Industry 4.0 Innovation

Subjects: Computer Science, Information Systems

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Industry 4.0 has revolutionized manufacturing processes and facilities through the creation of smart and sustainable production facilities. Blockchain technology (BCT) has emerged as an invaluable asset within Industrial Revolution 4.0 (IR4.0), offering increased transparency, security, and traceability across supply chains.

Keywords: Industry 4.0 ; blockchain technology ; smart manufacturing ; sustainable manufacturing

1. Introduction

Industry 4.0 (IR4.0) refers to the incorporation of innovative cutting-edge cyber technologies into companies' business operations, such as "blockchain technology" (BCT), "big data", "cloud computing", "Artificial Intelligence (AI)", "3D printing", "smart manufacturing", "autonomous robots", "Internet of Things (IoTs)", "RFID Tags", and so on. These innovative cutting-edge digital technologies are gaining much traction in management practices as digitalization (conversion to digital format), and this is regarded as a positive trend that can lead to a competitive edge, economic expansion, gaining innovative capability, and operational development [1][2][3][4]. While the practical use of such technologies (particularly BCT) in the context of firms' operational activities, logistics, and supply chain (SC) members is relatively new and unestablished, it is clear that this technology will undoubtedly reshape the relationship between businesses, logistics, and SCs members [5][6][7][8].

Furthermore, by implementing such cutting-edge digital technologies, businesses can gain a competitive edge over their rivals by differentiating themselves, cutting costs or improving efficiency, and supporting innovation [9]. They also assist companies in rethinking their economic paradigm (value propositions), optimally organizing their processes, streamlining the way they are structured [4], transforming their mechanism of value creation [10], and sharing widespread knowledge, data, and information across the entire company [11]. As such, implementing industrial 4.0 applications will result in an improved firm act. Nevertheless, the applications of IR4.0 technologies in the development of smart and sustainable manufacturing facilities have long been a source of contention in the world of management, with critics arguing that such investments might take a long time to pay off [3]. This is can be explained by the substantial costs and high level of knowledge and skills required for their deployment [12]. Alternative viewpoints posit that certain developed technologies may not yield statistically significant improvements in business performance within the realm of short-term investments [11][13].

More specifically, academics from different fields have extensively investigated the multifaceted outcomes of Industry 4.0 (IR4.0). The initial research primarily centered on its expediency and value-related benefits [14][15]. In contrast, newer studies have expanded their focus to encompass strategic and operational consequences, including innovation performance [3][16], supply chain management (SCM) effectiveness [13][17], and financial results [18][19]. However, due to the diverse fields and disciplines involved in studying the IR4.0—business performance relationship, the comprehension of how IR4.0 influences firm performance, the mediating and moderating factors affecting its effectiveness, and the mechanisms and barriers shaping its outcomes remains limited. While recent investigations have explored mediating variables such as competitive advantage [20], SC visibility [7][21][22], and technological functionality [23], contributing to our knowledge, inconsistent findings in earlier research and the complex nature of IR4.0 call for a deeper exploration of the underlying mechanisms and organizational determinants linking IR4.0 to business innovation [24] and the advancement of intelligent and sustainable manufacturing facilities [3].

2. Industry 4.0

IR4.0, as described by [25], is a framework that hinges on integrating vertical and horizontal value chains, digitizing services and products, and introducing innovative business models. It can be viewed as a "policy-driven product", as indicated by [26]. Ghobakhloo [27] outlines IR4.0 as a holistic system that creates value by integrating advanced technologies and processes that are guided by twelve "design principles" and influenced by fourteen contemporary technological developments. This concept comprises six aspects and principles, as well as four components, which encompass “vertical networking”, “horizontal integration”, “business solutions”, and “expanding technologies” [25].

Prior works, such as [9][28], have identified more than ten essential elements/factors of success for implementing Industry 4.0. Nonetheless, existing studies have predominantly concentrated on three aspects: “drivers and barriers”, “implementation patterns”, and “maturity assessment”. These drivers and barriers can be categorized into “technology, society, and environment”, with technology-related factors being central. For instance, the acceptance of IR4.0 is influenced by variables such as “information technology maturity”; “technology incentives” [29]; “investments in advanced manufacturing technologies”; “novel technologies” such as “BCT, big data, cloud computing, AI, 3D-printing, smart manufacturing, robotics, augmented reality, IoTs, RFID Tags” [13][30]; and so on. Technological advances that help in the integration of SC information [13][30] and enhance SC “collaboration” and “transparency” [31] are also pivotal drivers. Regarding to the “social factors”, these encompass “sustaining government policies” [29], “legislation, and public advisory systems” [32]. Ecological elements/factors encompass socioeconomic and business sustainability dimensions, with market environments in emerging or developed economies being examples of socioeconomic factors [9]. Various business environmental factors play crucial roles, including top management support [9][28][30][33], worker participation [32], human resource development [34], and change facilitation [28].

In addition, most of the research on how to implement Industry 4.0 focuses on using new information technologies, especially front-end technologies such as block chain technology and Digital Twin solutions encompassing “intelligent manufacturing”, “intelligent SCs”, and “smart manufacturing” serving as the core [9][35][36]. With regard to assessing the maturity of IR4.0 implementation, it is considered as another vital research area, aiding companies in understanding their current implementation level and guiding further improvement.

Manufacturing companies have tackled challenges arising from IR4.0 by innovating business models [37], fostering innovative ecosystems [38], achieving value-based innovation [39], formulating global strategies [1][40], adopting data-driven and sustainable manufacturing practices [41][42][43], and establishing smart factories [23]. Previous works has identified two noteworthy sets of IR4.0-related business practice relationships. First, studies have found a complementary impact on “IR4.0-lean management relationship” [44], enhancing existing practices like Lean Manufacturing principles [45], Lean Six Sigma [46], and “total quality management” [46]. These complementary relationships help to promote the circular economic system and sustainable growth [37][43]. However, some studies have suggested no significant improvements in environmental sustainability from all IR4.0 technologies [46].

Second, earlier works indicated that IR4.0 can benefit various aspects of SC management, including “innovation” [47], “technology transformation” [33], “sustainability dissemination” [31], resilience, ripple effects, and risk mitigation [48], and synergy with Lean Manufacturing principles [49].

Several categorizations of IR4.0 applications have emerged in the literature [50]. The most common classification distinguishes between “physical process-driven technologies” and “digital technologies”. The first is physical technologies, which encompass “hardware components” are primarily used to enhance tangible production processes. Examples include “additive manufacturing, collaborative robots, and transportation systems” [51]. The second is a broad range of “digital technologies”, categorized into three distinct subgroups. (i) “Digital Interface Technologies”: these encompass network-connectable hardware components, such as “BC”, “cyber-physical systems”, “IoT”, and “visualization technologies” [52][53]. (ii) “Network Technologies”: these are predominantly software components like “cloud computing” and “cybersecurity solutions” [54][55]. (iii) “Data Processing Technologies”: these are also information-driven software components, e.g., “artificial intelligence”, “simulation”, and “big data analytics” [56][57].

A common reference [50] is the “ten pillars of IR4.0 technologies”, which include “BCT”, “big data analytics”, “autonomous robots”, “simulation”, “horizontal and vertical systems integration”, “IoT”, “cybersecurity”, “cloud computing”, “additive manufacturing”, and “augmented reality” [13][50]. The interpretations of these pillars may vary, with some focusing on specific components. For instance, Frank et al. [36] emphasize “the connectivity and intelligence capabilities of IoT, cloud computing, and big data analytics”. Rojko [58] underscores the application of “cyber-physical systems” and “IoT”. Moeuf et al. [34] replace “additive manufacturing” with “cyber-physical systems”, change systems integration to “machine-to-machine” (M2M) communication, and revise “autonomous robots” to “collaborative robots”. Certain works, such as the work of Roblek et al. [59] have limited the focus to four major technological components: “cyber-physical systems”, “IoT”, “IoS”, and “smart factories”.

In the realm of “BCT”, its potential to facilitate the effective implementation of IR4.0 innovations has been highlighted [60]. The various applications of BCT, particularly in manufacturing and SC domains, are emphasized by [61]. Numerous enablers, drivers, and capabilities of BCT for IR4.0 innovation are discussed in the next sections and subsections.

More importantly, the utilization of BCT in the domain of decision-making shows promise. It forms an essential foundation for the future of manufacturing and SCM. An efficient decision-making process serves as the primary defense against uncertainties for any organization. A particularly promising potential application may involve using BCT to streamline and enhance decision-making. For any organization, ensuring a decision-making process is the most efficient way to deal with all uncertainties. SCM specialists are required by most businesses in order to develop and implement procedures used for making decisions to ensure competitiveness. An individual's decision-making is improved when a BCT protocol is used, facilitating outcome predictions. Studies such as [60][61][62] have shown how vital effective decision-making is to success through the tracking and monitoring tools of BCT.

Recent studies on IR4.0 innovation mostly adhere to the antecedents–practice–response–performance logic, with a focus on technical aspects [9]. The current focus of antecedents is primarily at the technical level. Similarly, the effects of "social and environmental factors", which are the focus of the research in the context of a sustainable manufacturing system, have received little attention. The practice of "IR4.0 innovation" primarily focuses on the implementation of relevant sophisticated technological innovations, whereas IR4.0′s "strategic response" discuss the digital and intelligent changes in businesses and their SCs enabled by these sophisticated technological innovations. Given the significant investment required in the early stages of IR4.0 adoption, it is not yet known how IR4.0 can be used to improve organizational financial performance. **Figure 1** outlines the existing research on IR4.0 innovation against this backdrop.

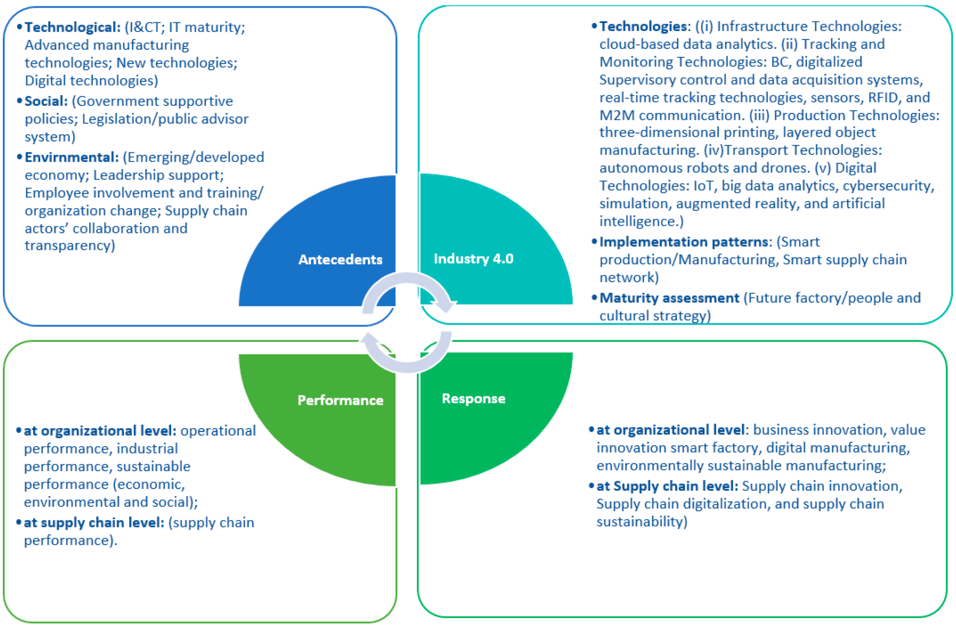

Figure 1. Theoretical framework of IR4.0 innovation.

3. BCT

"BCT" is a P2P process that does not require an intermediary. To this end, each of the different parties elaborated in any transaction functions as "nodes", and this process is verified through "cryptography" (i.e., "hash"). Records of these transactions are maintained in a single, transparent database across all participating organizations. Once a record is transmitted to the "distributed ledger network", it is nearly impossible to change, as it is in an unalterable record of past activity [63].

The cryptography, or hashing process, converts "tangible assets" (such as raw materials), or "intangible assets" (such as file ownership), into a digitally encoded "token". This token can be logged, monitored, and transmitted using a "private key" on the BCT [64]. The invention of BCT can be traced back to 2008 to Satoshi Nakamoto, an anonymous author of the "Bitcoin white paper", which describes a data structure that incorporates data records referred to as "blocks in a chain".

Following the studies of [21][65], BCT is characterized as follows:

(i) BCT is intended to be "*distributed and synchronised* via *networks*", allowing companies to connect and exchange data, and, therefore, is suitable for multi-actor enterprise networks that consist of SCs or financial partnerships.

(ii)

BCTs provide "*smart contracts*", which are agreements that parties form beforehand and hold within the network. "A smart contract" is a code protocol designed to promote, validate, or execute the agreed clauses and conditions of the contract on a digital basis. This allows for the execution of legitimate contracts without the need for third-party interference because it is entirely performed digitally. This also affords various parties on the network the mutual trust that everyone will comply with the rules.

(iii)BCT relies on using "*P2P networks*", where an agreement on the validity of a transaction is reached among all relevant parties, and these networks serve to keep incorrect or possibly deceitful transactions away from the database.

(iv)Lastly, BCT is considered "*data immutable*", which means that the agreed-upon transactions are logged and not altered. It offers a history of assets; thus, it is easy to know where it is, where it has been, and what has occurred in every object in its lifetime.

BCT stands apart from conventional information system architectures due to the incorporation of its four fundamental features, as shown in **Figure 2**:

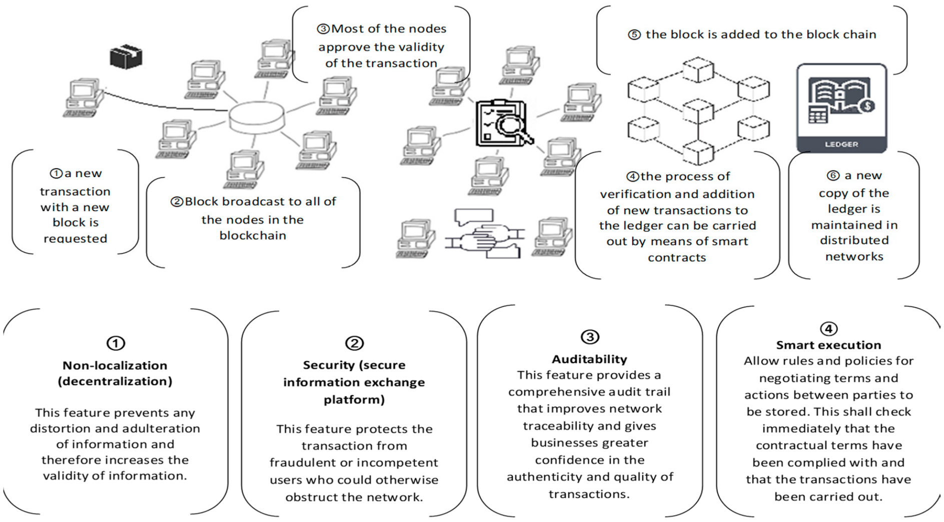

Figure 2. An overview of the steps and features of BCT information and transactions.

(i) Non-localization (decentralized database): Centralized databases are more vulnerable to hacking, manipulation, or crashing. By contrast, decentralized databases are more reliable and trusted due to the reliability of the intermediary or other network members [65];

(ii) *Security:* This is an essential requirement for reliable and long-term information exchange. It is necessary for managing the demands among members of the network [66]. Transaction history is only available to authorized network users, while no one else can remove or change data without the consent of others;

(iii) *Auditability:* BCT is a more open system, enabling auditors and third parties, such as compliance officers, to easily access the data. Due to its transparency and immutability, BCs force companies to operate within the framework of consumer protection legislation and regulations [65][67].

(iv) *Smart execution:* Another feature of BCT is the self-execution of digital transactions using decentralized cryptographic mechanisms that astutely bridge protocols and user interfaces to foster regulated and secure communications across computer networks [24].

4. Role of BCT in the Development of Smart and Sustainable Manufacturing Facilities

Earlier sections describe how BCT can be used to create a more secure, traceable, authentic, and collaborative environment while boosting demand forecasts and improving the manufacturing cycle. In this part, the researchers explain the role of "BCT" in the development of smart and sustainable manufacturing facilities, as found in both the literature and practical applications. According to [68], "BCT" has been widely adopted across diverse industries in industrialized and developed economies, leading to innovative applications in smart manufacturing within four key areas: ensuring data security; increasing data sharing, traceability, and trust mechanisms; increasing system development; and performance improvement. These areas are summarized in **Table 1** below.

Table 1. Key application areas of BCT in smart manufacturing.

Application Area	Explanation	Practical Example
Ensuring data security	BCT uses its chain storage structure with timestamps to ensure data security in smart manufacturing systems [63][68]. Every block of data in the BCT is immutable because it possesses a timestamp and a link to the former block. Furthermore, the encryption algorithm safeguards data security. BCT's traceability facilitates the optimization of manufacturing systems by tracking the journey of materials and products from source to destination within the SC [13][66]. This helps manufacturers to identify and address inefficiencies.	In an actual situation, BCT-enabled industrial IoT is able to mitigate the risks of information loss and malicious interference as a result of malicious activity on any single network node.
Increasing data sharing	BCT enhances data sharing through its distributed ledger technology, which allows all participants to simultaneously record and share information [69]. This enables both up-and-down-stream actors to share data in real time. Moreover, BC's privacy protection mechanisms encrypt sensitive data, addressing the inconsistencies between data privacy and sharing [35]. As a result, BCT can break down information silos and enable effective data sharing among various parties.	In a practical example, a BC-based logistics data-sharing platform can accelerate document transfer and reconciliation, improving overall logistics performance.
Traceability and trust mechanism	BCT can serve as a "trust machine and/or mechanism" for all parties in smart manufacturing [70]. Critical data throughout the design, production, and sales processes are cooperatively managed through trusted mechanisms [68][70]. Producers, vendors/contractors, distributors, and other smart manufacturing actors communicate transparent and trustworthy data, establishing trust relations between them [70].	In practice, BCT can eliminate the need for supplier background checks and product quality inspections, further reducing the cost of smart manufacturing.
System development and performance improvement	BCT significantly improves system coordination. Paperless, digital transactions and reliable electronic memory based on BCT critically enhance a firm's transaction efficiency [35][68]. Additionally, BC's smart contracts support partnership between up-and-down stream actors in the smart manufacturing and the entire SC. Consequently, BCT becomes a capable driver for the synchronized development of the entire "smart manufacturing system" [20][71][72].	In practice, a BCT-based smart procurement platform can advance procurement coordination and support the transparency of industry trade relationships.

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