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Research paper

Revolutionizing industry: the path to sustainable manufacturing

Ramesh G. Pungle *

Associate Professor, Department of Mechanical & Automation Engineering, P.E.S. College of Engineering, Chhatrpati Sambhajinagar (M.S.), India
**Corresponding author E-mail:rameshgpungle@gmail.com*

Abstract

In the Industrial Revolution, manufacturing has been a cornerstone sector. With each industrial revolution, the focus has been on optimizing the utilization of resources, including manpower, machinery, and materials. Industries aim to enhance manufacturing efficiency to meet societal demands, increase profitability, advance technology, and maintain product quality and variety. This paper illuminates the transitions from Industry 1.0 to 5.0, highlighting technological advancements, benefits, and challenges. Challenges encompass adverse environmental impacts, extensive consumption of natural resources for energy, escalating industrial waste, and an imbalanced industrial ecology. Furthermore, this paper delves into the domain of sustainable manufacturing, tracing its evolution across the industrial revolutions. It elucidates how sustainable manufacturing has emerged as a pivotal concept, grounded in industrial ecology principles and the circular economy. These complementary components are instrumental in promoting not only sustainable manufacturing practices but also sustainable development on a broader scale. Through an in-depth examination, this paper aims to separate out the intricate relationship between these concepts, providing insights into their significance and potential to foster a more environmentally conscious and resilient industrial landscape.

Keywords: *Sustainable Manufacturing; Industrial Ecology; Industry Revolution; Environment.*

1. Introduction

Industrial revolutions mark radical changes in the development of industry. These changes are characterized by certain achievement that influences both the direction of development of entire industry as well as new system solutions in the structuring of the production systems and the work organizations [1]. The industry revolution 1.0 has been the breaking point in human history. It was the transition to the position of the producer by taking care of the land with the settling of the migrant societies who were engaged hunting and gathering. The industry 2.0 refers to economic, commercial and social changes in the period 1870-1914. The decisive factors of industry 2.0 are the development of railways due to the technological transformation created by steel production, facilitated transportation, communication and distribution methods. Towards the end of the 1900s, the development of electricity, electronics and computer systems was called the informatics revolution and opened the doors of the third Industrial Revolution. Programmable machines which are being developed in 1968 with the more active use of scientific knowledge, has eventually led to the beginning of the third industrial revolution. Industry 4.0 is a collective whole of the concepts of technologies and value chain organizations. It is based on the concept of cyber-physical systems, internet of things and the internet of services [2]. This structure makes a great contribution to the formation of intelligent factories vision. Nowadays, there is a general agreement that Industry 5.0 diverges from previous industrial revolutions as it represents a stakeholder pulled socio-technological phenomenon that systematically shifts classic profit and consumption-driven economic models to circular, regenerative, sustainable, and resilient value-creating economic models [3].

Manufacturing industries are playing a crucial role in growing the economies of the countries across the globe [4]. However, in low-income countries this growth is coming at an unsustainable cost. Throughout the industry revolutions, manufacturing technologies have been improving products quality and variety with optimum cost. The monetary cost of waste is rising and many traditional manufacturing processes damage the environment and people's health. At the beginning of the industrial age, manufacturers have been evolving and adapting in response to new technological innovations and as per changing market demands. The major outcomes of industry revolutions related to production could be summarised as; Industry 1.0 gave birth to batch production using simple mechanisms, Industry 2.0 to mass production using electricity as a power, Industry 3.0 mass and quality products using electrical power, Industry 4.0 mass, quality, and variety in products with initiation of sustainable manufacturing. Today, the industry 5.0 is moving through another evolution, that has sustainability at its centre.

Sustainable manufacturing is the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers, NACFAM (National Council for Ad-

vanced Manufacturing — USA) [5]. Essentially, sustainable manufacturing aims to develop technologies that transform materials and products while reducing greenhouse gas emissions, minimizing the use of non-renewable or toxic materials, and decreasing waste generation. Pursuing sustainability entails creating and maintaining conditions where humans and nature can coexist harmoniously to support present and future generations. Sustainable manufacturing stands as one of the crucial pillars of Industry 5.0. Its conceptual foundation lies within the broader sustainability movement, which gained momentum in the late 20th century. This movement was fueled by a growing awareness of the finite nature of natural resources and the detrimental effects of industrial activities on the environment and human health [6].For a detailed overview of sustainable manufacturing, including a review of the latest technological trends, thematic frameworks, goal-setting, innovations, and the future needs and sustainability of Industry 4.0, refer to [7 - 12].
The primary objective to present this paper is to relate sustainable manufacturing with the industry revolutions, next-generation technologies and also to exhibit that the industry economic should grow by taking care of environment, society, natural resources, ecosystem and scope for future generations. To achieve the given objective, the rest of the paper is organized as follows. In section 2, a brief review about industry revolutions, I 1.0 to I 5 is given and showed that how sustainable manufacturing is introduced. In section 3, the concept of industrial ecology, circular manufacturing and its methods are discussed. Finally, paper results and conclusions are presented in section 4.

2. Industrial revolutions and beginning of sustainable manufacturing

The industrial revolution deserves the name with which historians have tagged it. It brought about thorough and lasting transformations, not just in business and economics but in the basic structures of society. Most historians place the origin of the industrial revolution in Great Britain in the middle decades of the 18th century [13]. The industry revolutions mean transformations of technologies in manufacturing as well as in overall business models. These revolutions have impacted society, economics, and environment globally. In the initial industry revolutions, the focus was to increase manufacturing by adopting contemporary technologies with little consideration of effects on society and environment. In Industry 5.0, the focus is on sustainable development with three key pillars: Society, economy and environment. The sections below (2.1 to 2.5) detail the progression from Industry1.0 to Industry 5.0

2.1. Industry revolution 1.0

The Industrial revolution 1.0 began in the 18th century, spanning the period between 1760 to 1840. It was characterized by major transitions that fundamentally changed the existing economies of different subcontinentsThis period marked the shift from handicraft and agrarian economies to those dominated by industry and machine manufacturing [14]. Manual and animal labour were replaced by the use of basic materials and mechanisms, primarily iron and steel. The sources of energy transitioned to fuels and motive power. Significant developments occurred in transportation and communication, exemplified by the advent of steam locomotives. There was also an increase in the application of science and, to some extent, technology to industries and manufacturing businesses.
The Industrial revolution 1.0 was a period of significant advancements in mechanisms and machines through the use of science and technology. It laid the foundation for future growth and set in motion the industrial momentum that continues today. One major shortcoming of the first industrial revolution was the high demand for production machines, which exceeded supply. Since these machines had just been invented, there were relatively few machines and technologies available to meet customer demands. This shortage led to increased pressure, primarily on workers, who were forced to work long hours under hazardous conditions.

2.2. Industry revolution 2.0

The second industrial revolution, or Industry 2.0, began in the 19th century, around the 1870s. During Industry 2.0, various management programs were implemented to enhance the efficiency of manufacturing facilities. Production management techniques such as the division of labour, just-in-time manufacturing, and lean manufacturing principles were invented and adopted by industries. Mass production of products became a standard practice during this period. This era also saw the birth of the modern ship as different technologies converged. Thus, this phase was marked by rapid standardization. Another notable aspect of the Second Industrial Revolution was the improvement in industry culture.
In summary, Industry 2.0 is known for accelerating and augmenting technological and manufacturing advancements, laying the groundwork for modern systems. Mass production and assembly line setups required fewer workers, significantly increasing production efficiency. However, the increased energy consumption and production burdened power plants. The excessive use of non-renewable energy sources led to higher levels of air pollution, initiating environmental issues during that period.

2.3. Industry revolution 3.0

The Third Industrial Revolution, commonly referred to as the "Digital Revolution," began in the 20th century, around the 1970s. During this period, significant advancements were made in technology, including the development of simple, relatively large computers. Additionally, the invention and manufacturing of various electronic devices, such as transistors and integrated circuits, played a crucial role in advancing technology. These innovations led to the creation of automated machines, such as CNCs and VMCs, and the automation of processes across industries. These technological changes resulted in several benefits, including reduced effort, increased speed, greater accuracy, and, in some cases, the complete replacement of human labour by machines. Furthermore, new economic models emerged during this revolution, and the concept of supply chain marketing was introduced, reshaping how goods were produced, distributed, and consumed.
Industry 3.0 was a turning point, transitioning from traditional to digital industrial practices. It made technology a fundamental part of how we live and work today. However, the Third Industrial Revolution had several major shortcomings: high energy consumption, heavy reliance on non-renewable energy resources, and increased pollution (air, water, soil, etc.). It also contributed to the rise in Earth's surface temperature due to the release of greenhouse gases. Additionally, electronic waste and related health issues became significant concerns during this period.

2.4. Industry revolution 4.0

The initial developments of Industry 4.0 were initiated in the 1990s, following the advancements in the telecommunication and internet industry. This revolution encompasses various fields, including artificial intelligence, robotics, the internet of things (IoT), autonomous vehicles, 3D printing, materials science, energy storage, and quantum computing. Industry 4.0 has facilitated the efficient networking, or interconnectivity, of systems, giving rise to "cyber-physical production systems." Consequently, smart manufacturing and factories have emerged, with production largely automated and enhanced communication among people and components facilitated through a unified network. This seamless distribution of information is made possible through the Industrial Internet of Things (IIoT).

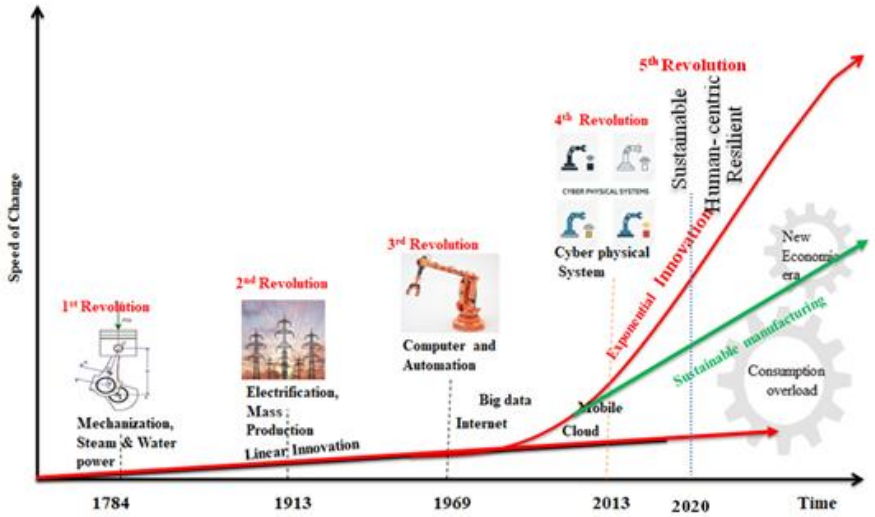

Fig. 1: Display of Industry Revolution Transformations I1.0 – I5.0.

From a sustainability perspective, industry 4.0 can be a step towards more sustainable industrial value creation. The new technological solutions promoted by Industry 4.0 are to enhance production efficiency and the environmental performance of products throughout their life cycle. Probably, industry 4.0, does not have a strong focus on environmental protection, nor has developed sound technologies to improve the environmental sustainability of the Earth [16].

Major challenges of Industry 4.0 include cyber security, network configurations, system failures, data privacy, data handling and storage issues as well as lack of digital skills among factory workers. The management of greenhouse gases, electronic waste and health issues are initiated to set in industry 4.0.

The evolution of industrial revolutions, depicted in figure 1, spans from the onset of the first industrial revolution in 1784 to Industry 5.0 in 2020. The figure illustrates the technological transformations occurring during these revolutions. Notably, the figure highlights the commencement of sustainable development within Industry 4.0, suggesting its potential to grow and evolve further in subsequent revolutions.

2.5. Industry revolution 5.0

In 2021, the European Commission introduced the term Industry 5.0 for the first time. Industry 5.0 expands beyond the use of modern technologies related to design, manufacturing, management, materials, production processes, robotics, automation, artificial intelligence, and cloud data storage. It encompasses every sector and organization imaginable. Industry 5.0 is characterized by three key pillars: human-centricity, resilience, and sustainability. Figure 2 illustrates these three key pillars of Industry 5.0. The collaboration among the technological, social, and ecological segments constitutes the essence of Industry 5.0. An emerging aspect of the industry 5.0 paradigm is the integration of artificial intelligence into people's daily lives.

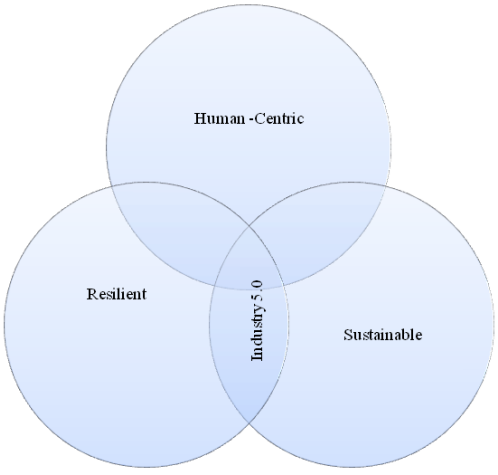

Fig. 2: Display of Industry 5.0 Model.

The brief summary of industrial revolutions with beginning of sustainable development and manufacturing, effects on society, environment and economy are given in table 1.

Table 1: Summary Industrial Revolutions

Industrial Revolution	Beginning of Sustainable Development	Effects on Society	Effects on Environment	Effects on Economy
1.0 (1784)	No	Shift from agrarian to urban society, rise of factory system, mass production.	Initial negative impacts due to pollution and resource depletion.	Rapid economic growth, increased productivity.
2.0 (Late 19th - Early 20th century)	No	Rise of industrialization, urbanization, labour movements.	Increased pollution, exploitation of natural resources.	Further economic growth, expansion of global trade.
3.0 (Late 20th century)	Limited	Information age, globalization, digital revolution.	Heightened environmental awareness, pollution regulations.	Technological advancements, globalization of markets.
4.0 (21st century)	Yes	Emergence of sustainable practices, focus on renewable energy, efficiency improvements .	Integration of green technologies, emphasis on sustainability.	Transition to digital economy, automation of processes.
5.0 (Emerging)	Yes	Human-centric, resilient, and sustainable approach.	Greater emphasis on eco-friendly technologies, circular economy.	Integration of artificial intelligence, societal well-being.

3. Industrial ecology

Industrial activities are increasingly coming into conflict with ecological systems. Continued natural resource exploitation and the environmental impacts of resource use and pollution are causes for concern worldwide. One broad approach emerging in response to these concerns is called Industrial Ecology (IE). IE offers important goals and organizing principles for reforming industry, providing concepts that are gradually being embraced by leaders in industry, academia, and government agencies.

IE is described as an information-driven field in which the advances of the "information revolution" can be harnessed to improve the environmental performance of industry. Frosch and Uenohara (1994:2) explain that "Industrial ecology provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems. To optimize resource use, managers need a better understanding of the metabolism of materials and energy in industrial ecosystems, better information about potential waste sources and uses, and improved mechanisms that encourage systems optimization of materials and energy use."

Within the broad field of sustainability, the concepts of industrial ecology and sustainable manufacturing (SM) are garnering increasing attention in both the research community and industry. In the manufacturing context, sustainability entails the transformation of resources into economically valuable goods through the operation of socially and environmentally responsible processes. Manufacturers are increasingly motivated to become more proactive in improving their environmental performance, with cost reduction being a significant driver: material and energy inputs, along with waste disposal costs, have markedly risen over the past decade as finite resources dwindle [20]. For a content analysis-based literature review on sustainable manufacturing, refer to [21].

3.1. Steps towards circular manufacturing

Circular manufacturing, derived from the principles of the circular economy, shares similar aims and goals, including designing for reuse, repair, repurpose, and recycling. A circular economy approach involves designing products with the intention of recycling or reusing materials at the end of their lifecycle. By adopting circular economy strategies, companies can minimize waste generation and reduce the need for resource extraction. Circular manufacturing is a production and consumption model focused on creating a closed-loop system. This means it employs principles such as reduce, reuse, recycle, repair, redesign, and remanufacture to keep resources within the loop rather than discarding them after a single use. The general open and closed-loop manufacturing model detailing the circular manufacturing model is explained in sections 3.1.1 to 3.1.3.

3.1.1. Open loop manufacturing model

The open-loop manufacturing model indicates that resources (such as materials, energy, machinery, and labor) used for the production of products/items are consumed and then discarded as waste by the customer after consumption. Initially, this model was preferred by certain industries when there was little awareness about the efficient use of natural resources and the utilization of renewable energy sources. This model is not suitable for industrial ecology and therefore is not included in industry revolutions. The general flow diagram of the open-loop manufacturing model is displayed in figure 3.

Fig.3: Open Loop Manufacturing Model.

3.1.2. Closed loop manufacturing model

This model illustrates that initially, all resources are utilized in production to create products. After the consumption of these products, some of them are recycled using suitable technology and energy, and the resulting recycled materials are reintroduced into the production process. In this model, the concept of industrial ecology is employed to enhance production efficiency and profitability through the principles of sustainable development and the circular economy. Particularly, in the context of Industry 4.0, manufacturing sectors have begun to adopt the concept of sustainable development. The general model of closed-loop manufacturing is shown in figure 4.

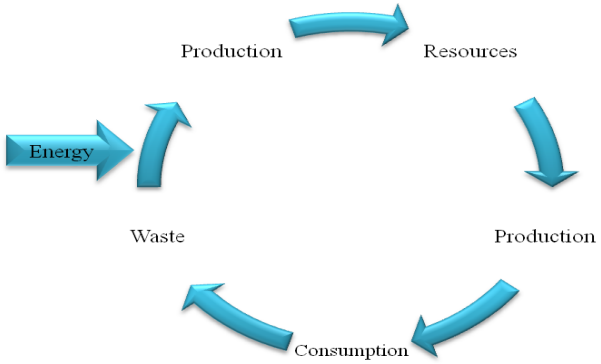

Fig. 4: GeneralClosed Loop Manufacturing Model.

3.1.3. Circular manufacturing model

The circular manufacturing model is an extension of the closed-loop model, providing comprehensive information about circular manufacturing practices. To effectively implement the circular manufacturing concept, the model shown in Figure 5 can be utilized. In both industrial revolutions and circular manufacturing, the initial focus was on the 3R model, which includes reduce, reuse, and recycle, and was preferred by industries. This model gained traction particularly when the lean manufacturing concept was implemented in industries. Lean manufacturing enhances production efficiency, reduces inventory, and minimizes waste.
However, as the need for more comprehensive sustainability practices grew, the 6R model emerged. This expanded model incorporates reduce, reuse, recycle, recover, redesign, and remanufacturing. The 6R model not only improves production efficiency but also aids in waste reduction, environmental protection, and the maintenance of the circular economy. The detailed outline and flow of both the 3R and 6R models in circular manufacturing are depicted in figure 5.

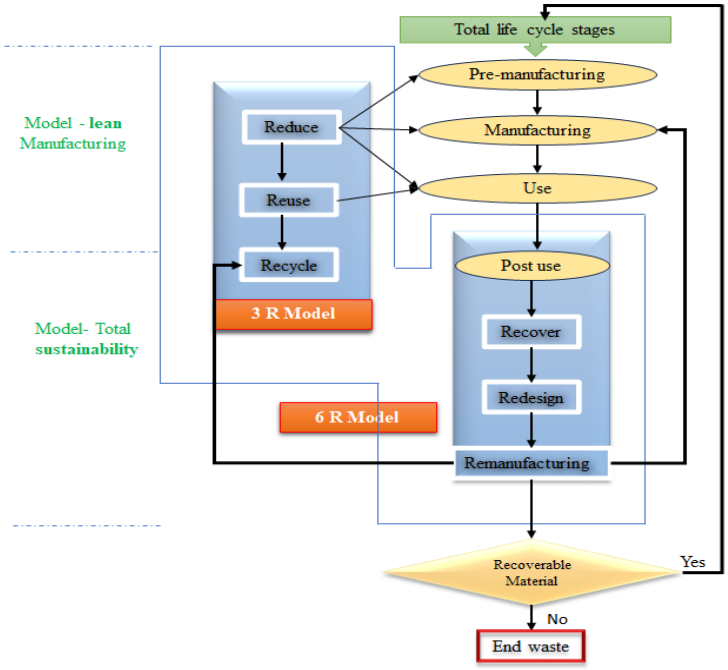

Fig. 5: Complete Circular Manufacturing Model.

4. Conclusion

This paper comprehensively examines the concepts of industrial revolutions 1.0 to 5.0, discussing the technological transformations and their impacts on society, economy, and the environment. It delves into the principles of industrial ecology and the developmental stages of circular manufacturing. Throughout these industry revolutions, several constructive changes have been observed, including advancements in manufacturing technologies, automation in production systems leading to improved product quality and variety, as well as technological upgrades, standardization, and process optimization.
However, alongside these advancements, adverse effects such as the excessive use of natural resources for energy demand have led to environmental issues, including the release of greenhouse gases contributing to global warming. Recognizing these consequences, scien-

tists, governments, and industries have begun to prioritize sustainable development and manufacturing. The concept of sustainable development and sustainable manufacturing was introduced in industry 4.0, and in industry 5.0, sustainability has become one of the key pillars.

Sustainable development and manufacturing are crucial for achieving long-term societal, economic, and environmental goals. By adopting sustainable practices, companies can not only reduce their environmental footprint but also enhance their competitiveness and resilience in the face of changing market dynamics. It is imperative that stakeholders across all sectors collaborate to accelerate the transition towards a more sustainable future.

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