



# Advanced Technologies in Smart Factories: A Cornerstone of Industry 4.0



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**Abstract:** The transition from manufacturing activities to an economy dominated by industrial production signifies the evolution of the Industrial Revolution. Presently, the global landscape is undergoing the Fourth Industrial Revolution, a natural progression from its digital predecessor, Industry 3.0. This era is distinguished by an influx of innovations across global business sectors. Solutions, particularly aiming to enhance industrial production and address volatile consumer demands, have gained paramount importance. These global shifts lead to profound structural transformations in industrial production. With the rapid integration of contemporary technologies in Industry 4.0, coupled with significant technical advancements, the notion of “smart factories” has emerged as a focal point in research, engineering, and practical applications. In the realm of sustainable business operations, the concept of the smart factory is frequently debated. While its intent is the diminution of manual tasks and the enhancement of customer service, it inherently demands the incorporation of various technologies inherent to Industry 4.0. Recognizing the profound impact of Industry 4.0 on production methodologies and the workforce’s perspective, emphasis is placed on understanding the pivotal role of advanced technologies within the smart factory paradigm. This abstract seeks to elucidate the core processes in the smart factory concept with a spotlight on refining intralogistics activities through the lens of Industry 4.0 technologies.

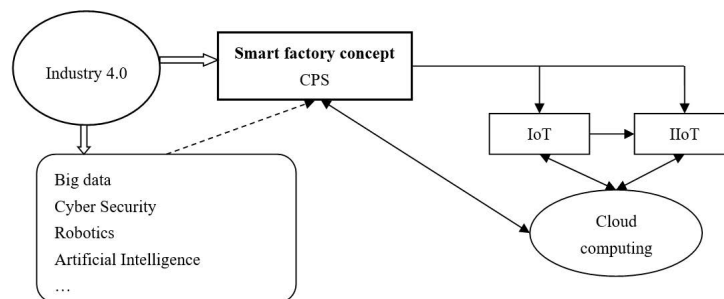
**Keywords:** Industry 4.0; Smart factory; Intralogistic activities; Internet of Things; Industrial Internet of Things; Cloud computing

## 1 Introduction

Since the inception of the First Industrial Revolution, various inventions and methodologies have emerged to enhance both the quality of life and efficiency of work. Innovations have evolved from the rudimentary steam engine to intricate, almost fully-automated intralogistic processes. In contemporary times, material processing activities are predominantly automated, enabling personnel to manage intricate technological processes across industries more effectively. Rapid technological advancements necessitate that businesses adapt to advanced solutions to remain competitive. A high frequency of changes characterizes this era, driven by unpredictable customer demands. The primary focus has shifted towards producing user-friendly, functional, and high-quality products to meet user specifications, encompassing not only tangible products but also information, energy, and services. The integration of Industry 4.0’s “smart” devices, supported by the Internet, ensures products and services are consistently and readily available, indicating an enhancement in both intralogistics and customer service activities [1].

In fiercely competitive markets, numerous companies have endeavored to elucidate how Industry 4.0 can bolster sustainability across production, logistics, and various other processes. This multifaceted explanation of the concept of Industry 4.0 has made it challenging to discern a universally accepted interpretation. However, in 2015, a significant stride towards establishing a common conceptual framework was made by a consortium of German experts. Their publication, “Design principles for Industry 4.0 scenarios: A literature review”, highlighted four pivotal elements of the digital revolution: Cyber-Physical Systems (CPS), Internet of Things (IoT), and the Smart Factory [2]. A majority of the research regards these technologies as foundational. Other technologies, such as Digital Twin (DT), 3D printing, robotic systems, and Artificial Intelligence (AI), among others, are perceived as extensions of these foundational elements, vital for realizing processes within the smart factory paradigm to deliver sustainable products and services [2, 3].

As technological innovations have matured, initial foundational technologies have been superseded by advanced counterparts including Big Data and analytics, Autonomous robots, Simulation, Horizontal and vertical system integration, IIoT, Cyber Security, Cloud Computing, Additive Manufacturing, and Augmented Reality. Studies have indicated that smart factory processes often falter due to an orientation towards tailoring products based on user demands [3, 4]. Consequently, this study aims to delineate the significance of specific Industry 4.0 technologies concerning their role in the seamless functioning of all processes within a smart factory. Figure 1 illustrates the interconnectedness of Industry 4.0 technologies from the aspect of the smart factory concept, where their direct and indirect influence on this modern concept is indicated. Following this introduction, a brief overview of the industrial revolution is provided, focusing on the transition from traditional manufacturing to smart factories. Subsequent sections delve into the processes, interconnections, and operational principles of the smart factory, emphasizing prevalent technologies. This will be followed by a detailed exploration of pivotal smart factory technologies, underscoring the criticality of their interplay for sustainable intralogistics activities. The concluding discussion encapsulates the implications of modern technology implementation within Industry 4.0 for the sustainability of the smart factory concept, highlighting potential challenges and avenues for future research.



**Figure 1.** The interrelationships of Industry 4.0 technologies considering the perspective of the smart factory concept

## 2 The Evolution of the Industrial Revolution and the Advent of the Smart Factory

The commencement of the industrial revolution remains a debated topic among scholars due to the multitude of economic and social transformations that accompanied it. The origins of the First Industrial Revolution during the 18th century are most frequently associated with Great Britain, subsequently spreading to Western Europe and North America [1–3]. Such alterations have been largely attributed to significant advancements in science, technique, technology, and Information and Communication Technologies (ICT), ranging from the first industrial revolution—defined largely by the advent of the steam engine—to the present era of Industry 4.0 [1–3].

The introduction of the steam engine, a paramount technological innovation, found its implementation in production and intralogistics operations. During its early adoption, production processes were managed traditionally, often localized. However, even during these nascent stages, certain ICT-related inventions were observed to enhance user services [1]. The subsequent Second Industrial Revolution of the 19th century, often termed the Technological Revolution, witnessed a proliferation of technological innovations [2, 3]. This era was significantly shaped by Tesla’s contributions, particularly in the realms of efficient electricity transmission, AC motors, and other technological applications that substantially augmented production processes. It was during this period that production process management began displaying elements of globalization. Concurrently, intralogistics gained prominence due to the emergence of innovative transportation modalities, vehicles, and material handling solutions [3, 4].

Dubbed the Digital Revolution, the Third Industrial Revolution was characterized primarily by the ubiquitous nature of the computer—a tool now integral to contemporary society. This wave of digitization prominently permeated sectors such as telecommunications, music, film, and photography [3, 5]. By the 1970s, a marked emphasis was placed on addressing the evolving consumer demands, leading to an expanded array of products and services [4]. Production process management during this phase exhibited the zenith of globalization, with exponential interconnectivity observed amongst companies, suppliers, customers, and other global entities, facilitated by cutting-edge ICT solutions like IoT, DT, 3D printing, and other Industry 4.0 technologies [5]. Postulations suggest that the inception of the “smart factory” concept occurred during this period, becoming a cornerstone for the ecological, economic, and social sustainability of supply chain operations [5, 6]. Given the exponential trajectory of advancements in science, technique, and technology, the 21st century is awash with novel technologies, permeating both professional and personal spheres [5, 6].

It has been posited that the Fourth Industrial Revolution, or Industry 4.0, operates concurrently with the tail end of Industry 3.0. This era emphasizes the need for comprehensive computerization, robotization, and automation

in production. The term “Industry 4.0” was first formally introduced in Germany in 2011 [5, 7]. Subsequent terminologies such as Logistics 4.0, Supply Chain 4.0, and Warehousing 4.0, among others, have also emerged [2–5]. Innovations in the past decade have redefined various facets of modern life, with the prevalent introduction of “smart” devices and technologies in daily use, culminating in what is referred to as the “smart environment” [4–6]. Given these advancements, it can be deduced that the smart factory concept, within the context of Industry 4.0, stands as a pivotal technological component for enhancing consumer advantages. Since a smart factory constitutes a singular entity in the supply chain, the integration of contemporary Industry 4.0 technologies remains imperative for sustainable customer service.

Industry 4.0 is delineated by the intelligent networking of industrial machinery and processes that rely on CPS, wherein embedded networked systems are employed for intelligent control. Historically, Industry 4.0 has been perceived as a technology-driven shift, primarily targeting enhanced manufacturing efficiency. As part of a high-tech governmental initiative, it was devised to bolster Germany’s global competitiveness [6, 7]. The metamorphosis of CPS into Cyber-Physical Production Systems (CPPS) is foundational to Industry 4.0, with the Smart Factory emerging as a pivotal initiative therein [4]. Yet, inherent challenges permeate Industry 4.0. The potential for a systemic overhaul of the prevailing operational modalities of Europe’s (and by extension, the world’s) industrial economy presents itself. A significant challenge lies in dissociating the consumption of natural resources from their deleterious impacts on the environment, climate, and societal structures [5]. Several dimensions characterize this evolution:

- The shift towards a circular economy, underpinned by regenerative industrial transformation practices. This ensures that all supply chain entities accrue economic benefits while adhering to sustainability tenets.
- A requisite emphasis on social sustainability. This mandates enhancements in employee welfare, ensuring their inclusive societal integration, and the deployment of technologies that augment rather than supplant human capabilities.
- The ecological dimension, which is implicitly characterized by transformative endeavors that phase out fossil fuel dependency, augment energy efficiency, harness nature-based solutions, rejuvenate carbon sinks, bolster biodiversity, and conceive novel avenues for socio-economic development, cognizant of natural ecosystem interdependencies.

It has been observed that contemporary civilization remains anchored in the second industrial revolution’s paradigms. The depletion of fossil reserves, pivotal energy sources, and essential raw materials, compounded with environmental degradation, signals an acute planetary crisis. Consequently, Industry 5.0 emerges as a strategic imperative, informed by its foundational principles, offering a roadmap to navigate this exigency. Departing from the narrowly defined technological focus of Industry 4.0, predominantly centered on digitalization and digital technologies, Industry 5.0 introduces a holistic spectrum, imbuing the paradigm with a richer, multi-faceted significance [1, 3]. From this perspective, the Smart Factory is identified as a linchpin, instrumental in pivoting the application of advanced Industry 4.0 technologies towards environmental and societal sustainability. A thorough comprehension and integration of the CPS concept become indispensable, laying the groundwork for the seamless orchestration of smart factory operations. Subsequent sections will elucidate the principles of CPS, establishing a foundation to explore the sustainable constructs and processes inherent to the Smart Factory paradigm.

### 3 Specificities of the Smart Factory Paradigm

With the advent of Industry 4.0, prevailing business models and management paradigms have been subjected to notable modifications and enhancements. Concurrently, a transition from historical manufacturing methodologies and interactions with supplier entities has been observed. An integral outcome of this transformation is the emergence of the “smart factory” concept. At its core, this advanced technology, aimed at streamlining production and intralogistics processes, is characterized by the ability to establish an autonomous smart network with self-regulation, optimizing underlying processes [3–5].

The term “smart factory” is postulated as a theoretical production solution encompassing automation, wherein a synergy of software, hardware, and, in certain instances, mechanics, seeks production optimization [3, 4]. Such a paradigm is synonymous with the reduction of superfluous human intervention and minimization of resource wastage. In these settings, activities spanning both the digital and tangible realms become intricately intertwined, rendering intralogistics operations within Industry 4.0 smart factories considerably intricate. Intralogistics is understood as overseeing the control, execution, and enhancement of internal material movement, information flow, and goods management across sectors, including business, commerce, and governance [5].

With the integration of nascent Industry 4.0 technologies in warehouses and distribution centers, the demands placed upon smart factories have amplified. These encompass parameters such as speed, accuracy, precision, flexibility, and productivity [5, 7]. Consequently, heightened emphasis is being placed on refining and transforming production processes. This positions the “smart factory” paradigm as pivotal for the seamless operation of sustainable supply chains [6]. Moreover, leveraging technologies such as the IoT, CPS, and Big Data, this contemporary, adaptable production model can be integrated with analogous systems across global supply chains.

### 3.1 Basic Principles Underpinning the Smart Factory Conceptual Solution

The foundational principles of the smart factory paradigm are intrinsically anchored on the CPS foundation, with a focal emphasis placed on the plausible sustainability of integrated operations spanning two or more smart factories. These principles are elucidated in Table 1 [7, 8].

**Table 1.** Design principles of the “smart factory”

Principle	Explanation
Conceptualization	In smart factories, a paramount degree of modularity is essential to promptly address user demands, thereby bolstering intralogistics resilience. This also includes delineating production system components and their interconnections.
Compatibility	Sustainability in a smart factory hinges on comprehensive information dissemination across all supply chain entities, covering technical product specifics to commercial data.
Decentralization level	Decisions concerning routine activities and adaptive measures in dynamic business and environmental contexts are made by employees. Furthermore, operations can be conducted with significant autonomy from central governance, yet without deviating from overarching corporate objectives.
Virtualization	Crafting simulated environments approximating reality facilitates real-time process monitoring and modeling, risk identification, and preemptive control. Such realms are advantageous for personnel training, system upkeep, and customer engagement during manufacturing.
Responsively	Real-time data acquisition and analysis are prerequisites for manufacturers to swiftly adapt to changing consumer needs or potential disruptions. This ties back to conceptualization and highlights the cyclical nature of smart factory design.
Customization	Beyond product offerings, customer support extends to tailored services, enhancing intralogistics endeavors. Adherence to the “7p” principle underscores user satisfaction and is hailed as a significant contribution of the smart factory paradigm.

Drawing insights from Table 1, it is inferred that CPS’s cardinal tenets, undergirding the smart factory notion, aim to augment efficiency across production, intralogistics, and related endeavors, striving to meet user anticipations. Distinguishing features such as seamless information flow, holistic employee engagement in decision-making processes, and meticulous production surveillance underscore the uniqueness of smart factories, setting them apart from traditional manufacturing. These attributes underscore the paramountcy of smart manufacturing operations in enhancing supply chain sustainability.

A salient strength of the smart factory is its adaptability to evolving user needs and the exigencies of competitive landscapes, aligning with the “7p” principle. Essential characteristics of a smart factory encompass Product, Price, Process, Promotion, Physical Evidence, Place, and People [8, 9]. Several defining features of a smart factory are delineated:

- **Connectivity:** Fundamental processes and material flows are interconnected, engendering requisite data for real-time decision-making. Within comprehensive smart factories, equipment is equipped with intelligent sensors, facilitating perpetual information generation from diverse sources, ensuring perpetual updates.
- **Transparency:** Contemporary data, validated and current, is made accessible to pertinent stakeholders, furnishing comprehensive insights into all “smart factory” operations. This transparency capacitates manufacturing firms to harness contemporary Industry 4.0 tools, offering real-time notifications.
- **Agility:** Smart factories are endowed with the capability to adapt to production and schedule variations with minimal human intervention. Advanced iterations can autonomously reconfigure equipment and material flows, contingent upon manufacturing requisites and requisite modifications.
- **Optimization:** Production endeavors are executed with diminished manual involvement and elevated reliability. Automated activities, synchronized assets, enhanced monitoring, and energy consumption optimization collectively contribute to increased profit margins, operational time reduction, overall cost minimization, and waste elimination.
- **Proactiveness:** Personnel are equipped to preemptively identify and navigate potential risks or challenges, whilst maintaining resilience in post-occurrence mitigation. This may encompass preemptive disruption identification, inventory replenishments, quality issue resolution, and safety issue monitoring.

### 3.2 Pivotal Aspects Underpinning the Evolution from Traditional Manufacturing to the Smart Factory Paradigm

Manufacturing systems of the third industrial revolution are recognized as foundational elements in the paradigm of Industry 4.0. Traditional manufacturing, characterized by robotization, Enterprise Resource Planning (ERP), 3D

printing, among other prevailing technologies, formed a cornerstone of the vast majority of factories operating within the confines of Industry 3.0. However, with the advent of Industry 4.0, innovative technologies such as the IoT, CPS, DT, and Cloud Computing have been introduced [6]. These technologies have enabled the amalgamation of disparate production components and their overarching frameworks into the contemporary “smart factory” concept, diverging from their previously standalone functionalities in Industry 3.0 [7].

Processes in Industry 3.0 were traditionally automated utilizing logical processors and integrated information technology. Nevertheless, with the proliferation of data-driven methodologies in manufacturing, a significant portion of the processes within Industry 4.0 have been automated, relegating human interactions, especially for repetitive tasks, to a peripheral role. For instance, the computer numerically controlled machine (CNC machine), a hallmark of Industry 3.0, necessitated human intervention for data input. In stark contrast, within the Industry 4.0 framework, the same CNC machine not only adheres to predefined programming parameters but also actively harnesses data to optimize manufacturing operations [8].

Table 2 elucidates the discernible differences between traditional digitalized factories and advanced “smart factories”, shedding light on the palpable transition from Industry 3.0 to Industry 4.0.

**Table 2.** Distinctions between traditional and “smart factories” [7, 8]

<b>Digitalized Factory</b>	<b>Smart Factory</b>
Centralized production systems	Decentralized, flexible production systems
Employee reduction via robotization	Collaborative model with robots undertaking strenuous tasks
Independent equipment controllers	Networked system controlling work machines based on dynamic information
Predetermined, preventive machine maintenance	Maintenance executed as per real-time machine requirements
Post-production quality assessment	Concurrent quality control during production and assembly
Manual data input with varied tools	Automated data entry via advanced interfaces
Emphasis on individual outcomes	Prioritization of collaborative success
Periodic employee training sessions	Continuous and on-site employee training
Relying on internet platforms for information	Multilocation, application-integrated cloud data sources
Production focused on product quality	Production oriented towards superior customer service
Enhancing individual performance	Accentuating team performance efficacy

Moreover, the extensive incorporation of avant-garde technologies in Industry 4.0 has been observed to not only bolster product quality in alignment with customer preferences but also to profoundly enhance the sustainability of all entities within the supply chain. Such enhancements are attributed to collaborative undertakings amongst supply chain partners in an atmosphere of mutual respect and understanding of each other’s necessities. The facilitation of these intricate interactions has been made plausible through the expanded capabilities of advanced technologies intrinsic to Industry 4.0, which will be elaborated upon in subsequent sections.

#### **4 Fundamental Characteristics of Pivotal Technologies Underpinning the Smart Factory Paradigm**

The smart factory is invariably recognized as a cornerstone of Industry 4.0, being perceived as the bedrock for the competitiveness of each constituent within the supply chain. Contrary to the misinterpreted objective of completely eliminating the workforce, the emphasis of integrating sophisticated technologies like the IoT and cloud computing into production automation has been placed on augmenting productivity, bolstering efficiency, and facilitating the realization of intricate production tasks. Enhanced information technologies are employed to enable efficient access to production-centric data, ensuring bidirectional communication. Intricately, smart factories epitomize the fusion of virtual and actual manufacturing realms, facilitated primarily by the advent of the IIoT. Within these virtualized environments, products, processes, and resources undergo rigorous modeling and testing, leveraging authentic data. Iterative assessments are conducted until discrepancies are identified and rectified. Subsequent to this virtual optimization, the refined solutions are seamlessly transferred and actualized within tangible factory settings. In light of these considerations, this section elucidates the salient benefits and inherent challenges posed by these technologies in the broader context of the smart factory concept.

##### **4.1 The Pivotal Role of IoT in the Smart Factory Framework**

In the evolution of Industry 4.0, myriad solutions have been established within the realm of information exchange. It is posited that the bedrock for the seamless attainment of customer requisites in this environment hinges upon digitization, with a notable emphasis on computer networking. Contemporary supply chains, it has been observed, stand incapacitated without the trifecta of swift, dependable, and fortified Internet connectivity [5].



Central to the progression and execution of the Industry 4.0 paradigm is the IoT. This phenomenon is defined as a comprehensive network framework intertwining tangible entities with their digital counterparts via amassed data and sophisticated communication tools [6]. Integral to this infrastructure are the ever-evolving networks and the Internet. Optimal, fortified, and unerring linkages among all chain stakeholders are deemed pivotal, not merely as a manifestation of the supply chain's architecture but also as an enabler of efficacious customer service [6]. For the seamless orchestration of information among suppliers, industries, distribution nodes, and end-users, such connectivity becomes indispensable. Through the deployment of IoT-fueled "smart" apparatus and systems, supply chains are discerned to undergo an "intellectual metamorphosis" [6].

Central to a resilient supply chain is the notion of the "smart factory". This construct leverages rapid information dissemination and process automation, surpassing the capabilities of erstwhile business templates. Through the lens of voluminous data, aggregated both by industrial-grade and conventional IoT coupled with cloud technologies, prognostications of machinery malfunctions become feasible, paving the way for curtailed unscheduled downtimes and cost efficiencies. From such observations, it might be inferred that the essence of a smart factory lies in its aggregation of "intelligent" components, with IoT as its linchpin.

While the pertinence of IoT to the digitized operations of Industry 3.0 factories has been underscored, its multifaceted utility within the smart factory paradigm emerges as a conduit for the sustainability and efficiency of supply chains [6, 7, 10]. Distinct functionalities facilitated by IoT technology include:

- Real-time tracking and localization of commodities, enabling the exploration of alternative trajectories, potentially leading to expedited product delivery to consumers [6, 7].
- The caliber of products, be it during fabrication, transit, or storage phases, is subjected to meticulous scrutiny via specific IoT instruments, ensuring timely interventions to optimize processes and elevate product quality [10].
- Ambient conditions of storage facilities and transportation mediums undergo vigilant surveillance through IoT contrivances, warranting product integrity by preempting potential damages or delivery aberrations.
- Contingency planning stands enhanced, as real-time monitoring by IoT tools identifies prospective vulnerabilities, reinforcing supply chain robustness, especially under adverse environmental scenarios.
- Prophylactic upkeep of assets is facilitated as data relayed from embedded devices within smart factory machinery interfaces with auxiliary software, detecting imminent operational anomalies.
- Traditional manual procedures, such as data cataloging and paper-based tagging, have been superseded by IoT devices, predominantly RFID tags, engendering unparalleled transparency in inventory management, thereby bolstering operational efficiency across the supply chain spectrum.

While the adoption of IoT within the smart factory framework is observed to bestow transformative advantages encompassing production cost optimization, heightened energy thriftiness, and adept information governance [6, 10], its practical implementation is not devoid of challenges. An examination of pertinent literature [11] unveils several barriers to the seamless integration of this technology:

- **Technological Dependence:** It has been reported that an overreliance on technology can be a double-edged sword. In scenarios where technological challenges or risks are encountered, the deployment and utilization of IoT-centric devices often become contingent upon the provision of robust and rigorously-tested support mechanisms.
- **Privacy and Security Concerns:** Enhanced information transparency, a hallmark of advanced ICT, while offering manifold benefits, simultaneously ushers in concerns related to information security. The increased accessibility of data, unfortunately, often inversely correlates with its safeguarding. Unintended exchanges of confidential or incorrect information can ensue due to the involvement of multiple stakeholders in data dissemination processes.
- **Human Capital Implications:** A pronounced shift towards an elevated IKT platform, mandating comprehensive IoT integration, invariably impacts employment dynamics within smart factories. It has been noted that there's an observable reduction in roles that previously entailed manual labor. While potential mitigation strategies encompass employee requalification and training, the evolving landscape invariably demands heightened IT proficiency and specialized software skills. A niche for IoT specialists, tailored specifically for smart factory operations, is discernibly emerging.
- **Implementation Complexities:** The introduction of avant-garde IKT solutions necessitates the confluence of compatible hardware, refined software, and a trained workforce. Moreover, a societal dimension, often labeled as the "apprehension towards novelty", further complicates the implementation matrix, especially for nascent IoT-related innovations.

In light of these challenges, it becomes evident that while the potential benefits of IoT in smart factories are manifold, stakeholders must be cognizant of the intrinsic complexities and address them proactively to realize the full spectrum of advantages.

## 4.2 The Criticality of IIoT Within Smart Factory Operations

Smart factories are conceptualized as advanced embodiments of manufacturing, where the efficacious networking of components is paramount, taking into account evolving consumer demands and ensuring supply chain sustain-

ability [6, 11]. Consequently, the imperative nature of discerning the appropriate technological choice, its setup, and the merits of IIoT and cloud paradigms cannot be overstated.

The IIoT is characterized as a conglomerate of intelligent devices connected to systems for monitoring, data acquisition, exchange, and analysis. Within the spectrum of industrial operations and processing, IIoT is postulated to be an essential subset of the overarching IoT framework, particularly evident in its applicability to smart factories, vital to sustainable supply chains [6, 8].

The diverse capabilities endowed by IIoT systems are witnessed across the entirety of the product lifecycle. The spectrum of these benefits is expansive, ranging from nuances of product design to intricate inventory tracking within supply chains. A notable implication of IIoT integration is the facilitation of preventive maintenance. Data accrued through IIoT mechanisms are postulated to substantially curtail production halt frequencies – a pervasive challenge in certain industries. Such a proactive approach not only mitigates downtime but also augments productivity by signaling forthcoming equipment maintenance needs [9–11]. Further advancements, facilitated by IIoT, encompass remote management capabilities, enabling personnel to interface with machinery, thereby providing distanced support. This, juxtaposed with the efficient oversight of machinery, and the incorporation of cutting-edge software, is deemed more efficient than conventional manufacturing methods. The ensuing benefits are manifested as cost efficiencies and enhanced responsiveness to consumer prerequisites – advantages predominantly driven by IIoT-mediated remote control.

The structural composition of IIoT closely mirrors its IoT counterpart, and can be demarcated into the subsequent segments [6, 11]:

- **Network of Devices:** This encapsulates intelligent apparatuses and sensors, including but not limited to temperature and pressure sensors, humidity detectors, and RFID tags. These entities are integral to the data acquisition essential for smart factory operations.
- **Gateway:** Comprising diverse networks, protocols, and methodologies pertinent to smart factory processes.
- **Cloud Computing:** The technological bedrock for real-time data capture, processing, management, and storage, with further elucidation provided in Section 4.2.
- **Analytics:** This module, often regarded as an intrinsic facet of cloud computing, is dedicated to data analysis, serving to distill actionable insights.
- **User Interface:** Representing the system’s tangible facet, it enhances the synergy between smart factory operations and its end-users.

Given the pivotal role of IoT and IIoT technologies in augmenting the efficiency and sustainability of smart factories, a comprehensive comparative analysis, as presented in Table 3, is deemed essential [6, 10, 12]. While IIoT is recognized as a subset of the broader IoT framework, its distinguishing feature lies in its emphasis on interconnecting machinery and devices across sectors, including manufacturing, healthcare, and multifaceted logistic undertakings such as transshipment, packaging, and warehouse operations [11, 13]. In contrast, IoT is commonly affiliated with an array of “smart” devices permeating daily life – encompassing appliances like refrigerators and air conditioners. The application purview of these technological constructs is elucidated in Table 3. A myriad of attributes, from flexibility to overarching objectives, delineates the nuances differentiating IIoT from IoT. This demarcation also prompts a paradigm shift, accentuating the broader applicability and universality of IoT in comparison to the industrially-centered IIoT.

**Table 3.** Distinctive attributes between IoT and IIoT within traditional and “smart factories” contexts [6, 10]

IoT	VS	IIoT
User convenience	<b>Focus</b>	Smart factory system management
Daily process automation		Ensuring maximal efficiency and seamless continuity across all operations
Smart devices	<b>Subject of Development</b>	Highly sophisticated components
Advanced sensors, enhanced controls, and progressive analytics	<b>Level of Implementation</b>	Streamlined applications with minimized risks
Standard safety protocols	<b>Safety and Risks Measures</b>	Elevated security and privacy measures Cyber-attack safeguards
Functional independence	<b>Interoperability</b>	Integration with contemporary operating systems
Limited adaptability	<b>Adaptability</b>	Superior adaptability
Critical monitoring	<b>Precision and Accuracy Levels</b>	Real-time synchronization
Simplified programming	<b>Software Implementation</b>	Comprehensive reprogramming with holistic software support
User convenience	<b>Key Objective</b>	Economic efficiency enhancement
Minimal or non-existent	<b>Flexibility</b>	Apparent, especially when disruptions arise
Customer-defined timelines	<b>Maintenance</b>	Pre-set intervals
Vendor-led		

Based on the insights presented in Table 3, while IoT fosters data dissemination throughout the supply chain spectrum, IIoT predominantly emphasizes the optimization of smart factory operations. In terms of adaptability, IIoT demonstrates greater flexibility relative to IoT, aligning with its specific application domains. However, the maximum efficacy of these technologies is observed when synergistically integrated towards implementation objectives. Whereas IoT aims to augment the convenience across the entirety of supply chains, the focus of IIoT remains on bolstering the economic efficiency within smart factories. Nonetheless, both technologies contribute substantially to enhancing facets of the sustainable supply chain, with IIoT honing in on intelligent manufacturing methodologies.

### 4.3 Cloud Computing: A Vital Component in Enhancing Smart Factory Competitiveness

In the quest for optimization, many supply chains are found to gravitate towards cloud computing; however, the efficacy of such a choice heavily relies upon the unique needs of each chain's components [14, 15]. As observed, manufacturers frequently harness solutions based on the IIoT, prompting an upsurge in cloud computing adoption among manufacturing enterprise managers. One salient advantage of integrating cloud computing with IIoT is identified as the ability of cloud service providers to address multifaceted ICT-related challenges, encompassing issues of security, scalability, user demand management, and both hardware and networking [14, 15]. Such an integration, consequently, enables supply chain enterprises to shift their focus predominantly on refining manufacturing procedures to augment customer service. By leveraging cloud technology, a more profound insight into production and intralogistics processes is obtained, fostering a rapid response mechanism against risks and potential disruptions in the operational milieu.

In light of the global crisis that witnessed a decline in manufacturing advancement, it is noted that the amalgamation of smart factories, IIoT technology, and cloud computing has emerged as indispensable technological conduits that underpin sustainable manufacturing endeavors. Through the extensive data amassed by IoT, IIoT, and cloud infrastructures, predictive measures concerning equipment failures are formulated, thereby circumventing unscheduled operational halts and optimizing cost strategies [13–15]. The emphasis, thus, is placed on understanding the intricate process of technology selection, its deployment modalities, and the plethora of advantages bestowed by cloud and IIoT infrastructures [13–15]. The operational backbone of smart factories is discerned to hinge on an astute focus on the production process. By incorporating cloud computing, manufacturers are observed to tap into advanced analytics and machine learning paradigms. Such a technology adoption paradigm allows producers access to a richer information reservoir, further enhanced by sophisticated analytical tools tailored for the operational environment [14–16]. Additionally, this knowledge arsenal can be supplemented by industrial equipment producers, which, it has been revealed, can offer a suite of digital services sourced from external platforms [14–16]. In essence, the synergistic interplay of IoT and IIoT, when undergirded by cloud computing, is recognized to be a significant catalyst propelling the aspirations of a sustainable smart factory, where the overarching objective remains the enhancement of customer service across all supply chain touchpoints.

## 5 Concluding Remarks

In the wake of the prevailing global crisis, supply chains have been identified as being susceptible to multifaceted disruptions. Driven by current trends, the evolution of Industry 4.0 technologies has been observed, with an emphasis on fortifying the inherent vulnerabilities within supply chains [14, 16, 17]. Manufacturing entities, particularly pivotal due to their interconnections within the supply chain ecosystem, are perceived to be profoundly influenced by both global suppliers and customer demands. By leveraging Industry 4.0's avant-garde technologies, notable enhancements in operations across supply chain stakeholders have been witnessed. In the intensively competitive contemporary business landscape, production has been deduced as a cornerstone in delivering unparalleled service to consumers. Essential prerequisites for this segment of the supply chain have been outlined as real-time information transparency, meticulous market demand monitoring, customization of offerings, decentralized autonomous management, and comprehensive globalization across supply chain strata [14, 16, 17].

While the continuum from Industry 3.0 to Industry 4.0 is discerned, distinctions between the two epochs remain evident. The sheer pace of technological evolution, characterized more by an exponential trajectory than a linear one, stands out prominently. The Third Industrial Revolution is acknowledged to provide foundational underpinnings, incorporating pivotal Industry 4.0 technologies like IoT, CPS, 3D, among others. These evolutions indicate a transformative shift, not only within industries and corporate landscapes but also on broader scales encompassing nations and societies. Such profound transformations underscore the imperative of understanding the "smart factory" concept, especially in its alignment with anticipated customer service deliverables [15, 17].

Advancements initiated by the assimilation of digital tools in Industry 3.0, such as ERP, 3D printing, CNC machinery, and big data frameworks, have been recognized as fundamental in charting the trajectory towards sustainable supply chains. The transition from conventional manufacturing paradigms to state-of-the-art production methodologies has culminated in CPS, elucidating the precursory constructs of the contemporary smart factory.



Supporting this paradigm shift are the pioneering technologies of Industry 4.0, predominantly IoT, IIoT, and Cloud computing. Even amidst the deceleration in production growth catalyzed by global perturbations, the proliferation of smart factories, buttressed by IIoT and cloud infrastructures, has been noted. While IoT's deployment is prevalently observed across supply chain entities, facilitating seamless real-time information dissemination, IIoT's application is pinpointed more towards bolstering industrial resilience and enhancing sustainability.

The present study was undertaken with the intent to elucidate the significance of the smart factory within the tapestry of a sustainable supply chain. A comprehensive discussion encompassed the merits, constraints, and challenges associated with the adoption of IoT, IIoT, and Cloud computing, delineating their pivotal roles in the smart factory schematic. Concurrently, a distinction between IoT and IIoT, in terms of their respective functionalities, roles, and relevance, not just within the smart factory framework but across the entire supply chain, was established. As future avenues of exploration beckon, several prospective enhancements beckon. Investigations into the smart factory's role in curtailing product manufacturing durations and optimizing logistics expenditures could offer insights into the supply chain's enhanced efficiency and competitiveness. Further inquiry might encompass the assessment of agility in accommodating evolving user stipulations, especially during ongoing manufacturing processes. Lastly, the adaptability and versatility of IoT, IIoT, and Cloud Computing, both within and beyond the smart factory paradigm, warrant extensive scrutiny, particularly concerning their implications on the broader supply chain dynamism.

### Data Availability

The data used to support the research findings are available from the corresponding author upon request.

### Conflicts of Interest

The author declares no conflict of interest.

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