



A Conceptual Investigation on Emergence of Industry 4.0

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Abstract

In the age of technological disruptions, it is important for everyone to understand the history of industrial sector development across the world. Metaverse like buzz word are shaping the features of new age technological innovations. In this connection, present exploratory work is based on highlighting the set of dimensions shaping evolving industries and its interlinkages with Industry 4.0. The industrial sector has gone through different revolutions, as this paper has attempted to highlight them. Each industrial revolution has changed the world, from coal and steam power to chemicals, electricity, and steel. Since the Third Industrial Revolution introduced collaboration and decentralisation, firms have changed and emphasised reciprocal partnerships. It expanded financial systems and technologies, helping globalise and introduce modern tools to numerous businesses. Advanced technologies like AI, IoT, and blockchain drove Industry 4.0, the Fourth Industrial Revolution.

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It revolutionised production and business patterns with automation, smart manufacturing, and interconnection. It generated ethical and societal concerns regarding privacy, data security, and the labour market. Moreover, this study outlined Industry 4.0's six design principles: decentralisation, virtualization, interoperability, modularity, real-time functionality, and service-centricity. These fundamentals underpin the transition from traditional industry to Industry 4.0. After navigating Industry 4.0's challenges and opportunities, it becomes clear that this revolution is a fundamental transformation that affects every area of our lives. Informed decision-making and responsible stewardship of these innovative innovations are crucial to the future of industry, economy, and society.

Keywords: Industrial Revolution, Industry 4.0, IoT, AI, Emergence of Industry, Metaverse

1. Introduction

Now a days, as the part of Industry 4.0, different applications are undergoing transformations as a result of the introduction of digital twins, metaverses, and virtualization. (Yao & Liu ,2025). Since its inception, the industry's history has been evaluated by the accumulation of profound know-how, significant outcomes, and groundbreaking inventions that have fundamentally transformed urban structures, demographics, product offerings, production processes, and labour dynamics, among various other factors (Gabriela Pereira Carvalho & Walimir Cazarini, 2020). The emergence of this industry can be attributed to the convergence of three pivotal factors: skill, investigation, and commercial innovation. These elements played crucial role in creating employment opportunities and fostering the development of novel products that cater to people's evolving needs. Consequently, the industry's evolution unfolds through distinct and equally momentous phases, characterised by the "First, Second, Third, and the imminent Fourth Industrial Revolution". It is worth mentioning that Industry 4.0 does not exist in isolation from its predecessors; rather, it builds upon the foundational pillars of earlier industrial revolutions, but with a heightened emphasis on combination, digitization, virtualization, advanced skills, and rapid responsiveness to stimuli (Roblek et al., 2016). Much like the industry itself, products, distribution methods, consumer demands, labour practices, and internal and external influences

have undergone significant transformations at each stage of its development. To harness the full potential of Industry 4.0 and explore new collaborative opportunities within this emerging landscape, a comprehensive understanding of its capabilities across various domains is essential.

In this context, this paper aims to introduce Industry 4.0 and its defining characteristics. To achieve this, the chapter is organized into three sections: the first addressing the historic progression of industry, the subsequent delving into origins and key concepts of Industry 4.0, and the third elucidating the design principles underpinning this innovative industrial paradigm (Kagermann, 2015). Even, Sankaran et al. (2025) explores that Smart Society 5.0 is possible with interventions like Artificial intelligence and Virtualisation.

2. History of Industrial Revolution

The historical record of the industrial revolutions goes beyond a mere list of innovations, discoveries in energy sources, new machinery, materials, or methodologies. However, it is vital to recognize that these elements have played a pivotal role in driving economic progress over the past two hundred and fifty years. standardization was also a prominent reason for industrial revolution and further technological advancements (Zhang et al., 2025).

While some technologies, such as hydrodynamic mills were for several decades, it is the widespread adoption and proliferation of these devices, often referred to as machinery, that define and distinguish this era from the earlier epochs (Hamilton Ortiz et al., 2020). Figure below shows the stages of industrial revolution.

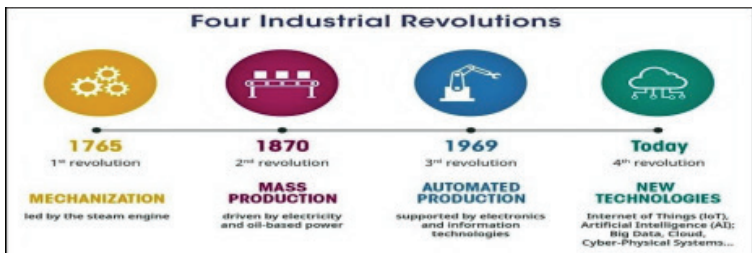


Figure 1. Industrial Revolutions at a Glance

Source: Authors.

Water, animal labour, and wood were the principal sources of energy prior to the beginning of the First Industrial Revolution in the middle of the 18th century. During this time period, the First Industrial Revolution took place. Wood, in addition to being the primary material for construction and fuel, played a crucial role in powering various activities. Iron quickly emerged as a central material in the construction industry, while coal gained prominence as the initial fuel source, and steam power emerged as a dominant engine technology. These three components synergized to establish a new technological paradigm during that era (Morales Velazquez et al., 2017). The rise of industrial civilization unfolded through distinct periods, with the first being termed the "First Industrial Revolution." This transformative period was catalysed by the development of the steam engine and prominently featured the economic theories of Adam Smith, who is widely regarded as its foremost proponent and the founder of economic liberalism. The onset of the initial industrial revolution, which began in the middle of the 18th century and extended well into the early years spanning the nineteenth century, marked a phase of profound societal transformation. During this era, there were significant expansions in manufacturing capabilities, encompassing a wider array of consumer goods and extending beyond the borders of England to international locations (Tang & Ho, 2019).

The mid-nineteenth century witnessed a revolution in transportation and communication, characterized by the proliferation of railways, the invention of the telegraph, and the introduction of transoceanic steamboats with robust steel hulls. These advancements facilitated activities that transcended national boundaries, blending elements of both business and adventure, and integrating them into the economic framework of expansion. These activities were seen as a fusion of entrepreneurial enterprise and adventurous endeavours. Following the commencement of the First Industrial Revolution, the "Second Industrial Revolution" emerged during the latter part of the 19th century. This transformative period was characterized by significant advancements across multiple industries, including chemical, electricity, oil, and steel. It brought forth a wide array of innovations, ranging from steam-powered steel ships, the

inception of aviation, improvements in food preservation, the mass production of consumer goods, mechanical refrigeration, preservation techniques, to the establishment of modern corporations. Crucially, this era marked a substantial shift in the global industrial landscape, with Germany, the U. S., France, and the U. K. rising as dominant industrial powers. In the United States, second industrial revolution is closely linked to Frederick Winslow Taylor's groundbreaking concept of scientific management, which he meticulously researched and implemented, leading to a revolution in the organization and execution of work. The transition from the First Industrial Revolution to the Second was driven by the integration of new sources of raw materials and energy, particularly focusing on the increasing adoption of electricity and, to a growing extent, oil as a source (Ngo et al., 2018). Toward the end of the 19th century, a noticeable cyclical momentum enveloped economies worldwide, a phenomenon that continues to resonate today. The development of the automobile and aviation industries, combined with advancements in telephony and radio transmission, hastened the revolution in communication and transportation that began in the early 20th century. The Second Industrial Revolution, spanning from the latter half of the nineteenth century into the early twentieth century, diverged from its predecessor, which relied on iron and coal-driven steam power. Instead, it hinged on electricity and steel, ushering in significant advancements in the realms of communication, chemistry, and the utilization of petroleum. However, it's essential to note that initially and in general, these innovations didn't completely supplant their older counterparts. Their full realization only came to the forefront in the twenty-first century, marking a moment when they truly distinguished themselves (Winroth et al., 2016).

The Third Industrial Revolution, which commenced during 1970s, fundamentally reshaped the architecture of capitalism and introduced a novel economic paradigm emphasizing collaboration as the cornerstone of success. It asserted that organizational goals could only be attained collectively, fostering a substantial rise in the number of businesses embracing this ethos. The growth of these enterprises was increasingly propelled by the pursuit of robust partnerships grounded in reciprocity. This revolution

revolutionized economic management, promoting a more horizontal and adaptable negotiation approach. It encouraged corporations to unite for more precise and cohesive economic endeavours. This transformative method of economic governance emerged as a direct outcome of the Third Industrial Revolution. Furthermore, the Third Industrial Revolution broadened the influence of financial system tools, often referred to as the market economy. This expansion accelerated advancements in communication and transportation, facilitating the global integration synonymous with globalization. Notably, this revolution is renowned for its technological advancements, particularly in Japan during the mid-1970s. These advancements covered a range of domains, including biotechnology, computer science, Computer Numerical Control (CNC), microelectronics, and integrated telematics systems, among others (Morales-Velazquez et al., 2017).

3.0 Industry 4.0 and its Prominent Characteristics

The Fourth Industrial Revolution, often referred to as Industry 4.0, is a term coined to describe a significant technological shift in how we live, engage in tasks, and interface with the world. It signifies the integration of multiple cutting-edge technologies such as artificial intelligence (AI), the Internet of Things (IoT), robotics, big data, blockchain, and various other digital advancements (Boyes et al., 2018). Key characteristics of the Fourth Industrial Revolution include:

- (i) **Automation and Smart Manufacturing:** The integration of AI and IoT into manufacturing processes allows in the automation and optimization of output. Manufacturing facilities and supply chains gain intelligence and enhance efficiency, ultimately resulting in higher productivity and reduced expenses. Even , hazardous processes are becoming workerless due to such smart robotics and automatic technologies.
- (ii) **Artificial Intelligence:** AI plays a central role in the Fourth Industrial Revolution, enabling machines to perform tasks that traditionally required human intelligence, such as learning from data, recognizing patterns, and making decisions.

- (iii) **Internet of Things (IoT):** IoT entails linking everyday objects and devices to the internet, allowing them to gather and share data. This connectivity leads to more informed decision making and improved services across various sectors, from healthcare to transportation.
- (iv) **Big Data and Analytics:** The massive amounts of data generated by IoT devices and digital interactions are analysed using advanced analytics techniques to gain valuable insights. This data-driven decision-making is essential for businesses and governments.
- (v) **Blockchain Technology:** Blockchain, originally developed for cryptocurrencies like Bitcoin, offers secure and transparent ways to record and verify transactions. It has applications beyond finance, such as supply chain management and identity verification.
- (vi) **Biotechnology:** Advancements in biotechnology, including gene editing and personalized medicine, are transforming healthcare and agriculture, leading to tailored treatments and improved crop yields.
- (vii) **Renewable Energy and Sustainability:** Industry 4.0 places a greater emphasis on sustainability and clean energy solutions. Technologies like solar power and energy-efficient systems are becoming more prominent. Capacho et al. (2025) observed that monitoring is easier in Industry 4.0 which is critical aspect in achieving operational efficiency.
- (viii) **Augmented Reality (AR) and Virtual Reality (VR):** AR and VR technologies are changing the way we interact with digital information and our environment, with applications ranging from gaming to education and training. **Metaverse** like emerging tech buzz words are attracting everyone's attention.
- (ix) **Cybersecurity:** With increased connectivity and data sharing, the importance of robust cybersecurity measures has grown significantly to protect against cyber threats and breaches.

The Fourth Industrial Revolution has far-reaching implications for industries, economies, and societies. It has the potential to disrupt traditional business models, create new opportunities,

and reshape the labour market. It also raises ethical and social questions related to privacy, data security, and the impact on jobs and human society. The term "Fourth Industrial Revolution" was popularized by the World Economic Forum (WEF) and has been the subject of extensive discussions in academic, business, and policy circles as the world adapts to the profound changes brought about by these technological advancements. Smart plants, smart manufacturing, and smart logistics all come together at the intersection of industry 4.0, which is the intersection of these three overarching considerations. The concept of the "smart plant" has evolved from the idea of the "digital factory" and is a critical component of the envisioned "smart infrastructure" of the future (Hamilton Ortiz et al., 2020). The "smart plant" not only places significant importance on advanced production systems and processes but also emphasizes the integration of network distribution within production facilities, essentially shaping the layout of the factory. Within this framework, "intelligent production" encompasses broader aspects such as industry-wide production logistics management, human-machine interaction (H2M), and the utilization of 3D/4D technology in industrial operations. This comprehensive approach forms a highly adaptable industrial chain that can cater to flexibility, personalization, and active maintenance within a networked environment. Furthermore, "intelligent logistics," facilitated primarily through the Internet and network integration of logistics resources, synergizes with enhanced logistics source competence on the supply as well as demand sides. This collaborative effort ensures that services align seamlessly with the logistical support required. These three fundamental elements function independently but collaboratively, culminating in the industry 4.0 production system through coordination and mutual interaction. It is interesting that the foundation of this new sector, whose goal is to produce items that are customised for clients, is smart manufacturing (Kagermann, 2015).

4. Principles of Industry 4.0

Industry 4.0 integrates six fundamental design concepts inside its framework. These principles, including decentralisation, virtualization, interoperability, modularity, real-time capabilities, and service orientation, serve as the guiding pillars of this

paradigm. The aforementioned concepts are commonly referred to as "design principles" because to their significant contribution to the design or transition process from the conventional industry, also known as Industry 3.0, to the advanced Industry 4.0 (Gabriela Pereira Carvalho & Walimir Cazarini, 2020).

(i) Decentralization

Decentralization, entails enhancing the capacity of local businesses, specific operations, and machines to independently make decisions. Instead of relying on central computers or hierarchical decision-making structures, this principle fosters flexibility and simplifies the utilization of expertise. It grants local operators the capability to swiftly react to alterations and adjust accordingly. This represents a shift away from the traditional production hierarchy, laying the groundwork for businesses to transform into decentralized self-organizing entities. It's important to note that the decentralization principle extends beyond machines, encompassing the independence granted to human coworkers within Industry 4.0. These individuals enjoy increased liberty to find critical attributes, analyse constraints, and make decisions, when necessary, all while keeping the broader interests of their industry sector and its overall well-being in mind.

(ii) Virtualization

The concept behind virtualization is that through machine-to-machine (M2M) connections and continuous monitoring, a simulated replication can be possible after the industrial setting. It involves linking sensor data to virtual plant and computer models, thereby enabling the creation of a simulated representation of the real world. If something goes wrong, an employee can be told. Also, all the important details, like the next steps to take or the safety rules, are still accessible. In business 4.0, virtualization is used by people as a very useful tool to help them do their work. This concept saves employees and established teams time, analysis, and decision-making by letting them get information, share it, and put it all together virtually, quickly, and in actual time. In a popular work, Ghobakhloo et al. (2025) explored that value creation is possible through virtualization in Industry 4.0.

(iii) Interoperability

Within the manufacturing landscape of Industry 4.0, interoperability signifies the capability of smart machines, intelligent storage systems, and advanced facilities to communicate, exchange information, initiate actions, and manage one another independently, without external assistance. This is called a cyber-physical system (CPS). By linking software and programmes, the integrated manufacturing systems are linked to both business processes inside industries and the value chain across the board. The capacity for humans to collaborate effectively with machines in harmony is also part of interoperability. This means that all industrial tasks can be done at the same time and with the same amount of effort.

(iv) Modularity

The concept of modularity involves the use of modular systems capable of flexible adaptation to evolving demands. These systems allow for the replacement or expansion of individual production modules, simplifying the process of adding or removing modules. Consequently, these modular systems demonstrate a high degree of adaptability, enabling them to seamlessly accommodate seasonal variations or shifts in product production requirements, including the integration of new technologies. This adaptability ensures that production remains agile, capable of responding to changing environmental factors, systemic shifts, and evolving customer requirements flawlessly, without any errors, disruptions in productivity, or customer dissatisfaction. This characteristic is highlighted in a review study by Narkhede et al. (2024) which says that “suitability of Industry 4.0 technologies is quite important in the areas like New Product Development, Supply Chain Management, Logistics Management, Production Planning and Control, Quality Management, and Maintenance Management”. In this way, modularity is quite an important facet of Industry 4.0.

(v) Real-time capability

It can be defined as the ability of intelligent machines, equipped with specialised software, to autonomously adjust to the manufacturing process and make decisions based on

Cyber-Physical Systems (CPS) in response to the production requirements. This enables continuous monitoring of product quality and facilitates timely decision-making as per the specific demands of the moment. The establishment of this link will serve to mitigate the occurrence of resource misuse, waste generation, material wastage, and concurrently enhance efficiency of energy. The ability to operate in real-time concept is a prominent feature of industry 4.0, as it plays a crucial role in enabling the industry to achieve optimal time it takes to react to stimuli from both within and outside the system. This is achieved by instantaneously exchanging, receiving, and analysing data and information.

(vi) Service Orientation

In alignment with the principle of service orientation, the availability of human, business, and CPS (Cyber-Physical Systems) services via the Internet, accessible to diverse stakeholders, facilitates the advancement of product-service systems (PSS).

These PSS are intentionally designed to be accessible both within and beyond the confines of the organization. This approach enables Industry 4.0 to uphold its network performance by engaging in collaborations with a wide spectrum of stakeholders, encompassing customers, partner industries, suppliers, and others. Through the utilization of virtual and digital platforms that remain consistently accessible to users, individuals can easily tap into valuable services, products, and industry-related information. **Stöber (n.d.) emphasizes the significance of responsible stewardship of these innovative technologies and informed decision-making, as the choices we make today will influence the future of society, economy, and industry. In a study by Abulibdeh et al., (2024), it is indirectly observed that** role of educational institutions is prominent in enabling other industries with intelligent and capable people who can maintain their service quality.

5. Conclusion

In this chapter, the development of Industry 4.0 has been described in a comprehensive manner. The history and prominent phases of Industry 4.0 have been narrated based on their industrial linkages and usages. Key dimensions of first

Industrial Revolution to Fourth Industrial Revolution (Industry 4.0) have been explained thoroughly with their prominence.

Present study explores that Industry 4.0 have promoted the growth of financial systems and technologies, which in turn facilitated globalization and introduced sophisticated tools to a no. of industries which can be observed in modern organisations. The Fourth Industrial Revolution, also referred to as Industry 4.0, was a transformative force that was supported by advanced technologies such as blockchain, IoT, and artificial intelligence (AI). It revolutionized production processes and business models by ushering in an era of automation, smart manufacturing, and interconnectedness. It is important to note that metaverse is another big segment in technology and Industry 4.0 which will influence major factors contributing to production and performance in industries to diverse set of business and social organisations.

References

- Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): An analysis framework. *Computers in Industry*, 101, 1–12.
<https://doi.org/10.1016/j.compind.2018.04.015>
- Gabriela Pereira Carvalho, N., & Walmir Cazarini, E. (2020). Industry 4.0 - What Is It? In *Industry 4.0 - Current Status and Future Trends*. IntechOpen. <https://doi.org/10.5772/intechopen.90068>
- Hamilton Ortiz, J., Gutierrez Marroquin, W., & Zambrano Cifuentes, L. (2020). Industry 4.0: Current Status and Future Trends. In *Industry 4.0 - Current Status and Future Trends*. IntechOpen. <https://doi.org/10.5772/intechopen.90396>
- Kagermann, H. (2015). Change Through Digitization—Value Creation in the Age of Industry 4.0. In *Management of Permanent Change* (pp. 23–45). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-05014-6_2
- Morales-Velazquez, L., Romero-Troncoso, R. de J., Herrera-Ruiz, G., Morinigo-Sotelo, D., & Osornio Rios, R. A. (2017). Smart sensor network for power quality monitoring in electrical installations. *Measurement*, 103, 133–142. <https://doi.org/10.1016/j.measurement.2017.02.032>
- Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials,

- methods, applications and challenges. *Composites Part B: Engineering*, 143, 172–196. <https://doi.org/10.1016/j.compositesb.2018.02.012>
- Roblek, V., Meško, M., & Krapež, A. (2016). A Complex View of Industry 4.0. *SAGE Open*, 6(2), 215824401665398. <https://doi.org/10.1177/2158244016653987>
- Stöber, H. (n.d.). *acatech STUDY Executive Summary and Recommendations*.
- Tang, T., & Ho, A. T.-K. (2019). A path-dependence perspective on the adoption of Internet of Things: Evidence from early adopters of smart and connected sensors in the United States. *Government Information Quarterly*, 36(2), 321–332. <https://doi.org/10.1016/j.giq.2018.09.010>
- Winroth, M., Almström, P., & Andersson, C. (2016). Sustainable production indicators at factory level. *Journal of Manufacturing Technology Management*, 27(6), 842–873. <https://doi.org/10.1108/jmtm-04-2016-0054>
- Abulibdeh, A., Zaidan, E., & Abulibdeh, R. (2024). Navigating the confluence of artificial intelligence and education for sustainable development in the era of industry 4.0: Challenges, opportunities, and ethical dimensions. *Journal of Cleaner Production*, 437, 140527.
- Narkhede, G., Mahajan, S., Narkhede, R., & Chaudhari, T. (2024). Significance of Industry 4.0 technologies in major work functions of manufacturing for sustainable development of small and medium-sized enterprises. *Business Strategy & Development*, 7(1), e325.
- Ghobakhloo, M., Iranmanesh, M., Foroughi, B., Tseng, M. L., Nikbin, D., & Khanfar, A. A. (2025). Industry 4.0 digital transformation and opportunities for supply chain resilience: a comprehensive review and a strategic roadmap. *Production planning & control*, 36(1), 61–91.
- Capacho, J. W. V., Pérez-Zuñiga, G., & Rodriguez-Urrego, L. (2025). Diagnostic analysis and performance optimization of scalable computing systems in the context of industry 4.0. *Sustainable Computing: Informatics and Systems*, 45, 101067.
- Yao, Y., & Liu, G. (2025, January). Enhanced Power Inspection System Utilizing Metaverse Technology. In *2025 International Conference on Multi-Agent Systems for Collaborative Intelligence (ICMSCI)* (pp. 764–769). IEEE.
- Sankaran, S., Arun, M., & Kottaimalai, R. (2025). Virtualization of Smart Society 5.0 Using Artificial Intelligence and Virtual Reality. *Networked Sensing Systems*, 297–321.
- Zhang, H., Meng, Y., Zeng, Z., & Zhao, L. (2025). A Leap Forward of Standardization (the First Industrial Revolution). In *Brief History of Standards* (pp. 21–69). Singapore: Springer Nature Singapore.