates over subsequent usage cycles, resulting in toxic waste and hazardous emissions. A scientific method is required to identify the conditions at the end of the lifecycle of the dielectric fluid in order to make the best decisions for environmental optimization and to maintain the quality of the final product. Both metal powders and dielectric fluids are both expensive and hazardous. This necessitates finding solutions for reusing and recycling them in a proper way.

Regarding electrodes, if they have not suffered considerable damage, they can be reused in subsequent machining processes. For reuse and/or recycling, they can undergo cleaning, reconditioning, or remanufacturing operations to remove deposits or restore their original shape and dimensions. Those contaminated during the electrical discharge machining process are considered hazardous waste and should be handed over to a specialized company.

Recycling resin waste depends on their condition and the availability of existing recycling technologies. In the case of contamination with metal particles or other impurities during the manufacturing process, they should undergo cleaning and separation before recycling.

Table 2.

Less valuable waste management to support circular economy reuse of materials

Waste type	Treatment/processing technologies	Results / Possible uses
Cleaning solutions	• Separate collection and storage • Collection of cans according to material • Collected by a professional company for the collection and disposal of hazardous waste in a manner that is both safe and environmentally responsible, depending on the instructions of the label	• This handling procedure does not endure reuse, but it is mandatory and also can provide benefits in the form of governmental incentives
Plastic scrap	• Separate collection of materials on different type of plastic • Possible inputs for plastic industries • Sorting/grinding/washing/regranulation • Hydrothermal recycling / Injection molding / Extrusion to create new products	• Reused for new plastic products, either directly or through other companies

Waste type	Treatment/processing technologies	Results / Possible uses
Temporary fixtures	• Separaration, storage • Recycling by type of material, usually metallic or plastics	• Reuse if it is possible in other cases / projects • Inputs for steelmaking/plastics factories
Packaging scrap	• Separate collection of materials by type • Inputs for different factories (as plastics companies, cardboard processors, etc.)	• Raw material for finished products • Energy recovery (when labels that cannot be removed or traces of dirt show up)
Labeling scrap	• Waste handling, and proper storage • Recycling: small quantities processed fairly easily by most recycling facilities	• Energy recovery through incineration
Glue leftovers	• Waste handling, and proper storage • Recycling: some companies specialize in recycling post-consumer adhesives • Most types of glue cannot be recycled (they have to be handed over to a hazardous waste collection company)	• Used to make new products, such as carpet backing and construction adhesive by the companies specialized in recycling post-consumer adhesives • Some can be incinerated to generate energy
Personal protective equipment	• Recycling • Co-processing in incineration plants	• Energy recovery through incineration

Temporary supports are primarily designed to support the parts during manufacturing, being made from the same material as the one used during additive manufacturing or from metal in the case of machining processes. They are reused or recycled taking into account the type of material from which they are made.

Green cleaning products protect health without harming the environment and are an optimal solution. In a circular economy, it is essential to purchase only what is necessary and use the cleaning product entirely, to minimize waste. Embracing sustainable practices saves financial resources and reduces environmental pollution. Some cleaning solutions can be reclaimed or even reused. Their processing and reintroduction into the production circuit is carried out through companies that have specialized installations.

The treatment of unused adhesive primarily depends on the manufacturer's specifications and the requirements of the subsequent production process, assessing the possibility of reuse in other stages of production. If possible, the packaging is recycled according to the labelling instructions. The solution to reduce/eliminate the risk of generating this waste comes from analyzing and redesigning the process.

Special attention must also be given to waste generated from personal protective equipment used in the manufacturing process. These can be recycled depending on the material used for their production. Those contaminated with hazardous substances during the manufacturing process are handed over to specialized companies.

By employing nonconventional technologies, the waste changes, so the recycling market must adapt at the same pace and provide innovative recycling technologies tailored to new types of materials. Due to the progress made in the nonconventional manufacturing sector, there is a trend towards reducing the amount of waste and even not generating it all together in the future. Until that moment, environmental concerns, and the conservation of natural resources, as well as the transition to a circular economy, remain at the forefront of implementing any manufacturing technology.

The types of waste identified in Table 1 and Table 2, especially the hazardous ones, determine the need for continuous improvement in both conventional and nonconventional fabrication technologies to ensure the that the production process has a low environmental footprint.

In the current context of recent studies on the use of recycled plastic, caution is necessary. Even though it is part of the circular economy transition plan, it must be handled sustainably given the health and environmental risks it poses (microplastics) and the use of hazardous chemical substances in the plastic industry [11].

4. CONCLUSIONS

Increasing mass production will lead to a greater need for sustainability. To promote sustainability, the manufacturing sector must continuously evolve and adapt to recent technologies through intensive research and development. Furthermore, to minimize waste, promote reuse and recycling in the context of implementing a circular economy and adhering to sustainability principles, improvements in manufacturing technologies and recycling technologies are necessary to recover a significant amount of material, considering the shortcomings observed in studies and practice.

Ecological design should be applied from the product development and design stage to improve end-of-life strategies, taking into consideration circular thinking, quality, production time, human health, and environmental impact. Therefore, more research is needed along the entire manufacturing and supply chain.

Regarding the recyclability of powders, studies are varied, and interpretations are still ongoing, thus allowing for more freedom to act. The results of current and future research depend on the specific process and powder used, and general statements cannot be made at the present moment.

Understanding and promoting cases of best practices within an industrial symbiosis framework can lead to the emergence of innovative manufacturing models. Over time, these can bring the necessary improvements to the production process with as little waste as possible, which can be reintegrated into the economy, resulting in durable end products.

By implementing effective projects [12] aimed to establish circular waste management strategies, nonconventional manufacturing can contribute significantly to a more sustainable and environmentally friendly future. This commitment contributes to the long-term resilience and viability of the manufacturing sector within the framework of global sustainability initiatives and aligns with the broader goals of transitioning to a circular economy, underscoring the importance of responsible and conscious waste management.

Further studies are required to investigate the types of waste generated by nonconventional technologies, taking into account their current improvements, which continuously change the structure, type, and quantity of waste. Limiting the amounts of waste produced will have a positive effect on recycling as well, because technologies with a smaller processing scope can become economically viable.

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Managementul circular al deșeurilor pentru susținerea sustenabilității companiilor care utilizează tehnologii de fabricație neconvenționale

Rezumat: *Tranziția către o economie circulară necesită îmbunătățirea continuă a proceselor de fabricație, identificarea de materiale noi și mai durabile și reducerea deșeurilor prin inovație și design ecologic. Această lucrare identifică și analizează potențialele deșeuri generate de o companie de producție care utilizează procese clasice de fabricație (prelucrare prin așchiere) în combinație cu procese neconvenționale (electroeroziune și fabricație aditivă), precum și o etapă finală de asamblare în care piesele sunt combinate pentru a forma produsul final. Lucrarea detaliază acele deșeuri care, prin reciclare și valorificare, pot reduce costurile cu materiile prime și cantitatea de deșeuri generate, precum și cele care necesită o atenție deosebită din cauza afectării mediului înconjurător.*

Elena-Bianca NEGOMIREANU, PhD. student, Technical University of Cluj-Napoca, Department of Design Engineering and Robotics, bianca.negomireanu@yahoo.fr
Mirela MANCIU-SIMIJDEAN, PhD. student, Technical University of Cluj-Napoca, Department of Design Engineering and Robotics, simijdeanmirela@gmail.com
Oana IUȘAN, PhD. student, Technical University of Cluj-Napoca, Department of Design Engineering and Robotics, oana.iusan93@yahoo.com
Mihai DRAGOMIR, Professor, Technical University of Cluj-Napoca, Department of Design Engineering and Robotics, mihai.dragomir@muri.utcluj.ro