The Integration of Computer Engineering and Economic Sustainability Forecasting in Smart Manufacturing

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Abstract. The imperative to reduce the manufacturing industry's environmental footprint has become a critical global issue due to rising living standards, increased demand, and resource scarcity. Manufacturing, central to product supply and modern life, faces significant sustainability challenges. Existing manufacturing models, based on outdated paradigms, are insufficient and require thorough revision. The sector must innovate, leveraging technology, culture, and economics to develop sustainable practices, including the revision of sustainability assessment tools. These tools must address growing sustainability concerns and incorporate the triple bottom line—environmental, economic, and social factors. Concurrently, the concept of smart manufacturing is emerging, harnessing advancements in AI, Cloud Computing, and IoT to enhance production. However, the interaction between smart manufacturing and sustainability is not fully understood. This study aims to merge sustainable and smart manufacturing by evaluating current models and identifying future research opportunities in this integrated field.

Keywords: Economic Sustainability, Economic Sustainability, Smart Manufacturing.

1 Introduction

The concept of "sustainable manufacturing" spans the entire industrial process from production to consumer, including all related resources and services within the manufacturing chain. In today's society, manufacturing is intertwined with all aspects of human life, providing essential products and services crucial for health, safety, and well-being. Given manufacturing's role in crafting products that enhance life quality and contribute to the global economy, it's imperative to examine it through a sustainability lens. Understanding "sustainable manufacturing" requires defining its goals, implementation steps, and assessment methods, as outlined in existing literature.

K. Zhang et al. (eds.), *Proceedings of the 2024 3rd International Conference on Economics, Smart Finance and Contemporary Trade (ESFCT 2024)*, Advances in Economics, Business and Management Research 305,
https://doi.org/10.2991/978-94-6463-548-5_11

As manufacturing consumes significant energy and resources within the product supply chain, adopting a "design of manufacturing" strategy is crucial for achieving sustainability. Viewing sustainable manufacturing holistically, it emerges as a key strategy for enhancing financial performance while meeting social and environmental goals and regulations [1].

Sustainable lifecycle design (SLD) has seen notable growth over recent decades and become a key focus in engineering and industrial applications. However, a gap remains in fully integrating sustainability into practice. Despite increased focus on sustainable development, further efforts are required to address economic, environmental, and social challenges. Additionally, there's a need for a framework that guides both practitioners and scholars in sustainable manufacturing, as many industries overlook the approach's benefits. This study presents a comprehensive discussion on:

The concepts, benefits, and opportunities of sustainable manufacturing implementation, leading to the development of a sustainable smart manufacturing (SSM) approach across various industries [2].

The challenges industries face in adopting the SSM approach.

This article is structured as follows: Section 2 reviews sustainability from the manufacturing perspective, discussing principles, assessments, and opportunities. Section 3 explores smart manufacturing and the fourth industrial revolution, proposing a novel business model that integrates factory 4.0 with sustainability. This section also examines the impact of factory 4.0 on the triple bottom line (TBL) sustainability dimensions. Section 4 outlines the main challenges of integrating factory 4.0 with sustainability. This work represents the first attempt to analyze industry 4.0 opportunities from a sustainable manufacturing standpoint and identify challenges in implementing this innovative approach [3].

2 Sustainable Manufacturing: Concepts and Opportunities

Sustainable manufacturing evolves from the traditional 3R approach to a more comprehensive 6R methodology, incorporating reduce, redesign, reuse, recover, remanufacture, and recycle (Figure 1). This approach aims to minimize resources and energy use throughout the manufacturing process, thereby reducing waste. It emphasizes the importance of reusing products and parts, recycling materials traditionally viewed as waste, and recovering components for new lifecycles. Redesigning products for sustainability and remanufacturing them to their original condition without losing functionality are crucial steps towards sustainable practices [4].

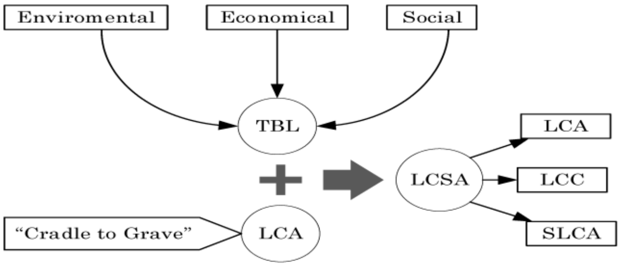

Fig. 1. Combined life cycle sustainability assessment.

Efforts to implement sustainable manufacturing have led to models and optimization tools for sustainable production and supply chains (Figure 2). Manufacturing professionals must prioritize sustainable processes and products, integrating sustainability throughout design, research, development, and commercialization phases to improve environmental performance and product lifecycle [5].

Emerging technologies like additive forming and laser-assisted machining reduce waste and energy consumption, highlighting the importance of sustainable manufacturing, which considers the triple bottom line (TBL) of environmental, economic, and social dimensions [6].

Life cycle analysis (LCA), life cycle cost (LCC), and social life cycle assessment (LCSA) provide a comprehensive view of a product's impact. Defining clear TBL indicators, especially for social and economic aspects, remains challenging. Developing key performance indicators (KPIs) and sustainability assessment frameworks aims to offer a holistic approach [7].

Sustainable manufacturing opportunities include energy consumption, cost reduction, waste management, environmental impact, and health and safety improvements. The "design for sustainable manufacturing" concept is essential for a reliable and adaptive process addressing functionality, environmental impact, and continuous improvement. Implementing an integrated sustainable system requires strategic approaches, smart work practices, process optimization, and new technologies [8].

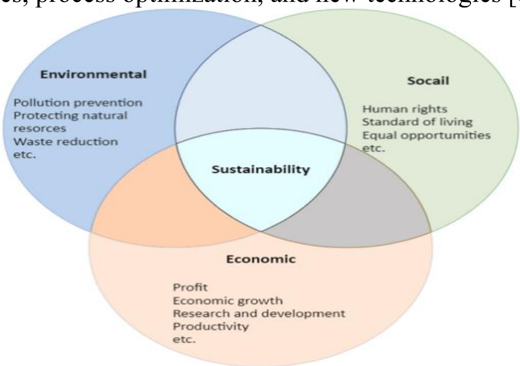

Fig. 2. The interactional concept between social, economic, and environmental directions.

3 Sustainable-Smart Manufacturing Approach: Industry 4.0 and Sustainability Aspects

As society propels forward with exponential technological growth, human activities and the consumption of resources like energy, materials, and water increasingly contribute to climate change (Figure 3). The modern industrial landscape is undergoing two pivotal shifts that redefine 21st-century production and consumption: the advent of the fourth industrial revolution (Industry 4.0) and the integration of sustainable manufacturing practices. Industry 4.0 promises to revolutionize not just industrial production but society as a whole, marking a significant leap from the mechanical innovations of the first industrial revolution, through mass production, automation, and now to the interconnected digital manufacturing ecosystem [9].

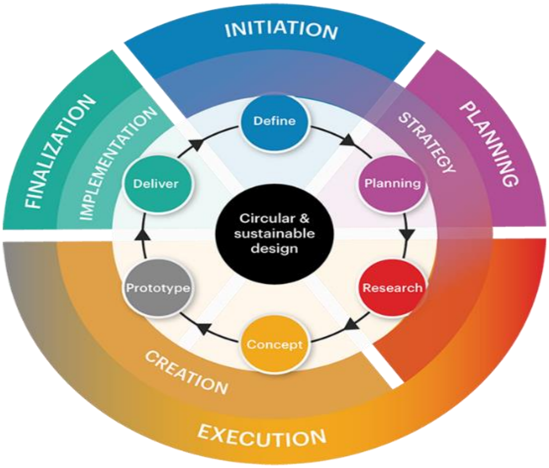

Fig. 3. Design for the integrated sustainable system.

This era of Industry 4.0 is characterized by the emergence of technologies such as Big Data Analytics and the Internet of Things (IoT), fostering an intelligent network that spans all production stages. This network promotes secure, real-time communication across departments, companies, and with customers, enabling machines to autonomously optimize production tasks and maintenance requirements. Such interoperability, categorized into vertical, horizontal, and end-to-end integration, enhances business models, operational flexibility, and product lifecycle management.

Industry 4.0's potential to enhance manufacturing efficiency by 15% to 20% stems from its ability to make factories more adaptable to varying product demands without human intervention (Table 1). This adaptability is crucial as the market shifts from mass production to catering to individual customer needs. Despite the technical focus of current Industry 4.0 research, its implications for economic, ecological, and social sustainability are profound. The Source System Service (3S) route encapsulates Industry 4.0's contribution to sustainability, emphasizing the use of environmentally friendly sources, system optimization, and waste minimization [10].

Table 1. Smart and traditional factories.

Smart factory	Traditional factory
Diverse Resources	Limited Fixed Resources
Dynamic Routing	Fixed Routing
Comprehensive connection	Shop Floor Control Network
Deep Convergence	Separated Layers
Self-Organized	Independent Control
Big Data	Isolated Information

Industry 4.0's environmental impact is twofold: while it can introduce new environmental liabilities through materials for electronic devices, it also enhances energy management and process efficiency, suggesting a net positive effect on sustainability.

Socially, automation technologies raise concerns about job displacement but also create new opportunities in system design, development, and maintenance. Emphasizing career sustainability, workers are encouraged to adapt and continuously learn.

Industry 4.0 sets the stage for Industry 5.0, which focuses on human-machine collaboration to enhance production quality and efficiency while maintaining job opportunities.

In conclusion, integrating Industry 4.0 with sustainable manufacturing practices can advance economic growth, environmental stewardship, and social well-being. By adopting decentralized management, leveraging advanced technologies, and promoting effective energy management, the manufacturing sector can achieve a sustainable and smart business model. The next step is to address the challenges of implementing this integrated approach for a sustainable future in manufacturing.

4 Challenges in Achieving Sustainable Smart Manufacturing

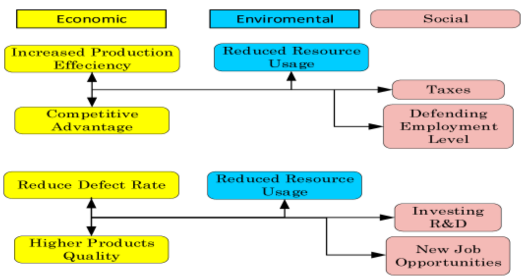

Fig. 4. Interactive benefits in TBL concept due to factory 4.0 implementation.

The preceding discussions have illuminated the potential of "sustainable manufacturing" and the prospects for forging a path towards smart, sustainable manufacturing practices. Despite the promise held by Industry 4.0 technologies, the journey towards their full implementation remains fraught with challenges, with many organizations still in the early stages of adoption (Figure 4).

5 Conclusions

In our interconnected world, manufacturing is crucial for human well-being and the global economy, necessitating a focus on sustainable practices. This study seeks to enhance manufacturing with sustainable smart manufacturing (SSM) techniques, while addressing sector challenges and the need for a guiding framework. It highlights the importance of sustainable practices and the barriers to implementing SSM, advocating for policies that improve operational efficiency for a better environmental future. The research outlines the potential and challenges of this approach and suggests future development of a model to assess the integration of sustainability with Industry 4.0.

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