Chapter

Industry 4.0 Technologies Impact on Supply Chain Sustainability

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Abstract

A supply chain is a network that links technology, activities, resources and organisations involved in the manufacturing and distribution of product and services. Supply Chain Operations Reference model (SCOR) defines basic processes of the supply chain (SC) into five categories as Plan, Source, Make, Delivery and Return. The search for a more sustainable production and consumption system is so relevant today that the United Nations (UN) have selected it as one of their paramount societal objectives for sustainable development. The implementation of sustainability in production and consumption processes aims to mitigate negative pressures on the ecosystem generated by products, services, and transportation. Industry 4.0 (I40) technologies have sparked interest in recent years. The advanced digital technologies of I40 such as big data analytics (BDA), artificial intelligence (AI), machine learning (ML), internet of things (IoT) and sensors, block chain technology (BCT), robotic systems (RS), cloud computing (CC), cyber-physical system (CPS), additive manufacturing (AM) /3D printing (3D), virtual reality (VR), augmented reality (AR), autonomous vehicles (AV), and drones have found applications in many processes of manufacturing, logistics and SC. The benefits are sustainability, efficiency, cost reduction, transparency, traceability, and collaboration. In addition to benefits, I40 implementation is not free from challenges.

Keywords: Industry 4.0, sustainable supply chain, triple bottom line, industrial internet of things

1. Introduction of industry 4.0 technologies

Industry 4.0, often known as smart manufacturing, is built on information technology (IT)-driven industrial processes [1]. It combines smart factories and products with the Internet of Things [2, 3], with the goal of providing real-time information on production, machines, and component flow, and integrating this data to assist managers in making decisions, monitoring performance, and tracking parts and products.

1.1 Industry 4.0 technologies

1.1.1 Big data analytics

Big data analytics (BDA) is the collecting of real-time data, the use of analytical tools, and the use of computer algorithms to derive relevant insights and patterns for better decision-making using data, text, audio, video [4]. Big Data 6Vs framework describe Volume, a very large amount of data; Velocity, the data are generated very quickly and must be processed in a very short time; Variety, a large number of structured and unstructured data types are processed; Value, the goal is to generate significant value for the organisation; Veracity, reliability of the processed data; and Variability, flexibility to adapt to new data formats by collecting, storing, and processing them. BDA aids in the achievement of long-term corporate success and competitive advantage [5].

1.1.2 Internet of things

Internet of Things (IoT) allows devices to communicate with one another without the need for human involvement [6]. The Internet of Things is based on a network of devices, each of which has its own unique identity to the computer system to which it is attached. IoT-controlled industrial systems are intelligent because they can accurately and efficiently operate all linked equipment from afar [7]. For example, big data has been utilised to enhance product development [8], SC demand forecasts [9], and green production strategies [8, 10].

1.1.3 Block chain technology

Blockchain is a distributed data structure—a distributed ledger—in which the data is shared on a peer-to-peer network. The network members and nodes communicate and validate the data following a predefined protocol without a central authority. Distributed ledgers can be either decentralised, giving equal rights to all users or centralised, providing specific users with special rights.

1.1.4 Artificial intelligence

Artificial intelligence (AI) is a field in computer science encompassing the development of systems capable of performing tasks that normally necessitate human intelligence. The science of making machines do things that would require intelligence if done by men. Three main functions are sensing and interacting, learning from the data and decision making.

1.1.5 Autonomous robotic vehicle

Autonomous vehicles as more environmentally friendly automobiles are capable of sensing its navigation without human input, thus the costs, emission level and working time can be reduced dramatically. They can be used not only for long distances, but also for operational level of the supply chain.

1.1.6 Additive manufacturing (3D printing)

Additive manufacturing (AM) begins with the creation of a three-dimensional digital model using computer-aided design software, followed by the formation of the finished object using a 3D printer [11]. AM helps to Industry 4.0 goals by generating personalised items in small batches and producing complex and lightweight designs with great precision [3].

1.1.7 Cloud manufacturing

Cloud manufacturing is a method of providing a shared network of manufacturing resources and capabilities through the internet by establishing a virtual and global environment. The logic of cloud manufacturing is service-based, which means providers and consumers interact to sell and acquire services such as product design, simulation, production, and assembly [12].

1.1.8 Cloud computing

The Cloud computing (CC) is an Internet-based third-party service provider for data or database storage. The cloud is housed at a faraway location, not at the area where production takes place [12]. The CC has the advantages of lower operating costs, faster service, and simple accessibility [13].

1.2 Sustainability

Sustainability is a multi-dimensional concept incorporating economic, environmental, and social dimensions of business. Primary goal of any commercial enterprise is to make profit for long tern economic sustainability by balancing costs and revenues in sourcing, production and distribution of goods and services. Due to global pressure, climate change and pollution, environmental sustainability has taken centre stage in today's business [14]. The focus is to minimise natural resources use, waste and pollution (air, water, land), and increased renewable energy use in production and distribution. Social sustainability includes working environment, employee morale and satisfaction, equity and social integration of communities. Industry 4.0 technologies (I4T) help manufacturing companies achieve long-term goals by reducing lead times, providing customised goods, improving product quality, improving the working environment, and employee morale [15]. Organisations have been compelled to adapt smart production systems which are more adaptable, intelligent, and agile, and allows to address the demands of a dynamic and global market [16].

2. Literature review

Sustainable development is crucial necessity for the survival of humankind, which should integrate sustainable production and consumption [17]. Sustainability is three-dimensional concept encompassing economic, environmental and social (triple bottom line). Sustainable supply chain enables the management of material, information and capital flows as well as the cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development (economic, environmental and social) into account which are derived from customer and stakeholder requirements [18]. One of the key features of Industry 4.0 enabled by CPS, IoT, and big data analytics, is data accessibility and real-time information, which may help companies achieve low cost, high quality, low risk sharing, more flexible SC planning and effective decision making. Industry 4.0 allows for long-term purchase of more personalised items [19]. I40 opens up new and long-term commercial prospects by maximising resource efficiency, enhancing manufacturing flexibility, and reducing time to market [20]. IoT controlled industrial systems are clever as they can accurately and efficiently operate all linked equipment from afar [7]. Various I4T is shown to have a good influence on the organisations' long-term success. However, there is a dearth of empirical evidence in the literature to substantiate the influence of I4T on sustainable operating practices in various industries [15]. I4T contribute to long-term operations management choices and new business models by connecting value chains through data collection and exchange [3, 21]. As a result, long-term operations management decisions help to establish a link between circular economy (CE) principles and Industry 4.0 concepts.

The search for a more sustainable production and consumption system is so important now that the United Nations Organisation (UNO) has made it one of their most important social goals for long-term development [22]. The ultimate goal of implementing sustainability into production is to take the industry to a world-class level of sustainable manufacturing [23]. Moghaddam et al. [24] developed several reference designs for sustainable smart I40 factories to dealt with the production of environmentally friendly products. Nascimento et al. [25] proposed a circular economy (CE) business model using I4T for recycling garbage. Kiel et al. [26] classified Internet of Things (IoT) issues and benefits that centred on the long-term value creation. Waibel et al. [20] investigated the effects of smart production systems in terms of resource efficiency and sustainability. Zambon et al. [27] proposed an Agriculture 4.0 through the virtualization of the Agro-food chain. Ding [28] conducted a literature review to identify the barriers of incorporating sustainability into the pharmaceutical SC and proposed I40 application in SC known as Pharma 4.0. Bag et al. [29] developed a framework incorporating thirteen enablers I40 affecting SC sustainability. Tsai and Lu [30] developed a I40 based production planning and control framework using a carbon price. Ghadimi et al. [31] suggested a multiagent system to automatically analyse and choose suppliers that contribute to sustainable SC. Belaud et al. [32] developed agriculture 4.0 by integrating I40 into a SC and waste valorization using big data to improve sustainability management. Sensing, smart, and sustainable technologies were identified as crucial aspects of future sustainable goods [33]. Bibaud-Alves et al. [34] used I4T to establish a relationship between the development process of new goods, digital transformation, and sustainable development. Paravizo et al. [35] offered a conceptual framework using I40 for developing gamified apps that focus on sustainable manufacturing. Kamble et al. [15] reviewed 85 articles on I40 and established a sustainable industry 4.0 framework. Stock et al. [36] carried out qualitative assessment of I40 that enables ecological and social sustainable development. Hidayatno et al. [37] proposed a conceptual model to assess the effect I40 technology on sustainable energy in Indonesian industries. Bonilla et al. [38] used multiple development scenarios to assess the impact and challenges of I40 implementation on long-term sustainable development. Man and Strandhagen [21] presented I40 and sustainability adoption into various business operations. Luthra and Mangla [39] conducted a literature analysis and categorised eighteen I40 implementation challenges of sustainable SC into four categories: organisational, strategical, legal, and ethical. Ardanza et al. [40] demonstrated a human–machine interface using I40 that enable operators to be more productive and safer. Meng et al. [41] carried out literature review on sustainability and energy efficiency in smart factories, their interaction, benefits and issues. Chaim et al. [42] examined the feasibility of using key performance indicators (KPIs) to assess sustainability in I40 virtual learning environment. Kamble et al. [43] analysed the barriers of I40 adoption in manufacturing industry.

Manavalan and Jayakrishna [44] examined the IoT application for a sustainable SC and suggested software to organise material resources in businesses. Birkel et al. [45] proposed a risk framework using I40 for sustainable manufacturing in SMEs using a long-term strategy. Jabbour et al. [46] identified eleven critical success factors for implementing I40 and environmentally sustainable manufacturing and proposed an integrated framework for future research. Kamble et al. [15] investigated the barriers to I40 adoption in Indian manufacturing and analysed their driving and dependence relationship. Monteleone et al. [47] suggested a water management conceptual model in agricultural 4.0. [48, 49] carried out empirical study of 234 manufacturing firms in Pakistan to investigate the effect of I40 on green practices in manufacturing and logistics, which have substantial effect on sustainability of the firms.

Chalmeta and Santos-deLeón [50] carried out literature review on I40, big data and sustainable SC. Mastos et al. [51] provided IoT application for scrap metal waste management. Strandhagen et al. [52] proposed I40 solutions to shipbuilding supply chains sustainability challenges in a case company. Yadav et al. [53] identified 22 I40 and CE based solutions measures to overcome 28 sustainable SC challenges in an automotive industry using BWM-ELECTRE.

Belhadi et al. [54] carried out empirical study by collecting data from 306 organisations in Europe, Asia and Africa to explore the role of digital business transformation, organisational ambidexterity and circular business models on the relationship between I40 capabilities and sustainable performance. Fatorachian and Kazemi [55] conducted exploratory research based on inductive reasoning and systems theory to explore the impact of I4T on SC performance in terms of integration, information sharing and transparency, processes improvement in procurement, production, inventory management and retailing through digitisation, automation, and analytical capabilities. Kumar et al. [56] analysed critical success factors for I40 implementation in circular SC. Kumar et al. [57] studied the barriers of integrating I40 and CE in the agriculture SC using ISM-ANP and concluded that government policies, support and incentives is major barrier. Kusi-Sarpong et al. [58] adopted I40 initiatives for sustainable supplier selection in circular SC. Mastos et al. [59] used I40 technologies to redesign SC for circular economy with key identified benefits of improved availability of personnel and fleet resources, and SC traceability through the full visibility and automation. Mubarik et al. [60] collected data from 154 electrical and electronics Malaysian firms and found that I40 application impact SC mapping and visibility. Sharma et al. [61] found in the study that the environmental and social factors were the highest-ranked drivers while organisational and environmental dimensions as the highly ranked barriers of I40 adoption with the sustainability context in multi-tier manufacturing SC. Umar et al. [48, 49] studied the effect of I40 on sustainable operations and green SC practices.

3. Industry 4.0 technologies enabling supply chain sustainability

Industry 4.0 technologies are intended to play a key role in guiding industrial and social organisations toward long-term sustainability [46]. I4T makes it easier to achieve a high level of process integration, which improves organisational performance across three aspects of sustainability [15]. Braccini and Margherita [62] explored the impact of I40 adoption in a case study of a ceramics manufacturing firm and found that product quality and productivity improvement, energy monitoring and consumption reduction, safe work environment and job satisfaction for workers. Birkel and Muller [63] provided a literature review on potential of I40 on SC triple bottom line of sustainability in planning, sourcing, logistics and recycling logistics. Digital and smart manufacturing processes, machines and devices are likely to offer advantages of manufacturing productivity, resource efficiency, and waste reduction [64].

3.1 Economic sustainability

On the economic front, I4T makes a significant contribution to value creation, production flexibility, and product customization, which lead to higher consumer satisfaction [3]. Automation and digitisation capabilities of I40 help manufacturers achieve shorter lead times, cheaper manufacturing costs, and higher quality [11, 65]. I4T helps in raw material inventory reduction and efficient capacity utilisation [66]. The data offered by cloud manufacturing and IoT may be used to alter the design, production, and logistics choices of sustainable operations management [46]. IoT applications enable the reuse of resources in a remanufacturing process. The data generated by IoT sensors is evaluated using a mathematical model in order to lower expenses and dynamically manage limited resources [67]. Blockchain capabilities can support sustainable supply chains, which can help reduce the product recall and rework, and trace actual footprint of products; and reduce fraud [68]. Dev et al. [69] adopted agent-based modelling and decision trees to facilitate inventory and supply chain reconfiguration issues of a mobile phone supply chain. The information gathered by I40 may be used to improve product life cycle and industry's economic performance. Using Additive manufacturing (AM) and IoT together can help create a more sustainable manufacturing process by increasing resource efficiency and reducing recovery procedures [70]. Big data technology can influence the SC methods in terms of eco-efficiency and long-term performance. Esmaeilian et al. [71] reviewed capabilities of Blockchain as enabler for the successful implementation of sustainability and circular economy concepts under four main categories of (i) promoting green behaviour through designing specialised tokens, (ii) enhancing the visibility of product lifecycle, (iii) increasing systems efficiency and decreasing development and operational costs, and (iv) enhancing corporate performance reporting and sustainability monitoring capabilities. Digital supply chain may offer benefits of higher operational efficiency, ad-hoc dynamic planning, collaborative planning, collaborative product design, marketing effectiveness, financial flow, and deeper customer integration [72]. CPS, IoT, and big data analytics, enable a flexible supply chain planning and effective decision making, which may help to achieve high quality with low cost and risk in sustainable purchasing [19].

3.2 Environmental sustainability

In terms of the environment, real-time data acquired from various value chain partners assists organisations in effectively allocating industrial resources such as materials, energy, water, and products [3, 46]. I4T also support reduced greenhouse gas emissions [73], energy consumption [74], reduced fuel consumption as a result of improved transportation and logistics planning; and the use of advanced tracking and monitoring systems [75]. The Big data offers predictive analytics that improve environmental and social sustainability [76, 77]. The inclusion of sensors in goods enables performance monitoring such as tracking maintenance requirements-allowing businesses to deliver high-quality service to clients on a proactive basis. Further, organisations may invest in extending product life spans by using the 3Rs (reduce, re-use, and recycle) and monitoring items throughout customer usage. Cloud manufacturing and IoT can gather data from processes and things, such as machinery, allowing for the faults detection that might result in waste. Managers may also monitor and regulate the performance of operations based on production and resource consumption criteria, such as energy usage; the use of sensors would allow them to intervene in processes, even during component/product manufacturing. Machine efficiency might also be monitored in real time in order to schedule maintenance and avoid wasting resources [46]. Blockchain offers visibility, transparency, relationship management, and smart contracting which in turn offers environmental as well as economic benefits and plays a positive role in circular economy [78]. Abdella et al. [79] proposed machine learning using a set of environmental, social and governance criteria to predict sustainability performance across the supply chain. The revolution of autonomous vehicles can provide several benefits particularly in transportation part of the supply chain to reduce the damaged products. Automated guided vehicles (AGV) help in efficient materials handling operations improving the environmental and social sustainability. Krueger et al., [80] analysed possibilities of shared autonomous vehicles implementation implemented in a logistic cluster in public transport industry to improve utilisation of assets and reduce environment effect. Additive manufacturing result in less material being used and requires recycling of tiny amounts of trash due to mobility of 3D printers [70]. The usage of AM also helps to improve the sustainability of a manufacturing process by lowering the materials use and energy consumption. I40 help in energy monitoring that will result into increased energy efficiency and lower CO2 emissions [81]. AM and IoT can aid in improving reverse logistics operations, such as tracking and tracing end of use and end of life items and monitoring recycling activities to pave the way for a long-term route toward circular manufacturing [82]. Cloud technology allows for the capture, exchange, and sharing of dynamic life-cycle data, as well as SC partnerships for environmental footprint assessment [83]. Cloud-based service platform can help in improved decision-making and thereby minimise greenhouse gas emissions in the transportation and logistics industries [84]. Big data analytics in process control, for example, might help in pollution control and natural resource management [85]. Cyber-physical systems aid in production without generating waste or consuming unnecessary resources; the IoT enables mass customization and production that meets demand without producing excess inventory; cloud manufacturing enables controlled resource consumption (e.g., raw materials, energy, water); and additive manufacturing proactively maintains products, saves energy, and reduces waste from defective products [2, 20, 86]. By designing goods based on precise consumption data, cyber-physical systems improve customer satisfaction. As a result, using the 5Rs technique (reduce, repair, re-use, recycle, and remanufacture) [86, 87], it is feasible to develop goods with longer life spans. CPS and IoT aid in the planning of energy and carbon-efficient logistics routes, as well as assisting suppliers in managing their own performance in terms of production planning, delivery quality and reliability, and environmental compliance via remote monitoring [88]. In smart factory, communication efficiency, transparency, surveillance, and control will minimise downtime, waste, defect, and risk across production processes [89].

3.3 Social sustainability

On the social front, I4T provides a plethora of options for employees to learn new technology, boosting morale and motivation [73, 74]. I4T provides employees with a better and safe working environment [15]. AI and data analytics can help in personalised career development programs based on the behaviour, experience, skills, personality, and learning patterns of each employee [90]. I4T will create new jobs in area of informatics, mechatronics, process engineering, and system integration [91]. Industry 4.0 technologies impact on supply chain sustainability is summarised in **Table 1**. Industry 4.0 sustainability benefits are shown in **Table 2**.

	Industry 4.0 Technology Features	
Automation	Integration	Modularity
Real-time capability	Flexibility	Interoperability
Virtualisation	Decentralisation	Data quality and availability
Servitisation	Product and service customisation	Transparency
	Supply Chain Sustainability	
Economical	**Environmental**	**Social**
Process and Production efficiency	Material and Resource use reduction	Worker's productivity improvement
Cost effectiveness	Energy Consumption reduction	Working condition improvement
Quality improvement	Water Consumption reduction	Worker's Health and safety improvement
Scalability	Waste reduction	Equity
Profit Margin improvement	Air pollution and GHG emission reduction	
	Reverse logistics reduction	

Table 1.
Industry 4.0 technologies impact on supply chain sustainability.

4. Discussion on Industry 4.0 sustainability

Industry 4.0 technologies such as AI, ML, IoT, Big data, Block chain technology, VR, AR, CPS, Industrial Autonomous Robotics, Cloud computing etc. are being adopted in manufacturing and supply chain throughout the world but slowly. Researchers and professional managers believe that I40 offers integration, interoperability, real-time capability, quality data, modularity, decentralisation, product customisation, servitisation, collaboration, transparency and virtualisation, which may positively impact sustainability. On economic dimension, I4T adoption in supply chain will improve supply chain efficiency, quality, resilience, customer specific planning, production and logistics alignment, on-time delivery, order accuracy, downtime prediction, and repair and maintenance, supplier selection and procurement, and reduce lead time. Economic sustainability will reduce cost and improve profitability. I40 acts environment friendly as its adoption will lead to reduction of raw materials and resources, energy consumption, GHG emission, scrap and waste, physical prototyping, transparency, tracking and traceability. It will enhance sustainability processes and transportation and environmental monitoring. Regarding social sustainability dimension, I4T can offer safe working environment and flexibility, reduce stress and hazardous tasks, and improve learning and development. It is not free from challenges. Human activities such as inventory tracking, quality control, and even product distribution may be performed by Industrial robots, automated vehicles, and intelligent machines and there would be loss of jobs [96]. At the same time, it will provide opportunity for new jobs in I4T. Most of the studies are theoretical. Hence, it needs to be supported by qualitative and case studies.

	Sustainability Benefits	Herrmann et al. [74]	Peng et al. [84]	Despeisse et al. [70]	Hofmann and Rüsch [88]	Waibel et al. [20]	Zhao et al. [85]	Keil et al. [26]	Fatorachian and Kazemi [92]	Ghobakhloo [93]	Jabbour et al. [46]	Kamble et al. [15]	Luthra & Mangla [39]	Muller et al. [94]	Stock et al. [36]	Stone et al. [90]	Tortorella and Fettermann [64]	Ghobakhloo & Fathi [91]	Braccini & Margherita [62]	Saberi et al. [68]	Dev et al. [82]	Garcia-Muina et al. [95]	Khan et al. [78]
Economic	Lead time reduction				x																		
	Customer specific planning				x														x				
	Autonomous supplier selection and procurement				x	x																	
	Improved supply chain resilience				x																		
	Downtime prediction							x						x									
	Aligned production and logistics	c				x								x	x								
	Logistics process efficiency				x									x	x								
	Faster delivery					x					x	x											
	Order accuracy				x																		
	Recycling cost reduction										x	x											
	Repair and maintenance efficiency							x														x	
Environmental	Resource consumption reduction						x				x						x						
	Energy consumption reduction	x									x								x				
	Sustainable Process optimisation																		x				
	Environmental monitoring easier				x																		
	Physical prototyping reduction			x																			
	Scrap reduction																x		x				

	Sustainability Benefits	Herrmann et al. [74]	Peng et al. [84]	Despeisse et al. [70]	Hofmann and Rüsch [88]	Waibel et al. [20]	Zhao et al. [85]	Keil et al. [26]	Fatorachian and Kazemi [92]	Ghobakhloo [93]	Jabbour et al. [46]	Kamble et al. [15]	Luthra & Mangla [39]	Muller et al. [94]	Stock et al. [36]	Stone et al. [90]	Tortorella and Fettermann [64]	Ghobakhloo & Fathi [91]	Braccini & Margherita [62]	Saberi et al. [68]	Dev et al. [82]	Garcia-Muina et al. [95]	Khan et al. [78]
	Transport optimisation				x																		
	Transparency																						x
	Tracking and tracing of recycling										x	x		x	x					x	x		
	GHG emission reduction		x				x																
Social	Safe working environment											x	x						x				
	Reduction of hazardous tasks and stress	x						x											x				
	Learning and training improved	x														x							
	Hazardous recycling process reduction										x	x											

Table 2.
Industry 4.0 sustainability benefits.

5. Conclusion

Data collection and monitoring, information sharing, tracking, decision-making, and coordination between organisational areas and SC partners are technical and organisational factors that could influence the integration of Industry 4.0 and environmentally sustainable SC decision-making. This paper argues for an integrated approach to the issues that Industry 4.0 technologies may unleash the full potential of ecologically sustainable SC. The impact of Industry 4.0 technologies in economic dimension of triple bottom line is efficiency, flexibility, productivity and quality, which will enhance economic performance. On the environmental dimension, better resources utilisation, more quantity production, reduction of waste and energy will result into environmental performance. Finally on societal dimension, better labour utilisation and safe working conditions due to digitalisation and automation. The goal of this paper is to highlight the convergence of two important subjects; Industry 4.0 and sustainable SC with triple bottom line considerations. These two aspects have mostly been investigated separately. Industry 4.0 has the potential to increase ecologically sustainable production, distribution and consumption by allowing for the creation of green products, green manufacturing processes, and green SCM in ways that have never been possible before. On the other hand, the synergy between Industry 4.0 and ecologically sustainable production and distribution is contingent on a number of important success factors. Industry 4.0 adoption is faces few challenges. I4T need to be connected continuously and massive data centres will increase energy consumption. Therefore, it is necessary to balance energy savings and additional energy requirement in I40 adoption. I40 device replacement may also create additional waste. In recycling, sharing information about product by manufacturer, product use and transparency is also a matter of concern that needs to be addressed. Initial high investment and return also need to be studied. Major limitation of the study is the theoretical aspect. It is suggested that these theoretical research propositions be further explored, either through qualitative research or further investigated using quantitative methodology.

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