Adopting Circular Economy Principals for Sustainable Manufacturing

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Abstract

The world is currently facing the concerning issue of an increasing consumption rate on a global scale. This is closely tied to the prevalent use of linear economy models in manufacturing processes. These models are fundamentally flawed in a way that they fail to consider a product’s entire life cycle in terms of the environment, society, and economy. As a result, the notion of a better future in which no resources are depleted gains paramount importance. An out-of-the-box vision where all products, upon reaching the end of their primary utility, are not discarded but instead recuperated, entering into a cycle of reduce, reuse, recover, remanufacturing, recycling, and redesign, perpetuating their value across multiple lifecycles, known as “circular economy”. As such, the notion of “circular economy” must shift from being a mere idea to an absolute necessity. However, as this notion gains attention rapidly, its practical implementation remains somewhat inadequate in its technological blueprint. In that regard, this paper represents an ongoing project focusing on developing a model that considers the 9R-based components of circularity which are essential not just for economic growth but also for environmental and social protection. Considering this complex problem, this study aims to develop a closed-loop supply chain model focusing on sustainable manufacturing. In a nutshell, this study aims to develop a model suitable for various products and purposes for a more sustainable future in manufacturing.

**Keywords**: Circular economy, Sustainable manufacturing, Life Cycle Assessment.



* 1. Introduction

The business transformation from the traditional model the linear economy, to the circular economy in the last few decades has become a global debate (T.B.J., Coenen et al., 2020). This debate has been fueled by a significant increase in attention from governments, non-government organizations, and academics towards environmentally friendly manufacturing policies. As consumers are becoming increasingly conscious of the sustainability aspects of their purchasing decisions, companies are advancing towards the implementation of circular economy principles (Giuffrida, G, M. and Mangiaracina, R., 2020). To achieve sustainability within manufacturing, companies need to focus on various perspectives such as reducing waste, reusing materials, recycling products, refurbishing goods, recovering resources, and redesigning processes (K.Stylianopoulou et al.,2023 & K.Stylianopoulou et al., 2022). Implementing the 9R strategies in sustainable manufacturing is crucial to achieving a circular economy. By adopting the 9R strategies, companies can not only reduce their environmental impact but also optimize resource utilization and create new business opportunities. This approach ensures that products and resources are used efficiently, waste is minimized, and the environmental impact is reduced. By embracing the 9R strategies for sustainable manufacturing and adopting circular economy principles, companies can transition from a linear economy model to a more sustainable and inclusive circular economy model that promotes economic growth, environmental protection, and societal well-being.

* 1. The 9R Framework

The 9R framework is a comprehensive approach designed to promote sustainability and circularity in the manufacturing industry. This framework consists of nine strategies, each beginning with the letter 'R', aimed at reducing waste and maximizing resource efficiency. In the realm of circular economy, the 9R framework plays a crucial role by emphasizing strategies like reduction, reuse, recycling, recovery, redesign, remanufacturing, refurbishing, repurposing, and rethinking. These strategies are crucial for optimizing the use of resources while minimizing waste generation. When implementing these strategies, it is essential to consider various elements, such as the availability and cost of resources, the environmental impacts, and the efficiency of the processes involved. While transitioning to a perfect circular economy free of waste is a challenge, the principles embodied in the 9R framework offer a guide away from disposable culture and adopting sustainable practices. Its core principle is to maintain the utility of resources for the longest possible duration, maximize their value during usage, and subsequently ensuring the recovery and rejuvenation of products and materials after their service life concludes. (K. Stylianopoulou et al., 2023, J. Mast et al.,2022 & European Commission, 2020).

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| --- | --- | --- |
| R0 | Refuse | Abandon product or offer the same product with a radically different product |
| R1 | Rethink | Use of a product more intensive (e.g. Sharing products) |
| R2 | Reduce | Increase efficiency in product manufacture or use by consuming fewer natural resources and materials |
| R3 | Re-Use | Reuse by another consumer of discarded product which is still in good condition and fulfills its original function |
| R4 | Repair | Repair and maintenance of defective product so it can be used with its original function |
| R5 | Refurbish | Restore an old product and bring it up to date |
| R6 | Remanufacture | Use parts of discarded product in a new product with the same function |
| R7 | Repurpose | Use discarded product or its parts in a new product with a different function |
| R8 | Recycle | Process materials to obtain the same (high grade) or lower (low grade) quality |
| R9 | Recover | Incineration of material with energy recovery |

Table 1: 9R Strategies for pursuing Sustainable Manufacturing in Circular Economy (adapted from J. Mast et al.,2022 & European Commission, 2020)

This strategy is particularly vital for sustainable development, especially in the manufacturing sector. It plays a significant role in resource conservation, reducing environmental impacts, and inspiring innovation and economic growth. Essentially, the 9R framework in sustainable manufacturing revolves around the concept of innovative utilization of resources to minimize consumption and waste, thereby maximizing efficiency (K. Stylianopoulou et al., 2023, J. Mast et al.,2022 & Eur. Commission, 2020).

* 1. Methodology

In the contemporary landscape of industrial manufacturing, sustainability has transitioned from a peripheral concern to a central operational imperative. This shift is driven by a growing recognition of environmental challenges, regulatory pressures, and evolving market expectations. Sustainable manufacturing, which aims to minimize environmental impact while maintaining economic viability, has emerged as a crucial practice. To this end, the development of an optimization model that holistically considers cost, environmental impact, and energy usage becomes paramount.

* + 1. Model Development

The approach that is intended here is that the development process involves integrating sustainability principles into traditional manufacturing optimization, addressing complex interdependencies between various manufacturing aspects. The model was developed to address the complex interactions between various elements of manufacturing - resource utilization, waste management, energy consumption, and production efficiency - all under the umbrella of sustainability. The first step was to identify the critical elements affecting sustainable manufacturing, such as resource use, waste generation, energy consumption, and compliance with environmental standards. Then the principles of the 9R framework to ensure a comprehensive approach to sustainability were taken into account. Based on these factors, the model defines a set of variables (both decision and state variables) and constraints that represent the limitations or requirements of the manufacturing process.

* + 1. The Objective function

The optimization model developed for sustainable manufacturing incorporates the principles of the 9R framework elements into a mathematical structure. The objective function is to achieve an optimal balance between cost, sustainability, and energy efficiency, with the understanding that advancements in one aspect may result in concessions elsewhere. At the core of the model is a multi-objective function, as presented in Eq. (1), placing emphasis on three primary objectives: minimizing cost (C), environmental impact (E), and energy use (U). The objective function is expressed as:

|  |  |
| --- | --- |
| $$Minimize Z=αC+βE+γU $$ | (1) |

In this context, "Z" symbolizes the total weighted impact of the manufacturing process. Within Eq. (2) symbolized as C, includes the cost of materials, labor, production and miscellaneous costs that could influence the manufacturing process.

|  |  |
| --- | --- |
| $$C=C\_{materials} + C\_{labor} + C\_{process} +C\_{other} $$ | (2) |

Regarding the environmental factor E, highlighted in Eq. (3), a scoring system is used to quantify the impact on the environment. Additionally U, as defined in Eq. (4), indicates the level of energy used throughout the production process. This adjustment was made to give a more comprehensive view that includes not merely the quantity of energy consumed but also accounts for the nature of the energy sources used and how long each process lasts, which collectively influence both energy efficiency and ecological consequences.

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| --- | --- |
| $$E =\sum\_{}^{}\left(w\_{R}\*R\_{iscore}\right)+\left(w\_{w}\*W\_{kscore}\right)+\left(w\_{E}\*E\_{jscore}\right) $$ | (3) |
| $$U=\sum\_{}^{}U\_{jrate}\*T\_{j}\*S\_{j}$$ | (4) |

The weighting factors (α, β and γ) included in Eq. (1) indicate the varying significance of distinct factors aligned with the strategic priorities and processes of a given industry. These factors underscore the importance of cost, environmental impact and energy use in the manufacturing process. They are determined based on objectives related to sustainability within the industry, regulatory requirements and market pressures. For instance, a higher weight on environmental impact (β) signifies a stronger emphasis on sustainability, possibly in response to strict environmental regulations or market demands for sustainable products.

* + 1. Variables and Constraints

Fundamental to the model are the variables and constraints. Variables include decision variables such as resource usage, production output, and energy consumption rates, as well as state variables depicting current inventory levels and waste generation. Constraints were formulated to enclose the limitations and requirements underlying the manufacturing process, ensuring adherence to sustainability objectives. The variables and constraints are designed to balance cost-efficiency, environmental sustainability, and energy conservation.

* + - 1. Constraints

Firstly, the constraint of resource management is introduced. This constraint aims for optimal use of resources and a reduction of waste. Following that, the constraint on energy consumption and efficiency is presented, which controls energy use by encouraging energy efficient processes. They are presented as follows:

|  |  |
| --- | --- |
| $$R\_{i}\leq R\_{iavailable}+R\_{ipurchased}-R\_{iwasted} , ∀i$$ | (5) |
| $$U\leq U\_{jmax} , ∀j$$ | (6) |

The next constraint is environmental scoring, which uses a scoring system in the manufacturing process where product are evaluated for their environmental impact and assigned corresponding scores. Each score reflects the relative environmental impact, with higher scores indicating a greater negative impact.

|  |  |
| --- | --- |
| $$E\leq E\_{limit}$$ | (7) |

Additionally, the waste management constraint makes sure that waste management, including recycling, recovery and disposal, does not exceed waste generation.

|  |  |
| --- | --- |
| $$W\_{krecycled}+ W\_{krecoverd}+W\_{kdisposed}\leq W\_{kgenerated} , ∀k$$ | (8) |

The next constraint is Quality and Compliance. This constraint ensures that the products meet established quality standards and compliance requirements, factoring in associated costs. The manufacturing process not only focuses on producing high quality products but also meticulously complies with necessary regulatory standards. It helps maintain customer satisfaction and legal compliance, critical in sustainable manufacturing.

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| --- | --- |
| $$Q\_{l}+C\_{lcomplince}\geq Q\_{lstandard} , ∀l$$ | (9) |

Last but not least, Market Dynamics and Demand constrain is presented. This constraint aligns production with market demand, considering inventory levels to avoid overproduction or shortages. Matching production output to market demand, considering the inventory available. Thus, it ensures that the total production output minus the inventory available is sufficient to meet or exceed market demand. It avoids both the shortfall of not having enough product to meet demand and excessive overproduction, producing more than what is needed leading to wasted resources and increase storage costs. It is a crucial part of efficient inventory management and ensuring customer satisfaction.

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| --- | --- |
| $$\sum\_{}^{}P\_{j}-I\geq D $$ | (10) |

* + - 1. Variables

There are two main types of variables that were considered: decision variables and state variables. Decision variables are unknown in an optimization problem; they can change according to the needs of the manufacturing industry, while state variables are fixed parameters that the model uses to make decisions but does not directly control.

|  |  |  |
| --- | --- | --- |
| Category | Variable | Type |
| Resource Management | Ri | Decision |
| Riavailable | State |
| Ripurchased | Decision |
| Riwasted | Decision/State |
| Energy Consumption | U | Decision |
| Ujrate | State |
| Tj | Decision |
| Sj | State |
| Environmental Scoring | E | Decision/State |
| Elimit | State |
| Waste Management | Wkrecycled | Decision |
| Wkrecoverd | Decision |
| Wkdisposed | Decision |
| Wkgenerated | State |
| Market Demand | Pj | Decision |
| I | State |
| D | State |

Table 2: Key Variables in the Optimization Model for Sustainable Manufacturing

* 1. Conclusions

In conclusion, this optimization model offers a comprehensive approach for manufactures to address the complexities of sustainable production, balancing economic, environmental and energy considerations to achieve more sustainable and efficient outcomes. This optimization model presents a structured and comprehensive approach to sustainable manufacturing. The model integrates various aspects of sustainable manufacturing, including resource efficiency, energy management, environmental conservation, waste reduction, product quality and market alignment. It is adaptable to different industrial contexts and can be tailored to prioritize specific aspects, such as reducing environmental impact or minimizing costs, with the aim of guiding manufacturers toward more sustainable and efficient production methods. The model serves as a decision making tool guiding manufacturing in optimizing their processes for sustainability and efficiency. The constraints provide a structured approach to managing resources efficiently, controlling energy consumption, minimizing environmental impact, managing waste responsibly, ensuring product quality and compliance, and aligning production with market demand. The model's flexibility in weighting different objectives (cost, environmental impact, energy) makes it adaptable to various manufacturing contexts and sustainability goals. However, this optimization model represents a preliminary framework, and its empirical validation is pending. Future implementation is contingent upon extensive data collection, which is necessary to corroborate the model's efficiency and clarify its parameters. This ongoing process of data acquisition and analysis will enable a more robust and reliable application of the model in practical scenarios.

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