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Towards Circular Economy in Manufacturing Industries Based on Industry 4.0 Technologies

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Abstract - **The drive for competitiveness in smart manufacturing compels organizations to embrace the circular economy (CE) within their industries. This emerging trend combines artificial intelligence with the latest digital technologies, particularly industry 4.0 technologies like the Industrial Internet of Things, Cyber-Physical Systems, big data analytics, and more. The goal is to offer an alternative to the traditional linear economy (take-make-waste). This research aims to present an architectural framework that utilizes I4.0 technologies for the adoption of the CE in various industry sectors. In doing so, we consider every component of the manufacturing process, including input and output stations, manual service centers, machinery, equipment, and others, all integrated within the cyber-physical system. Furthermore, smart technologies are integrated into this system to replace the linear economy model. Additionally, this article demonstrates how the 4R principle (repairing, remanufacturing, recycling, and replacing) plays a vital role in the transition away from the linear economy. Undoubtedly, the adoption of this approach will provide managers with the means to achieve sustainability and foster ongoing economic development.**

Keywords - **Circular economy, Environmental sustainability, Industrial AI, Industrial internet of things, Cyber-physical systems**

I. INTRODUCTION

Circular economy in manufacturing industries

The adoption of a CE in manufacturing industries is important because of some compelling reasons. Firstly, it enables resource conservation by reducing the usage of finite resources through recycling, reusing, and remanufacturing. This enhances the sustainable usage of resources and reduces the negative impact on the environment. Secondly, implementing CE practices helps minimize waste generation and enhance responsible waste management, leading to environmental sustainability and cost savings for companies [1-2]. Additionally, embracing circularity leads to innovation, promoting differentiation in manufacturing, and meeting the increasing demand for sustainable products. Additionally, it aids in conforming to rigorous environmental regulations, minimizing risks, and bolstering the reputation of companies. Lastly, with increasing consumer consciousness and preferences for environmentally friendly products, the CE aligns with customer preferences and supports long-term customer satisfaction and loyalty. Ultimately, the adoption of a CE in manufacturing industries is crucial for achieving sustainability, minimizing environmental impact, and assuring a resilient future [2-3].

I4.0 technologies in circular economy

The utilization of digital technologies associated with Industry 4.0 (I4.0), including Industrial Internet of Things (IIoT), Artificial Intelligence (AI), Cyber-Physical Systems (CPS), and cybersecurity, plays a vital role in enabling the transition towards a CE. These technologies offer cost reduction opportunities through recycling and remanufacturing processes [4]. With the increasing availability of I4.0 solutions in recent years [6], the implementation of cyber-physical facilities has become feasible across various manufacturing industries. This accessibility highlights the immense potential for adopting CE practices within these industries [7]. Currently, industries are confronted with challenges related to market demand and revenue growth [5, 8]. Failure to embrace new technologies not only escalates production costs but also results in material losses, value degradation, and diminished performance. Consequently, management seeks a transformative shift towards a CE to address these challenges by improving system efficiency, productivity, and flexibility. This necessitates the integration of AI and the 4T framework consisting of Data Technology (DT), Platform Technology (PT), Analytics Technology (AT), and Operation Technology (OT) with emerging technologies such as IIoT, cloud computing, CPS, and big data analytics.

Objectives and contributions

The integration of I4.0 technologies not only enables the adoption of cyber-physical manufacturing facilities but also facilitates the implementation of CE principles within the manufacturing industries. The incorporation of these technologies offers greater flexibility, enhances monitoring and control capabilities, and improves overall system performance. Simultaneously, embracing CE principles enhances environmental sustainability, promotes environmental awareness, and provides better control over manufacturing facilities. Considering these objectives, this study aimed to accomplish two main goals: (1) present an architecture for adopting CE practices in the manufacturing industry, and (2) demonstrate the utilization of enabling technologies to overcome challenges associated with the adoption of CE. The proposed architecture in this study encompasses various facilities, including I/O stations, MS centers, and associated workstations with machines and equipment, which represents a novel contribution. Additionally, through a comprehensive literature review, this study integrates essential technologies necessary for the successful adoption of CE, marking another significant contribution of this research.

II. METHOD TO ADOPT CIRCULAR ECONOMY IN AN INDUSTRY

To show how a circular economy can be adopted in an industry based on the I4.0 technologies, we divided our entire research work into the following three sections:

A. *Adoption of CPS in manufacturing facilities*

CPS and IIoT offer immense potential in the development of intelligent systems that seamlessly integrate cyber technologies with physical processes for the next generation. CPS combines computational elements with physical entities to effectively manage physical phenomena. In a similar manner, CPS enables the connection of machines, equipment, I/O stations, and MS centers, as illustrated in Fig. 1. This interconnected system leverages computing, communication, and CE virtually over the internet, creating an information structure that supports decision-making and the application of machines. Machines act as a crucial link between the digital realm and the physical world, enabling continuous monitoring and tracking that can greatly contribute to CE practices. As depicted in Fig. 1, the IIoT connects various manufacturing facilities, allowing the industry to incorporate CE data and other relevant information into Manufacturing Operations Management (MOM) and Enterprise Resource Management (ERM) systems [9].

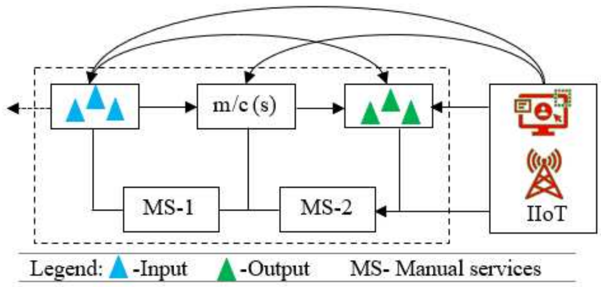

Fig. 1. Interconnection of facilities in a manufacturing industry

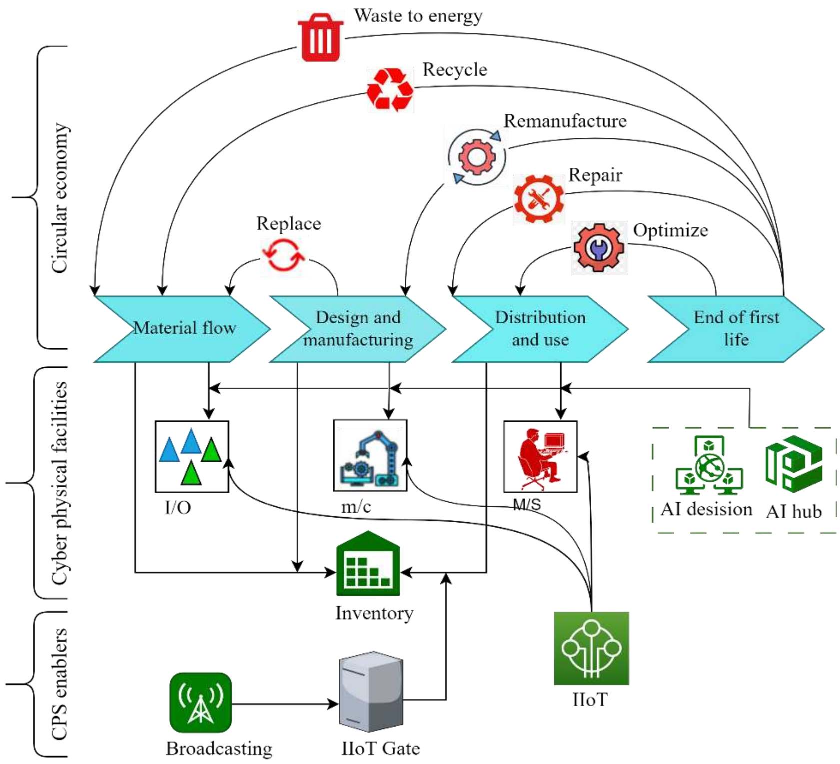

Fig. 2. The proposed architecture to achieve circular economy

B. Proposing an architecture for the adoption of circular economy

Fig. 2 illustrates an architecture designed to achieve CE within an industry by leveraging cyber-physical manufacturing facilities. The interconnectedness among these facilities ensures that information regarding raw materials and used materials remains constantly updated in cloud storage. This up-to-date information proves invaluable to the CE system, particularly when making decisions related to waste-to-energy, optimization, repair, remanufacturing, recycling, and replacement (WO4R). Notably, AI plays a pivotal role in decision-making for WO4R processes, enabling efficient and informed choices. Furthermore, AI assists in selecting the most appropriate facility for materials following the WO4R procedures. The introduction of AI and machine learning into the manufacturing facilities, as depicted in Fig. 2, enables industry management to embrace CE practices effectively. Moreover, this architecture highlights the CPS enablers essential for the facilities to successfully achieve CE objectives.

C. Usage of enabling technologies for CE goals and challenges

According to Lee et al. [10], 4T can adopt 4S (self-awareness, self-comparison, self-prediction, and self-optimization). Additionally, DT facilitates interaction among facilities, data storage and transfer, and connects physical spaces to cyber spaces and vice versa. PT requires a compatible hardware architecture for data analysis and problem-solving in any facility. A cloud-based platform enables rapid customer service, knowledge integration, and scalability visualization. AT converts sensory data into actionable information for management, while OT provides assistance. To implement CE, we establish the following objectives: (1) taking quick decisions on materials; (2) reducing decision costs; (3) increasing decision accuracy; (4) updating materials' information automatically; and (5) ensuring better resource utilization. We also addressed some challenges associated with the following issues: (1) data filtering; (2) resource distribution; (3) item variation control; (4) knowledge management; and (5) cyber security. Fig. 3 integrates the necessary technologies for CE adoption in the manufacturing industry, considering the goals and challenges mentioned above. The existing literature on AI, machine learning, and 4T offers substantial evidence of meeting the aforementioned challenges and goals, indicating the feasibility of implementing CE in an industry [9-11].

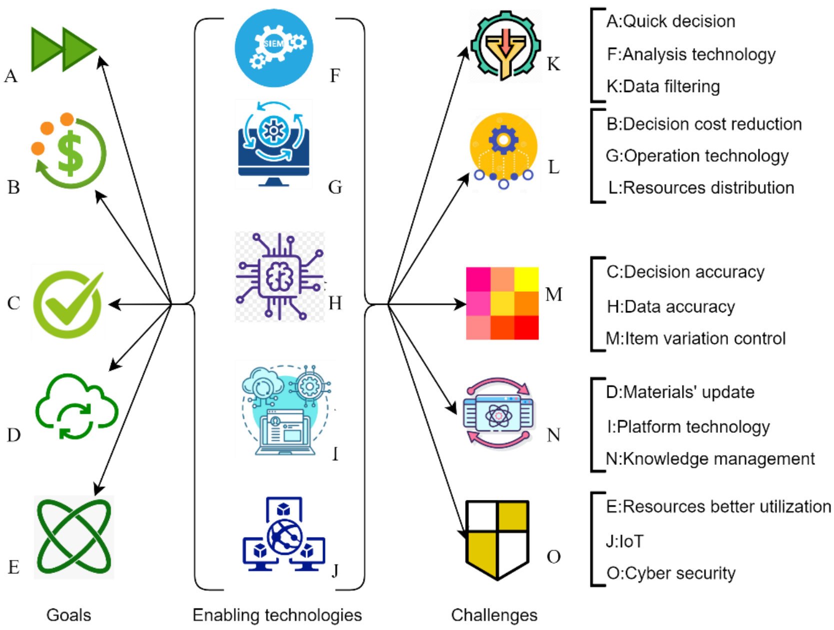

Fig. 3. Goals and challenges with enabling technologies for the circular economy

III. POTENTIAL BENEFITS AND ADOPTION CAPABILITY

In recent decades, the advancement of I4.0 technologies has made it possible to transform manufacturing facilities into intelligent entities, a concept previously deemed unattainable. The implementation of CPS for controlling manufacturing facilities has significantly enhanced productivity in manufacturing units. Nowadays, the adoption of smart industries or smart manufacturing systems has become widespread [13-15], offering manufacturers benefits such as improved efficiency and reliability of their systems. CPS increases quality control by providing real-time data on facility performance, enabling early detection of defects, and ensuring better quality. Furthermore, CPS enhances worker safety by automating hazardous tasks and monitoring worker health conditions. It improves resource utilization, decreases costs, and enhances predictive maintenance to reduce downtime. The availability of I4.0 solutions from companies like Intel Corporation, IBM Corporation, and Cisco Systems Inc. has made the adoption of CPS more accessible and feasible [6], as depicted in Fig. 4.

The adoption of the CE model within the manufacturing industry brings about numerous advantages. To begin with, it actively encourages the efficient use of resources by diminishing the necessity for new materials, reducing waste generation, and prolonging product lifecycles through activities such as repair, remanufacturing, and recycling [1-2]. Furthermore, embracing circularity stimulates innovation as companies are motivated to develop fresh business models, products, and services that prioritize durability, recyclability, and longevity [16-17]. Moreover, the implementation of a CE creates novel employment opportunities, particularly in sectors like waste management, refurbishment, and recycling [18-19]. In addition to that, it lessens reliance on imports since local production and recycling processes are promoted.

Currently, manufacturers are increasingly embracing the concept of CE to ensure sustainability and continuous economic development. CE has the potential to leverage the emerging I4.0 technologies [11]. In Fig. 3, we illustrate an architecture for adopting CE in the industry, highlighting its potential benefits and adoption capabilities, as depicted in Fig. 4.

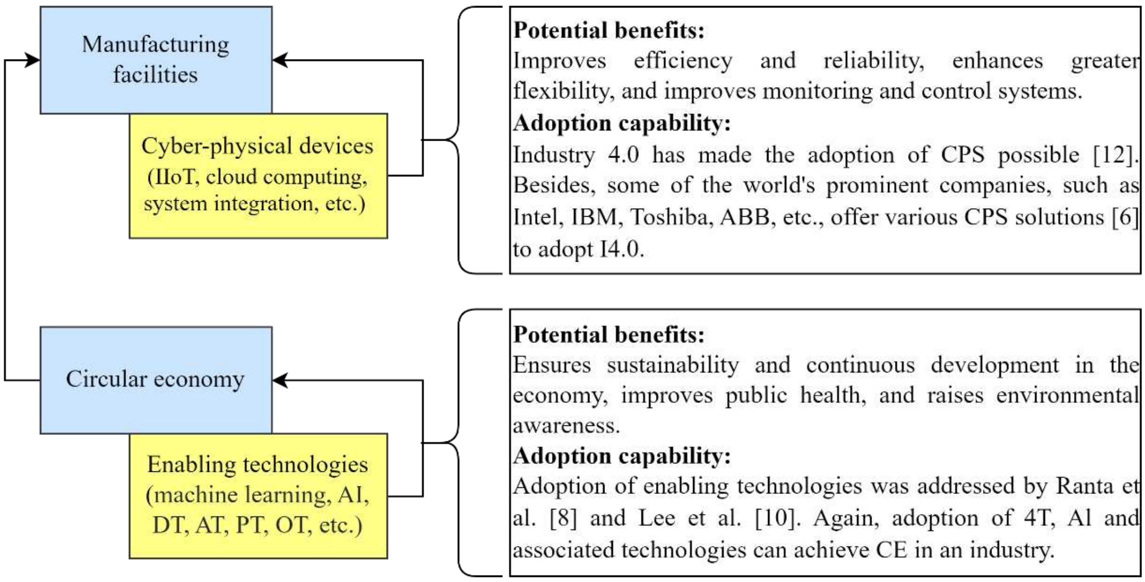

Fig. 4. Potential benefits and adoption capability of adopting cyber-physical manufacturing facilities and CE in a manufacturing industry.

IV. CONCLUSION

Our research aimed to accomplish two objectives in order to promote sustainability and raise awareness about the environment within an industry. Firstly, we demonstrated how the implementation of I4.0 technologies can enable better monitoring, control, and flexibility in manufacturing facilities. This study addressed the associated technologies for smart manufacturing facilities, highlighting their potential benefits and adoption capabilities. Secondly, we showcased the adoption of CE principles in the industry, specifically focusing on cyber-physical manufacturing facilities (refer to Fig. 2). Furthermore, this study thoroughly examined the potential challenges and enabling technologies associated with each objective.

CPS integration enhances overall operational performance by integrating physical machinery and equipment with advanced digital technologies, such as sensors, actuators, and data analytics. This integration ensures real-time monitoring, automation, and optimization of manufacturing processes, leading to better productivity and enhanced quality control. Adopting CPS in manufacturing industries delivers benefits such as enhanced operational efficiency, data-driven decision-making, increased flexibility, improved worker safety, and enhanced collaboration, leading to improved productivity and a competitive edge in the market. Managers with an interest in harnessing the benefits of CPS and CE for economic and environmental improvements would greatly benefit from understanding the proposed architecture outlined in this article. Our study suggests that managers planning to leverage I4.0 technologies would find adopting CE particularly intriguing, as it can enhance system performance by reducing material and labor costs. In addition, the adoption of circular principles not only enhances the reputation of a brand but also cultivates customer loyalty, as today's consumers place growing importance on sustainability and hold businesses accountable for responsible practices. As a result, transitioning to a CE in manufacturing offers economic, environmental, and social benefits, enabling companies to establish long-term resilience and make meaningful contributions to a more sustainable future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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