The Multiple Applications of CE-I4.0 Nexus to Achieve Sustainable Development in the Construction Industry

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Abstract
Construction is a resource-intensive industry, and many efforts have been made to change the linear path it assumes by propagating the circular economy model. This paper aims to link the circular economy model (CE) with the Fourth Industrial Revolution (I4.0) pillars to assist in spreading knowledge about the nexus of CE-14.0 to reach the pinnacle of sustainable development. The objective of this paper is to review how digitalization brings about improvements to the circular economy model in the construction industry, which will enhance the sustainability of construction projects, by examining case studies that implemented the CE-I4.0 nexus. By doing so the paper scrutinizes the applicability of Industry 4.0 tools in the Circular Economy's context by studying the existing body of knowledge that addresses the linkage between both the concepts. This is critical as the collaboration of circular economy and Industry 4.0 concepts has created a medium of efficiency and productivity for the construction industry which will bring about substantial progress in the sustainable development agenda. However, the current shortage of information regarding this topic and the several barriers associated with implementing these concepts impede achieving sustainable construction processes. This paper sheds light on the possibilities and benefits associated with the CE.I4.0 nexus. The methodology employed is a narrative literature review approach that scrutinizes authoritative publications and real-life case studies to gather existing information on the topic. This paper ultimately discusses how the CE-I4.0 nexus will bring about Industry 5.0, which will create a symbiotic relationship between technological change (I4.0) and people.

Keywords
Industry 4.0 (I4.0), Circular Economy, Internet of Things (IoT), Construction, Sustainable Development

1. Introduction

Construction is the oldest and most antiquated profession that has embraced many other fields to promote the growth of civilizations and populations. The construction industry is resource-intensive and has undergone many advancements to alter the linear way that undertakes the "take, make, throw" model. The generation of waste has increased exponentially in the past decades, thus, the introduction of modernized techniques designed to reduce the waste will benefit the industry as well as the environment. Therefore, the concepts of circular economy (CE) and industry 4.0 (I4.0) were introduced to the industry to cut down on the large amount of waste generated as well as to help sustain planet Earth for future generations. Despite the substantial importance of these two paradigms, the existing literature highlights that there is a shortfall in empirical evidence as to how the principles of CE and I4.0 are applied in the construction industry (Rosa et al., 2020). Therefore, the aim of this paper is to link the nexus of CE with I4.0 tools to enhance the sustainability of the construction sector. The paper presents multiple applications of the nexus of CE.I4.0 in the different phases of a construction project. The objective of this paper is to comprehend how digitalization brings about improvement to circular economy in the market which will automatically reflect on the sustainability of the construction industry and to scrutinize the applicability/the feasibility of I4.0 tools in the CE context to ultimately meet the Sustainable Development Goals (SDG) by studying the existing body of knowledge that addresses the linkage between both the concepts. The implementation of CE-I4.0 in construction processes will bring about substantial progress in the sustainable development agenda. However, the current shortage of information regarding this topic and the several barriers associated with implementing these concepts impede achieving sustainable construction processes. This paper discusses the possibilities and subsequently, the benefits associated with the

CE.I4.0 nexus in the multiple phases of a construction project, where actual applications of the CE.I4.0 nexus are discussed in detail.

2. Research Methodology

The research methodology undertaken in this research is a narrative literature review approach, which thoroughly examines credible publications to gather existing information covering this topic and subsequently, the paper seeks to identify any research gaps in the existing literature. The paper synthesizes published literature, to encompass the values and significance of the nexus to achieve sustainable development goals. Moreover, real case studies from the industry will be discussed to interpret the methodologies followed by enterprises and organizations to fulfill the goal of accomplishing sustainable development through the concept of CE-I4.0.

3. Results and Discussion

3. 1 Historical Timeline, Definitions and Components of Industry 4.0

Advancements in technology have driven significant growth in industrial productivity since the Industrial Revolution (Rüßmann et al., 2015). The first industrial revolution, known as Mechanization, occurred in 1764. It marked the shift from manual to mechanized manufacturing processes using water and steam power. The second revolution, Electrification, utilized electricity to transform assembly lines, leading to more efficient mass production and the rise of automated factories. The third industrial revolution, Automation, expanded industrial capabilities through the adoption of computers and automation. The fourth industrial revolution is the most recent modernization in manufacturing and production. It integrates higher technologies such as artificial intelligence, cloud-based platforms, and cyber security to enhance industry operations more securely and efficiently (Britannica, 2022). The key difference between the third and fourth revolutions lies in the human role. In the fourth industrial revolution, the human role is to monitor the connected systems rather than directly connecting the digitized world with the physical one (Klinc & Turk, 2019). The result is a web of interconnected systems that analyze data, forecast potential failures, and adapt to changes (Rüßmann et al., 2015).

Industry 4.0 (I4.0) is a paradigm encompassing several advanced digital technologies allowing the gathering and the analysis of the data across multiple machines, thus enabling quicker and more efficient processes that produce high-end quality products at decreased costs. I4.0 integrates Cyber-Physical Systems (CPS) into multiple processes through the utilization of digitization for value creation (Vrchota et al., 2020). There is no consensus among experts about what are the exact technologies encapsulated under the I4.0 umbrella (Rosa et al., 2020). Other terms such as smart factory, smart manufacturing, smart production, etc., have also been used to define this broad paradigm (Sawhney et al., 2020). The Boston Consulting Group identified nine pillars as the main constituents of I4.0. These include big data and analytics, autonomous robots and vehicles, additive manufacturing, simulation, augmented and virtual reality, horizontal/vertical system integration, Internet of Things (IoT), cloud, fog, and edge technologies, blockchain, and cyber-security (Rüßmann et al., 2015). Digital twins and Artificial intelligence are considered as of the I4.0 pillars as well. (Klinc & Turk, 2019).

To begin with, the Internet of Things (IoT) is a set of technologies that enables the interaction, collection, and exchange of data, between the physical and the computerized worlds by utilizing modern wireless telecommunications (Rüßmann et al., 2015) (Nasiri et al., 2017) (Cagno et al., 2021). On the other hand, Big data and analytics (BDA) is the implementation of modern data analysis techniques for the management of large datasets to transform them into value (Rosa et al., 2020) (Cagno et al., 2021) by optimizing production quality, minimizing energy consumption and enhancing equipment/machinery service (Rüßmann et al., 2015). The other pillars include Cloud/Fog/Edge Technologies (CLOUD) which are cloud-based software that is currently being utilized by several enterprises, as I4.0 resulted in more production undertakings that mandate the increase in data sharing across the enterprises' boundaries where CLOUD technologies come into play (Rüßmann et al., 2015). Additive manufacturing (AM) is a technology that utilizes the concept of layering to facilitate the production of individual components through prototyping (Rosa et al., 2020). Autonomous Robots (ROBs) are robots that are capable of functioning completely autonomously by interacting with other ROBs and humans. They can work safely side by side with humans whilst learning from them, enhancing the decision-making process and creating a symbiotic work environment with humans (Rüßmann et al., 2015) (Cagno et al., 2021). Cyber-physical Systems integrate physical and computational processes. where embedded networks monitor and subsequently control physical processes with feedback loops, hence, the physical processes impact the computational processes and vice versa (Rosa et al., 2020). Simulation (SIM) utilizes mathematical programming techniques and real-time data to mirror the physical world into a virtual world, thus assisting in the testing and the optimization of processes before the physical changeover (Rüßmann et al., 2015) (Cagno et al., 2021). Horizontal and Vertical System Integration (HVSYS) allows for the emergence of universal data integration networks, resulting in cohesive departments and functions (Rüßmann et al., 2015). This universal data integration mode enables a digitized value chain within an organization or across many organizations, as it can link a variety of products, manufacturers, and even customers (Cagno et al., 2021). Cybersecurity ensures the reliable, secure, sophisticated access management of machines and users, whilst minimizing cybersecurity risks drastically (Rüßmann et al., 2015). This tool or set of guidelines guarantees protection in the cyber environment, where valuable and confidential information is located (Cagno et al., 2021).

Augmented Reality (AR) with computer-generated information allows designers to enhance some aspects of users' real-world surroundings in AR. Designers produce inputs for digital material that react in real-time to alterations in the user's environment, often movement. Virtual Reality (VR) refers to the virtual environment that brings forth a flexible digital platform by exposing users to multidimensional, hyper-realistic visual stimuli (Ayoub et al., 2019). A blockchain is a designed network that contains several blocks connected according to a sequential time frame where each block has the admixture of the previous block which creates the blockchain. The structure of the blockchain will facilitate a vigorous, transparent, and auditable record or register of all the archived blocks and transactions (Casino et al., 2019). Digital twins include designing a digital model reflecting its physical model to create a bi-directional relationship between the two models to bridge the gap between reality and virtual worlds. There are three components of the digital twin which are the physical model, the digital model, and the connection between the two models. This enables the prediction of behaviors, risks, deficiencies, and failures while ensuring that the information used in the virtual model reflects the latest data from the physical model (Frontoni et al., 2018).

3. 2 Existing Research on Industry 4.0

To confirm that the undertaken topic is relevant in terms of its recency in the existing body of knowledge, the keyword “Industry 4.0” was researched under Scopus. As a result of which, Scopus produced 3,636 document results. The research results were limited to “Open Access” documents, years from “2014 to 2023, subject area of focus selected was “Engineering” and documents included were limited to “Journal Articles”, “Book Chapters”, “Conference Papers” on the “Final” stages of publication in “Journals”, “Conference Proceedings”, “Book Series” and “Books”. The timeframe from 2014 to 2023 was selected to ensure relevance and currency so that the analysis is focused on the most current and relevant data The number of publications and cumulative publications on a year-to-year basis on Industry 4.0 are presented in Figure 1 which confirms that Industry 4.0 is receiving an increased interest in the research field as annually the number of publications covering this topic is increasing, hence the selection of this topic was deemed suitable.

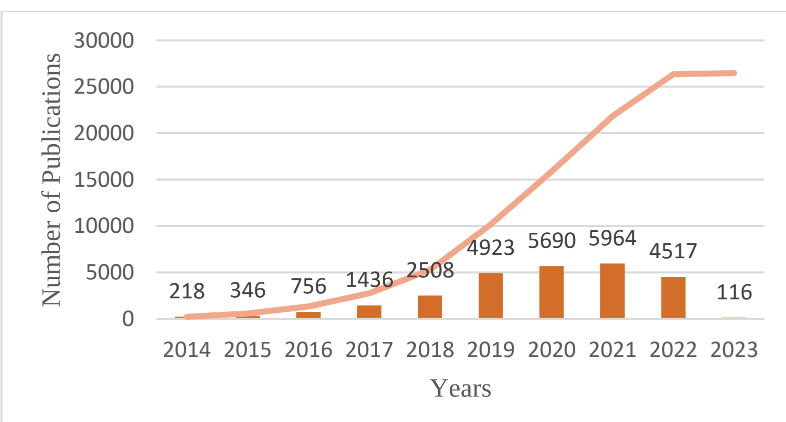

Fig. 1. Annual Publications and Cumulative Publications on Industry 4.0

The documents extracted from Scopus were exported into VOSviewer for further analysis. Based on the following analysis: type of analysis: “Co-occurrence” and unit of Analysis: “all keywords”, the keywords that VOSviewer generated are shown in Figure 2. It is important to note that the Internet of Things (IoT) was the most common keyword that was generated by VOSviewer with 285 occurrences. As a result of which, IoT was particularly selected from all the other pillars of Industry 4.0 as the focus of the paper. Other important keywords such as “sustainable development” and “sustainability” were generated. Hence, the relationship between searches concerning Industry 4.0, IoT, and Circular economy was established in the existing body of knowledge. As illustrated in Figure 3, globally there are many countries where Industry 4.0 is being addressed in research, which further emphasizes how this topic is currently being addressed on a global scale highlighting its prominence.

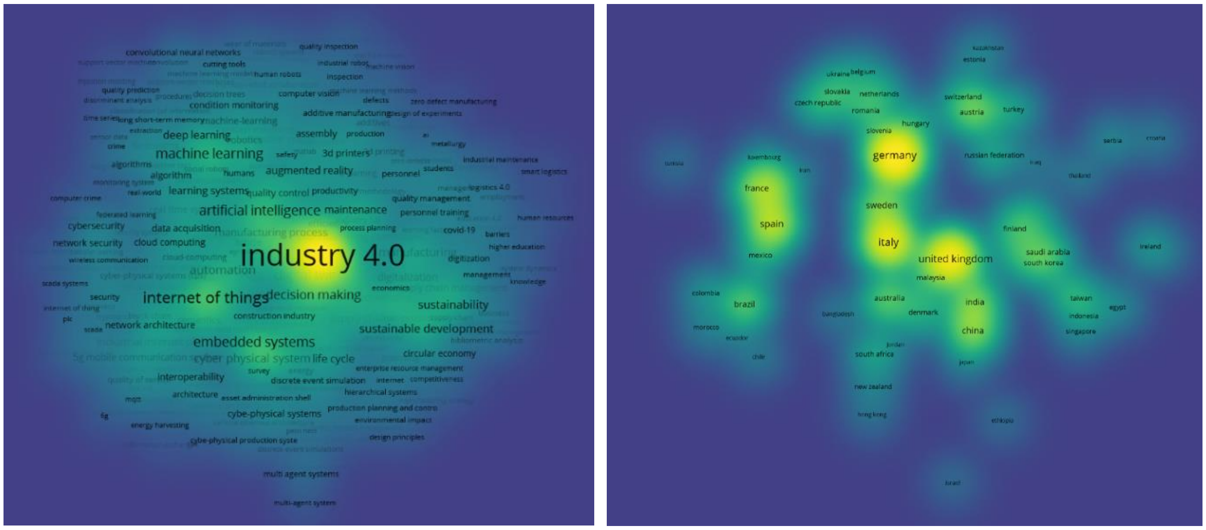

Fig. 2. Density Visualization of the Keywords and Countries that Addressed I4.0. Generated by VOSviewer.

3. 3 Historical Timeline, Definitions and Barriers of Adopting Circular Economy

The concept of CE was officially mentioned in 1989 by the environmental economists David W. Pearce and Kerry Turner in one of their theoretical studies that was based on the ecologist Kenneth Boulding (Su et al., 2013). The idea emerged as a conceptual framework to preserve the ecological, environmental, and economic balances as they are interrelated (Wautelet, 2018). Pearce and Turner critiqued the existing traditional open-ended linear systems by identifying that they lacked the built-in tendency to recycle any materials, systems, and processes as these linear models perceive the environment as a waste bank (Böcke et al., 2021), (Su et al., 2013). Upon the authors' critical examination of the conventional linear economic system, they created a new economic model called the CE that uses the first and second laws of thermodynamics where the total matter and energy remain the same in a closed system as opposed to an open system. Their research was influenced by the work of Kenneth Boulding and others who talked about the biophysical constraints of the current economic system, which is based on excessive consumption and a mounting ecological deficit, a few decades earlier. In 1966, Boulding proposed the idea of closed systems and envisioned a future economy that would run on recycling waste outputs and replicating the finite supply of inputs. CE is commonly defined as an economic global model that reduces the dependence and thus the exhaustion of non-renewable resources by utilizing superior smart materials, systems, and product design (Rosa et al., 2020). CE, which is characterized as a closed-loop system, aims to prevail over the traditional open-ended linear economy model (take, make, dispose) in which there is no innate tendency to recycle, restore, or regenerate (Su et al., 2013). CE allows for economic prosperity without the constraints of being dependent on finite resources, whilst simultaneously providing businesses with opportunities to generate revenue, create value, and reduce costs (Manninen et al., 2018).

CE is still not adopted in several organizations due to the barriers associated with its implementation such as lack of financial support from management departments; inadequate management systems; lack of appropriate technology and resources; lack of consumer interest towards the environmental aspects and effects; lack of awareness and public institutions; and the absence of sincere commitment from leaders and company owners. Other barriers discussed by (Wilts, 2017) include low quality of information where the quality of recycled materials is often uncertain, the lack of transparency of information about available quantities of recycled resources on the market, the misuse or direction of the high-quality recycled materials in the market, the increased transaction and search costs, unclear information about the background of the quality of secondary materials, lack of information is leading to complications in the pricing processes, the secondhand customers have a distorted perception, lack of information on the optimization of the secondary materials, technological barriers for adopting CE.

3. 4 Implementing CE through I4.0 Technologies: CE-I4.0 Nexus

Circular Economy and Industry 4.0 are currently listed as the key concepts that will be shaping the future (Spaltini et al., 2021). The prominence of these two topics has resulted in a substantial body of knowledge covering these two aspects as shown in Figure 4. Upon researching these two keywords "Industry 4.0" and "Circular Economy" on Scopus and limiting the search to "Open Access" documents, years from "2016 to 2023", subject area of focus selected was "Engineering" and documents included were limited to "Journal Articles", "Book Chapters", "Conference Papers" on the "Final" stages of publication in "Journals", "Conference Proceedings", "Book Series" and "Books", 416 documents were generated. Figure 4 illustrates that there is an increasing trend in the research covering these domains.

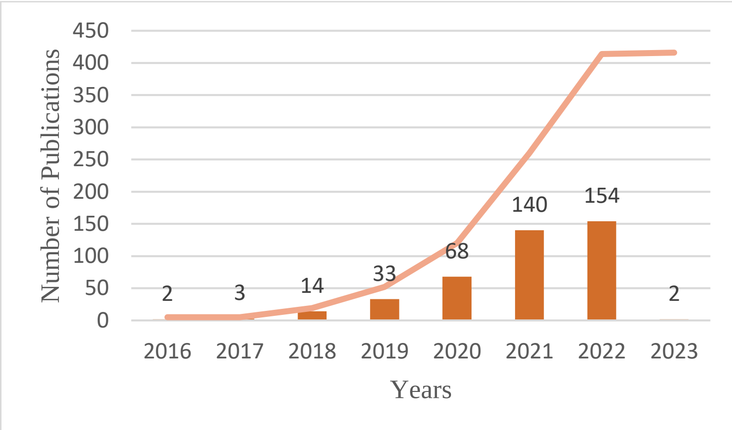

Fig. 4. Annual Publications and Cumulative Publications on Industry 4.0 and Circular Economy

Current studies highlight that there are very minimal contributions made in terms of literature concerning the type of I4.0 technologies that can support the CE principles (Rosa et al., 2020). Furthermore, in terms of practical applicability, there were minor cases where the attainment of CE's benefits was attained by adopting I4.0 digitization (Angioletti et al., 2017). Sustainable development is an underlying objective shared by all nations and thus it is essential to use innovative technologies, behavioral transformations, and systematic modifications to the means of production and consumption. Therefore, the following section discusses the potential linkage between CE and the I4.0 pillars.

3. 4. 1 Big Data and CE Linkage

Utilization of big data in construction and business will ameliorate the effectiveness of decision-making and the resources used. The reason behind it is a better understanding of the information and data being handled. Identifying the different sources of information and data will define the action and direction to follow with consideration of minimizing the waste and increasing the use of recyclable materials and products. Therefore, it will provide a better management of the material life cycle. Organizations can use the information related to the history of the company by analyzing capabilities and integrating good formwork to get the best course of lessons learned and actions to solve present problems and create new digitized solutions. (Awan et al., 2021)

3. 4. 2 Additive Manufacturing and CE Linkage

The current trend in the construction industry is to adopt AM processes such that the economic, social, and environmental pillars of sustainability are addressed, thus meeting the principles of CE. For instance, the AM of certain construction components made particularly of metals is deemed high sustainability and optimal CE due to their high recyclability rates (Henry et al., 2020). Implementing AM technologies in any construction manufacturing process can result in high production efficiency rates in terms of the costs associated with the manufacturing processes in a CE framework (Henry et al., 2020).

3. 4. 3 Autonomous Robots and CE Linkage

The operation of autonomous robots, that utilize Artificial Intelligence algorithms, can facilitate the highly complex process of recycling construction waste, wherein the robots are capable of sorting and reprocessing waste. Initially, autonomous robots separate construction waste with high levels of accuracy and precision, resulting in attaining a substantial percentage of pure secondary materials. This is because the error-free separation process results in materials going through the correct recycling path. Zen Robotics, an enterprise launched in 2007, created a new market for waste sorting through autonomous robotics and has confirmed that this technology is cost-effective as any additional costs needed to implement this technology to sort the waste accurately, will be counterbalanced by the savings generated from the value of the retrieved materials (Uçar et al., 2020).

3. 4. 4 Cyber-physical systems and CE Linkage

The transition from the traditional linear economic model to the circular model can be facilitated by advancements in technology such as Cyber-Physical Systems. Implementing CPSs within CE can minimize waste and increase efficiency, therefore, it assists in achieving different Sustainable Development Goals (Ahmed et al., 2021). The remote operation of a construction activity is done through machines connected to a Web Wirelessly that can receive instructions remotely. This is brought into practice in activities that pose a risk to a worker's safety thus addressing social sustainability (Arowoiya et al., 2020) (Oke et al., 2021). The design information feedback system under the CPSs serves as a decision-making tool that can be used by designers to select the materials as a detailed database of existing products including real-time updates on the lifetime of a product is available. Furthermore, results from extensive testing and simulation of materials' behavior are made available to decision-makers (Ahmed et al., 2021).

3. 4. 5 IOT and CE Linkage

Several actuators and smart devices are connected via the Internet of Things, making IoT play a principal role in delivering valuable information on assets thus helping enterprises run more effectively (Askoxylakis et al., 2018). IoT ensures the supply replenishment of construction materials. Radio Frequency Identification tags label the materials available on site, therefore, an actual accurate count of the materials is available through on-site systems. When the supply drops below the computed benchmark, the system alerts the central system to procure the necessary material quantities. This achieves economic sustainability as construction costs are reduced as excessive supply is prevented, further minimizing waste and energy consumed in the sourcing, manufacturing, and delivery of unneeded construction material, thus aligning with the CE principles. (Arowoiya et al., 2020). Tracking of construction tools and equipment is also enhanced by IoT, as it reduces the time consumed searching for misplaced tools and subsequently reduces the chances of re-ordering a tool that is already in stock (Oke et al., 2021)

3. 4. 6 Cybersecurity and CE Linkage

Cybersecurity ensures safety and secured access, which reflects on the rate of depletion of resources in a given period. In other words, the security and safety of the construction site or the organization has many outcomes such as lower scarcity of resources, higher productivity, improved comfort levels, and increased transparency among stakeholders. These outcomes will indirectly touch upon sustainability and ensure the emphasis of its practice as the resources of the project or even the assets of the organization are safeguarded and not wasted.

3. 4. 7 Cloud and CE Linkage

The cloud-based platforms play a vital role in monitoring and controlling a project or an organization. The higher the levels of control and monitoring, the better the performance and productivity levels as well as the quality of the end result. In the construction industry, the cloud can rephrase the concepts of the circular economy as the resources are being monitored and all stakeholders are enabled access to the platform to check the progress of work, status of material/resources available at the site, monitor attendance of involved personnel, and have live feedbacks and reports about the work. This is a motivation to participate in the circular economy which takes the participants a step forward towards sustainable development.

3. 4. 8 Blockchain and CE Linkage

The vision of CE is to operate a closed-loop system with the concept of reducing, reusing, and recycling products to enhance sustainability. Blockchain technology is a social tool of interconnectivity and coordination of multiple databases simultaneously and provides accessibility to all users with the adoption of decentralization, tamper-resistance, and distributiveness. This simultaneous cooperation between the parties within the same loop or network is the major feature of the blockchain which will lead to the outcomes of the CE. Blockchain can be used for smart contracts, supply chain management, and reducing the carbon footprint. (Upadhyay et al., 2021).

3. 4. 9 Digital Twin and CE Linkage

A digital twin is considered a virtual collection of data of the entire lifecycle of a product, commencing from its design phase up to its end of life. If the physical product encounters any changes in its variables, the same is reflected in its digital twin. Thus, with this high level of transparency and traceability of the entire product's life cycle offered by the digital twin, models that can be highly sustainable and beneficial to the construction industry such as "predictive maintenance and repair services" can be developed (Cagno et al., 2021). The information offered by the digital twin can drastically improve the operations and maintenance phase of construction projects and elongate the life of a construct by analyzing the condition of the digital twin of any component/service throughout a construct's life. Upon the frequent examination of the digital twin, the users will be able to predict the needed repairs and maintenance, before the emergence of any issue (Cagno et al., 2021), thus directly touching upon the economic pillar of sustainability. There is an immense opportunity for construction companies to enhance their productivity through the advanced digital technologies and platforms under the Industry 4.0 notion (Hossain & Nadeem, 2019).

3. 5 Implementation of the CE-I4.0 Nexus using IoT

3. 5. 1 Existing Research Addressing the CE-I4.0 Using IoT

As discussed in the above sections, IoT was the most common keyword generated by VOSviewer for the term Industry 4.0, subsequently, IoT was selected from the other pillars of I4.0 for further analysis. Furthermore, VOSviewer generated “sustainable development” and “sustainability” as recurring keywords for the term I4.0. Hence, the relationship between I4.0, IoT, and CE was established in the existing body of knowledge. Therefore, the three keywords “Industry 4.0”, “Circular Economy” and “Internet of Things” were researched on Scopus and only 78 documents were generated which highlights that there is insufficient research available covering these three key concepts together. There is a trend that research covering these three topics together is increasing as evident in Figure 5. Hence, the lack of research covering these three concepts with the recent increasing trend to address these topics can be identified as a knowledge gap in the existing literature. The documents extracted from Scopus were exported into VOSviewer for further analysis. Based on the following analysis: type of analysis: “Co-occurrence” and unit of Analysis: “all keywords”, the keywords that VOSviewer generated are shown in Figure 6. As shown in Table 1, globally there are very few countries where research covering Industry 4.0, CE, and IoT were addressed collectively, further emphasizing that this topic needs further research.

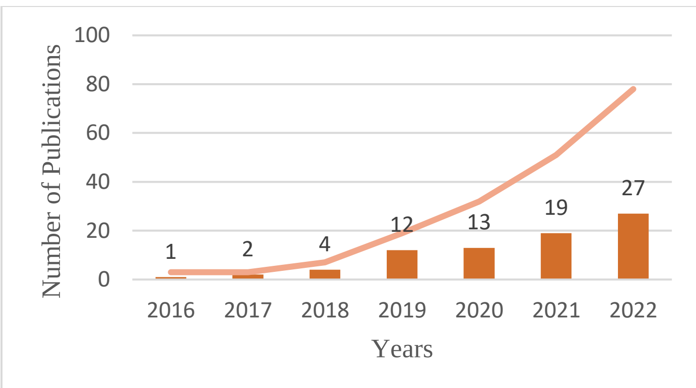

Fig. 5. Annual Publications and Cumulative Publications on Industry 4.0 and Circular Economy and Internet of Things

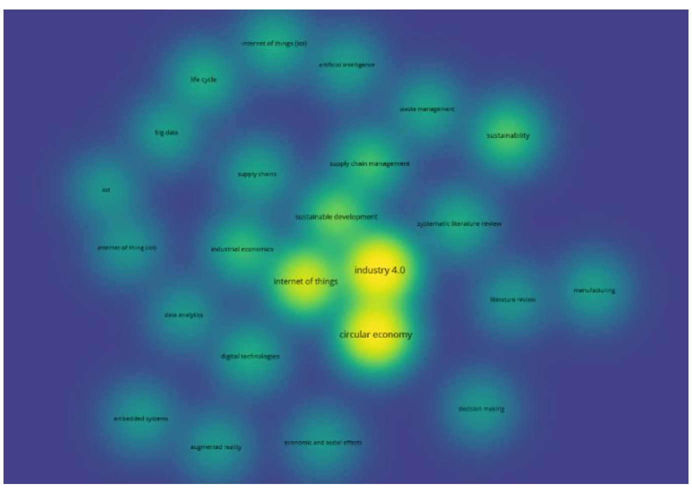

Fig. 6. Density Visualization of Keyword related to Industry 4.0 and Circular Economy and Internet of Things

Table 1. Countries that addressed Industry 4.0 and Circular Economy and Internet of Things in Research

Countries	Documents	Citations	Total Link Strength
United States of America	5	268	7
China	8	330	6
India	10	220	6
Germany	10	264	5
Finland	5	247	3
Italy	9	551	3
Spain	7	274	3
United Kingdom	15	313	3

3. 6 Application of the CE-I4.0 Nexus using IoT

3. 6. 1 RAMI 4.0

Despite the diverse interpretations of I4.0, most academics and industry experts concur on the Reference Architecture Model (RAMI 4.0), created by the German Electrical and Electronic Manufacturers' Association (Isa, 2019). A framework for improving and developing production and business plans is offered by RAMI 4.0 to companies with the primary objective of ensuring all participants involved in I4.0 initiatives have a common framework to promote and facilitate communication between them. RAMI 4.0 is illustrated as a three-dimensional coordinate system that shows how Industry 5.0 systems are designed. Derived from the IEC 62264 standard, the "Hierarchy Levels" axis illustrates various functionalities found in factories or facilities. The "Life Cycle Value Stream" axis depicts the life cycle of facilities, while the "Layers" axis explains how a machine breaks down into its properties (Isa, 2019).. Axis 1 is the Hierarchy Level, which incorporates work products and IoT connections and is a representation of different functionalities in factories and facilities based on IEC 62264, an international standard for enterprise IT and control systems that has been improved for I4.0. Based on IEC 62890, Axis 2, which is the Product Life Cycle makes a distinction between "types" and "instances" throughout the life cycle of facilities and products, changing a "type" to an "instance" after design and prototyping is finished. According to standard information and communication technology practices, Axis 3 comprises the Layers, which are the vertical axis, depicting the digital mapping of a machine through six layers, outlining a machine's properties layer by layer. RAMI 4.0 enables the categorization of objects such as machines by mapping all the key components of Industry 4.0 along these three axes. A gradual transition to the Industry 4.0 era is made easier by this model, which supports the explanation and application of adaptable Industry 4.0 concepts.

3. 6. 2 Design Management and Manufacturing

Sustainable development is improved when Industry 4.0 and the circular economy (the CE-I4.0 nexus) are integrated into the building process. A closed-loop circular economy requires careful handling of materials, starting with the design and manufacturing stages. Radio Frequency Identification (RFID), special machine learning techniques, agent-based computer-aided process planning (A-CAPP), computer-aided manufacturing (CAM) toolpath generation, and interoperability between CAD/CAM and CNC are the five stages of material design and manufacturing that integrate IoT for a successful CE-I4.0 workflow (Anbalagan and Moreno-Garcia, 2021). During these stages, IoT integration saves time, boosts output, and guarantees adherence to workplace policies. To increase productivity and efficiency, the idea is to create an AI-based program that can think, learn, and make decisions on its own (Anbalagan and Moreno-Garcia, 2021).

3. 6. 2 Industrial Waste Management

Through the integration of circular economy concepts and Industry 4.0 principles, the CE-I4.0 nexus seeks to advance sustainability in the construction industry through the adoption of a closed-loop methodology. Monitoring, control, productivity, efficiency, and sustainable development are all improved by digitizing construction platforms and equipment. Significant environmental risks are posed by construction and demolition, which generates 40% of carbon emissions and 33% of global waste (Miller, 2021) therefore, IoT-enabled smart recycling and waste management are essential. Operational, tactical, and strategic layers make up the three-layer framework that a C&D waste management facility in Hong Kong has developed (Kang et al., 2022). The operational layer uses IoT-enabled smart objects to handle waste and carry out demolition. The tactical layer facilitates decision-making and project management by managing data and smart objects. Using these services, the strategic layer develops waste management applications like real-time demolition management, BIM-based surveying, and efficient waste transportation. Using smart technologies like IoT and BIM, this framework seeks to maximize the reuse and recycling of demolition waste, thereby supporting CE.

5. Conclusions

The implementation of CE-I4.0 in construction processes will bring about substantial progress in the sustainable development agenda. However, the current shortage of information regarding this topic and the several barriers associated with implementing these concepts impede achieving sustainable construction processes. To promote sustainable practices in the construction industry, this paper discussed the connection between CE and I4.0. The research methodology followed a narrative literature review where numerous credible publications, journals, and conference papers were reviewed to extract the relevant information. The paper discussed multiple examples of linking the pillars of I4.0 to CE and provided some case studies wherein the CE-I4.0 nexus was adopted in different organizations. The principal aim was to comprehend how digital technologies, like the Internet of Things (IoT), bolster

CE in the construction sector, consequently augmenting the sustainability of construction endeavors. Additionally, Vos viewer was utilized to construct and visualize the bibliometric networks between the keywords of the paper. Vos viewer has helped find the resources required containing all the keywords such as “industry 4.0”, “circular economy”, “sustainability”, “IoT” etc. The collaboration of the circular economy and industrial 4.0 concepts creates a medium of efficiency and productivity in the construction industry. The CE-I4.0 nexus emphasizes the utilization of a closed-loop economy that implements reusing, repurposing, recycling, and minimizing waste generation. In addition, the technological introduction of digitalized platforms administers productivity and efficiency in processes. Implementing the CE-I4.0 nexus brought many adopting companies and organizations positive returns in terms of increased productivity, increased efficiency, and better monitoring and control practices over products and services. The nexus supports the initiative of approaching a wider spread of promoting greener practices in the field as well as emphasizing the key attributes to reach sustainability and sustainable development. The main obstacle found to implementing the nexus in many companies; was the lack of digital culture and training, and the resistance to adopting new technologies. The intersection of I4.0 and CE will evolve into Industry 5.0, which is an official extension of Industry 4.0 with a specific focus on social goals that go beyond job creation and economic growth, emphasizing the value of innovation and research for long-term human benefit.

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