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Supply Chain 4.0 performance measurement: A systematic literature review, framework development, and empirical evidence

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ABSTRACT

Companies require a greater understanding of the Supply Chain (SC) benefits that can be gained from industry 4.0 (I4.0) and, more specifically, which technologies and concepts that can improve certain SC performance measures. A state-of-the-art systematic literature review (SLR) has been done on supply chain performance measurement linked with various industry 4.0 technologies. Based on the findings of the review through content analysis, this paper presents a framework for exploring the usage of I4.0 technologies to identify the potential supply chain performance measures. This framework includes the dimensions of Procurement 4.0, Manufacturing 4.0, Logistics 4.0, and Warehousing 4.0. As a scientific contribution, this study has validated the proposed framework through case studies, where the existing studies are limited. Finally, several fruitful future possible extensions have been discussed based on the proposed framework.

1. Introduction

First, the development of steam engines changed the production processes. Combustion engines and the innovative assembly line introduced by Henry Ford then initiated the second industrial revolution. The third industrial revolution was characterized by the automation of production processes (Kuznaz et al., 2015). Today, increasing globalization and competition has led to the emergence of the Fourth Industrial Evolution also known as Industry 4.0 (I4.0). I4.0 was first introduced in Germany at the Hannover Messe in 2011, as “a completely automated and intelligent production project, capable of communicating autonomously with the main corporate

Abbreviations: AI, Artificial Intelligence; AM, Additive Manufacturing; AR, Augmented Reality; BDA, Big Data Analytics; BD, Big Data; CPS, Cyber-Physical System; DL, Deep Learning; DT, Digital Twin; ERP, Enterprise Resource Planning; IIoT, Industrial Internet of Things; IoS, Internet of Services; IoT, Internet of Things; IT, Information Technology; I4.0, Industry 4.0; KPI, Key Performance Indicator; MES, Manufacturing Execution Systems; ML, Machine Learning; RFID, Radio Frequency Identification; SC, Supply Chain; SCM, Supply Chain Management; STG, Sanovo Technology Group.

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Table 1
Review of reviews I4.0 and SC performance.

Search	Search criteria	Scopus
#1	Topic: TITLE-ABS-KEY ("Industry 4.0″ AND "supply chain performance") Language: EnglishRefined by: Document type: (Review) Timespan: All years	0
	Final number of relevant papers after careful reading	0

Table 2
Summary of previous literature in SC performance.

Title	Author	Year	Summary	Journal
Defining and Measuring Supply Chain Performance: A Systematic Literature Review	Lehyani et al., 2021	2021	This review investigates and explores the overview of the existing methods used for supply chain performance measurement.	Engineering Management Journal
Big data-driven supply chain performance measurement system: a review and framework for implementation	Kamble and Gunasekaran, 2020	2020	This reviews tends to identify varies performance measurement systems which are relevant to big data driven supply chain performance.	International Journal of Production Research
A systematic review of humanitarian operations, humanitarian logistics and humanitarian supply chain performance literature: 2005 to 2016	Banomyong et al., 2019	2020	This review explains the effective methodologies for conducting comprehensive state of the art review through humanitarian supply chain as a case.	Annals of Operations Research
Quantitative models for supply chain performance evaluation: A literature review	Lima-Junior and Carpinetti, 2017	2017	This review deals with the exploration of different existing models for supply chain performance measurement.	Computers & Industrial Engineering
Supply chain performance measurement systems: A systematic review and research agenda.	Maestrini et al., 2017	2017	The review deals with SC performance measurements in relation to resources, output, and flexibility.	International Journal of Production Economics
Review of supply chain performance measurement systems: 1998–2015	Balfaqih et al., 2016		The review deals with the existing studies on different supply chain performance measurement system published within 1998–2015.	Computers in Industry
Performance measures and metrics in outsourcing decisions: A review for research and applications	Gunasekaran et al., 2015	2015	The review deals with financial and non-financial SC performance measures.	International Journal of Production Economics
Warehouse performance measurement: a literature review	Staudt et al., 2015	2015	The review deals with warehouse performance measurements in relation to time, quality, cost, and productivity.	International Journal of Production Research
Humanitarian supply chain performance management: a systematic literature review	Abidi et al., 2014	2014	The review deals with various humanitarian supply chain management measurement frameworks and indicators.	Supply Chain Management – An International Journal

players relying on the horizontal and vertical integration of production systems driven by real-time data interchange and flexible manufacturing to further enable customized production" (Piccarozzi & Aquilani, 2018). This new combination of manufacturing and information technologies has brought a whole new perspective to the industry on how manufacturing can collaborate with new technologies to get maximum output with minimum resource utilization (Kamble et al., 2018; Gorecki et al., 2020; Bag et al., 2021a,b).

I4.0 is not limited to the internal value chain of a company; it attempts to advance the SC management (SCM) "which covers the entire series of manufacturing industry operations from product design to sales and maintenance in order to enable mass-customization" (Asakura, 2016). With the goal of understanding how I4.0 technologies and concepts can improve SC performance (Schniederjans et al., 2020; Fatorachian and Kazemi, 2021), this work presents the development of a framework based on the findings of a systematic literature review of I4.0 technologies, concepts, and SC performance measures. During the systematic literature review, a sample of papers are selected and used in a descriptive and thematic analysis. Furthermore, the state-of-the-art key technologies and concepts within I4.0 in relation to SC performance are identified and listed. The findings from the literature review serve as a basis for creating the framework to relate the identified technologies and concepts to the identified SC performance measures.

In addition to the significance of the study, several contributions have been offered to the academic community to strengthen research in the field of supply chain performance measurement 4.0. Some of these key contributions are:

- This study interrelates the supply chain performance with individual industry 4.0 technologies with an understanding of the SC benefits gained. This contributes to the literature by highlighting the most effective and least effective industry 4.0 technologies with the concern of SC benefits.
- A framework has been proposed based on the SLR which includes Procurement 4.0, Manufacturing 4.0, Logistics 4.0, and Warehousing 4.0, and the same has been validated with real cases in which existing studies are limited. With such validation, in addition to the academicians, practitioners can also consider the validation findings to improve the implementation of necessary technologies based on their SC performance requirements.

Table 3
Summary of previous literature review of I4.0 and related technologies and concepts.

Title	Author	Year	Summary	Journal
Industry 4.0 and demand forecasting of the energy supply chain: A literature review	Nia et al., 2021	2021	This review focused on the influence of Industry 4.0 technologies with demand forecasting in energy-based supply chain management.	Computers and Industrial Engineering
From technological development to social advance: A review of Industry 4.0 through machine learning	Lee and Lim, 2021	2021	The review analyzed key issues related to the application of Industry 4.0 in text mining with unsupervised machine learning algorithms.	Technological Forecasting and Social Change
Potentials of industry 4.0 for supply chain management within the triple bottom line of sustainability e A systematic literature review	Birkel and Müller, 2021	2021	Review deals with the potential opportunities in the betterment of triple bottom line in supply chains with the implementation of Industry 4.0.	Journal of Cleaner Production
Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic	Spieske and Birkel, 2021	2021	Review deals with verifying various opportunities for implementing Industry 4.0′s resilience strategies under COVID-induced supply chain disruptions in the automotive sector.	Computers and Industrial Engineering
Industry 4.0 ten years on: A bibliometric and systematic review of concepts, sustainability value drivers, and success determinants	Ghobakhloo et al., 2021	2021	Review deals with the classification, concept, definition, scope, and determinants of Industry 4.0 within the implications of the triple bottom line.	Journal of Cleaner Production
Progress and trends in integrating Industry 4.0 within Circular Economy: A comprehensive literature review and future research propositions	Agrawal et al., 2021	2021	Review deals with the benefits of integrating Industry 4.0 and CE through network analysis on literature in the specific focus of logistics and supply chain applications.	Business Strategy and The Environment
A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology	Aoun et al., 2021	2021	Review deals with limitations, challenges, and barriers of implementing Industry 4.0 and further compared with blockchain fundamentals.	Computers and Industrial Engineering
A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach	Lim et al., 2021	2021	Review deals with evaluating and identifying the existing challenges and potential opportunities for the implementation of Industry 4.0 technologies in the palm oil industry,	Renewable and Sustainable Energy Reviews
Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review	Pivoto et al., 2021	2021	Review deals with the characteristics and introduction of CPS architecture models for the	Journal of Manufacturing Systems
The challenges, approaches, and used techniques of CPS for manufacturing in Industry 4.0: a literature review	Dafflon et al., 2021	2021	Review deals with the key drivers, techniques, and approaches that could function as key enablers in implementing CPS in the manufacturing sector under Industry 4,0 transition.	The International Journal of Advanced Manufacturing Technology
Industry 4.0 and the circular economy: A literature review and recommendations for future research	Awan et al., 2021	2021	Review deals with the interests and expectations among Industry 4.0′s stakeholders towards the circular management.	Business Strategy and The Environment
Technology enablers for the implementation of Industry 4.0 to traditional manufacturing sectors: A review	Jimeno-Morenilla et al., 2021	2021	Review deals with the recent developments on scientific-technological advances which could induce the implementation of Industry 4.0 in traditional manufacturing sectors.	Computers and Industrial Engineering
The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review	Sartal et al., 2020	2020	Review deals with the interpretations of Industry 4.0 with sustainable manufacturing along with consistencies and inconsistencies.	Advances in Mechanical Engineering
Industry 4.0, digitization, and opportunities for sustainability	Ghobakhloo, 2020	2020	Review deals with the sustainability functions of Industry 4.0 through analyzing their interrelationships.	Journal of Cleaner Production
Literature review of Industry 4.0 and related technologies	Oztemel and Gursev, 2020	2020	Review deals with the existing roadmaps of Industry 4.0 implementation related to technologies.	Journal of Intelligent Manufacturing
A review of emerging industry 4.0 technologies in remanufacturing	Kerin and Pham, 2019	2019	Review deals with the extensive applications of Industry 4.0 technologies in remanufacturing context.	Journal of Cleaner Production
Evolutions and revolutions in manufacturers implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework	Calabrese et al., 2020	2020	The review deals with the managerial perspectives of Industry 4.0 enabling technologies.	Production Planning & Control
Analysis and synthesis of Industry 4.0 research landscape Using latent semantic analysis approach	Wagire et al., 2019	2020	The review deals with the various taxonomies of Industry 4.0 research landscapes for providing novel scientific breakthroughs.	Journal of Manufacturing Technology Management
Industry 4.0 in management studies: A systematic literature review	Piccarozzi & Aquilani, 2018	2018	Review deals with papers published on the Industry 4.0 within management literature.	Sustainability
Pharma Industry 4.0: Literature review and research opportunities in sustainable pharmaceutical supply chains	Ding, 2018	2018	Review identifies potential sustainability barriers of pharmaceutical supply chain and how I4.0 technologies could be applied to mitigate those barriers.	Process Safety and Environmental Protection

(*continued on next page*)

Table 3 (*continued*)

Title	Author	Year	Summary	Journal
Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review	Dallasega et al., 2018	2018	Review proposes a framework which uses Industry 4.0 concepts to overcome challenges and to identify the benefits for construction supply chains.	Computers in Industry
Industry 4.0: A survey on technologies, applications and open research issues	Lu, 2017	2017	The review deals with a profound research regarding I4.0 concept and its key technologies and provides an overview with the results.	Journal of Industrial Information Integration
Industrie 4.0 and Smart Manufacturing – A Review of Research Issues and Application Examples	Thoben et al., 2017	2017	The review deals with application possibilities and technologies within I4.0.	International Journal of Automation Technology
Intelligent Manufacturing in the Context of Industry 4.0: A Review	Zhong et al., 2017	2017	The review deals with the technologies enabling I4.0.	Engineering
Literature review on the 'smart factory' concept using bibliometric tools	Strozzi et al., 2017	2017	The paper reviews the concept of smart factory which is a synonym of I4.0; this is done by creating a systematic literature review.	International Journal of Production Research

Table 4
Literature Keywords.

Keyword Area	Keywords
I4.0	"Industry 4.0″, "Industrie 4.0″, "I4.0″, "I4″, "Fourth industrial revolution", "digitization", "4th industrial revolution", "4IR", "Digital operations", "Digital industry", "smart factor*", "manufacturing 4.0″, "smart manufactu*", "Smart Product*", "smart industry", "Calm system", "Cyber-physical system*", "Cyber physical system*", "CPS", "smart analytics", "Human-machine interaction", "Big Data", "big data analytics", "additive manufacturing", "3D print*", "3D scanning", "Cloud computing", "cloud manufactur*", "vertical integration", "horizontal integration", "decentralize intelligence", "Cybersecurity", "Augmented reality", "digital twin", "Internet of Things", "IoT", "industrial internet of thing*", "IIOT", "Industrial Internet", "Near field communication", "internet of service*", "IoS", "digital supply chain*", "supply chain 4.0″, "digital supply chain networks", "DSN", "digital logistics", "logistic* 4.0″, "smart logistics", "cobot*", "M2M", "Machine-to Machine", "predictive maintenance", "Smart warehousing", "iBin", "AIDC", "automatic identification and data collection", "RFID", "visual computing", "procurement 4.0″, "sourcing 4.0″
Supply Chain Performance	"supply chain*", "supply chain performance*", "performance measure*", "performance metric*", "Order lead time", "Receiving time", "Order picking time", "Delivery Lead Time", "Queuing time", "Putaway time","Shipping time","Dock-to-stock time", "Equipment downtime", "Manufacturing lead time","Throughput time", "Customer response time", "Cycle time", "Lead time", "On-time delivery", "Customer satisfaction", "Order fill rate", "Physical inventory accuracy", "Stock-out rate", "Storage accuracy", "Picking accuracy", "Shipping accuracy", "Delivery accuracy", "Perfect orders", "Scrap rate", "Orders shipped on time", "Cargo damage rate", "Stockout probability", "Product lateness", "Average lateness of orders", "Average earliness of orders", "Stockout probability", "Number of backorders", "Number of stockouts", "Average backorder level", "Shipping errors", "Customer complaints", "Information accuracy", "Information timeliness", "Delivery performance", "Design revision time", "Prototyping time", "Safety stock level", "Inventory cost", "Order processing cost", "Labour cost", "Labor cost", "Distribution cost", "Maintenance cost", "Manufacturing cost", "Operating cost", "Obsolescence", "Rework", "Total supply chain cost", "Transportation cost", "Work-in-process cost", "Finished goods inventory cost", "Return on investment", "Total revenue", "Profit", "Recovery cost", "Market share gain", "demand gain", "Set-up cost", "Cost of defective parts", "Shortage cost", "Material handling cost", "Cost of goods sold", "Labour productivity", "Labor productivity", "Throughput", "Shipping productivity", "Transport utilization", "Warehouse utilization", "Picking productivity", "Inventory space utilization", "Outbound space utilization", "Receiving productivity", "Turnover", "Inventory level", "Equipment utilization", "Component Standardization", "Energy usage", "Pollution effect", "Solid waste", "Air emission", "Water waste", "Chemical waste", "Thermal pollution", "Transport distance", "Possibility of reuse", "Material usage", "Transportation greenness", "Demand forecasting", "Demand management", "Flexibility", "Customer satisfaction", "Information flow", "Supplier performance", "Risk management", "Personnel requirements", "Real-time monitoring", "Production process control", "Forecast horizon", "Forecast error", "Forecast frequency of update", "agil*", "responsiv*", "organizational performance*", "Delivery Performance to Customer Commit Date", "Documentation Accuracy", "Perfect Condition", "Perfect Order Fulfillment", "Order Fulfillment Cycle Time", "Upside Supply Chain Adaptability", "Downside Supply Chain Adaptability", "Value at Risk", "Cost to Return", "Cost to Deliver", "Cost to Make", "Cost to Plan", "Inventory days of supply", "Cash to cash cycle time"

- Finally, this study contributes to the research community with several propositions in the form of research questions. These questions are derived from various dimensions of the proposed supply chain performance measurement 4.0 framework.

This paper is structured as follows: Section 2 is dedicated to previous literature reviews research. Subsequently, Section 3 deals with the theoretical background regarding SC and the I4.0 concept. Section 4 refers to the methodology used which is the systematic literature review. In Section 5, the descriptive and thematic findings are presented. Section 6 refers to the creation of a framework. In Section 8 the conclusions are presented. Lastly, in Section 13 the limitations are presented and discussed.

2. Background

In this section, a summary of previous scientific literature reviews in the domain of SC performance and the concept of I4.0 will be presented. This foundation justifies the need for a literature review of the impact of I4.0 technologies and concepts on SC performance.

2.1. Previous literature reviews

To justify the need for a literature review of I4.0 and SC performance, an examination of reviews on the topics was conducted. The search on Scopus showed that there have been no literature reviews conducted on the subject of I4.0 and SC performance. The search string identifying the reviews is listed in Table 1. The gap of literature reviews within I4.0 and SC performance clearly justifies the need for a literature review.

Since no literature reviews in the field of I4.0 and SC performance have been conducted, the aim of separate searches for literature reviews in the fields of SC performance and I4.0 is to find keywords for a new literature review that addresses the current gap. Reviews of I4.0 have mostly taken place from 2015 to 2021 since the concept of "The Fourth Industrial Revolution" is new; therefore, it has only recently attracted the interest of academicians. This novelty is the primary reason there is still room for further exploration in the field of I4.0.

Table 2 illustrates the literature reviews regarding SC performance measurements, while Table 3 illustrates the most prominent literature reviews of I4.0. Most of the reviews of SC performance listed in Table 2 review the financial, non-financial, and sustainable performance measurements of a SC. The I4.0 literature reviews in Table 3 have focused on creating an understanding of the I4.0 concept while examining its key technologies and application possibilities.

None of the literature reviews listed in Table 2 and Table 3 deals with the linkage between I4.0 technologies and concepts and SC performance. Most of the papers interpret the meaning of SC performance measurements, performance measurement systems, and I4.0 by analyzing several of its key technologies in relation to specific implementation areas. The lack of linkages between SC performance and I4.0 technologies and concepts in these articles indicates a significant and relevant research gap; therefore, the purpose of the literature review of this work is to find the linkages between I4.0 technologies, concepts, and SC performance measures. The literature reviews listed in Table 3 and 4 are used to map the field and to create a list of search words in relation to SC performance measurements and I4.0.

3. Theoretical background

This section presents the theory required to better understand the remaining sections of the paper. It covers the topics of SCM, SC Performance, and I4.0.

3.1. Definition of supply chain

There are several definitions of what a SC is, but many are quite similar. Goetschalckx (2011) provides a definition that accounts for several of the other definitions: *"A supply chain is an integrated network of resources and processes that is responsible for the acquisition of raw materials, the transformation of these materials into intermediate and finished products, and the distribution of the finished products to the final customers."*.

According to Chopra and Meindl (2001), "SC consists of all parties involved, directly or indirectly, in fulfilling a customer request. The SC includes not only the manufacturer and suppliers, but also transporters, warehouses, retailers, and even customers themselves. The term SC conjures up images of product or supply moving from suppliers to manufacturers to distributors to retailers to customers along a chain.".

3.2. Definition of SC management

The literature has provided several definitions of SCM. The research of Stock & Boyer (2009) suggests a definition of SCM which combines opposing definitions: "*The management of a network of relationships within a firm and between interdependent organizations and business units consisting of material suppliers, purchasing, production facilities, logistics, marketing and related systems that facilitate the forward and reverse flow of materials, services, finances and information from the original producer to final customer with the benefits of adding value, maximizing profitability through efficiencies, and achieving customer satisfaction.*" The SCM research can be classified into three categories (Huan et al., 2004).

3.3. Definition of performance measures

This section explains what performance measures are and how they help companies in achieving their goals. According to Lebas (1995), performance is defined as *"The ability to meet certain criteria, the time it takes, and the path used to get there."* Performance measures are therefore used to indicate how well this is done (Lebas, 1995). Neely et al. (1995) further define performance measurement as: *"The process of quantifying the efficiency and effectiveness of action"* and performance measures as *"A metric used to quantify the efficiency and/or effectiveness of an action."*.

The responsiveness and efficiency performance of a SC is based on the interaction between a number of drivers of SC performance.

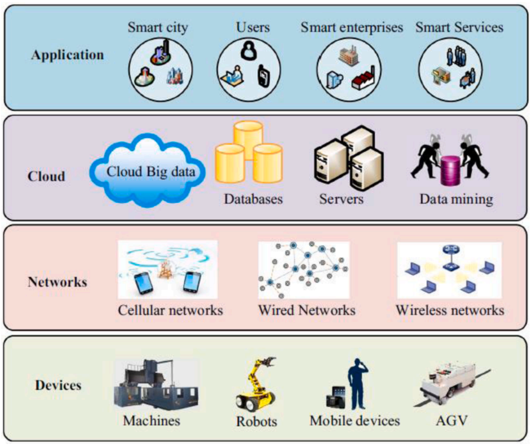

Fig. 1. Layout of Industry 4.0 - Source: Reproduced from (Li et al., 2017).

Those drivers include inventory, facilities, transportation, sourcing, information, and pricing (Chopra & Meindl, 2001; Jermsittiparsert and Boonratanakittiphumi, 2019a).

3.4. Description of Industry 4.0

I4.0, which was first proposed by the German government at the Hannover Messe in 2011 is related to the IoT, CPS, and smart factory concepts. The fourth industrial revolution will intellectualize manufacturing, while increasing transparency and automation and facilitating customized production in place of mass production (Li et al., 2017; Li et al., 2020). Several articles and academic papers have been published attempting to define what I4.0 is and what possible implications the related technologies might have on the whole manufacturing industry (Schwab, 2016; Bag et al., 2020; Zheng et al., 2021). In the I4.0 paradigm, automation and computers are used together, for example, by having robots with remote connections to computer systems that can control and improve the robots with minimal human input through machine learning algorithms. One technology used in I4.0 is the cyber-physical system that allows for decentralized decision-making of the machines in the production process (Lin et al., 2017; Pandey et al., 2020). Furthermore, CPS can be explained as being the foundation of I4.0 because it allows humans to integrate the physical and digital worlds in numerous ways (Schwab, 2016; Morella et al., 2020; Yavas and Ozkan-Ozen, 2020; Tang and Veelenturf, 2019; Pivoto et al., 2021). Through the wireless web, physical systems and entities in the system are able to communicate and cooperate with each other, and with human operators in real-time, forming an IoT (Garrido-Hidalgo et al., 2019). Integration of interdisciplinary knowledge and technologies can be facilitated through the use of the cloud, wireless networks, and mobile terminals. Some of the key features of I4.0 are Interoperability, where devices, machines, sensors, and operators are connected and able to communicate; Information transparency, where information is contextualized through the creation of a virtual copy of the physical world using sensor data; Technical assistance, which refers to the assistance in solving problems and decision-making that the systems can provide people or assistance in dangerous or difficult tasks for humans in the process; Decentralized decision-making, which refers to machines becoming autonomous in the CPS (Lin et al., 2017). One characteristic of I4.0 is the interconnection of ICT and physical entities in production, which also is referred to as IoT. It facilitates integration of established structures within an enterprise and with other enterprises. There are two distinct types of integration in the context of I4.0, namely vertical integration and horizontal integration. Vertical integration looks within an organization and seeks to increase the level of collaboration and information exchange across different hierarchy levels. Horizontal integration refers to increased collaboration among several enterprises (Tupa et al., 2017).

The goal of I4.0 is to achieve greater flexibility, efficiency, adaptability, and improving communication between consumers and producers by integrating and connecting traditional industries (Li et al., 2017; Rahman et al., 2022). Furthermore, a primary purpose of I4.0 is to enable mass customization by merging the concepts of custom manufacturing and line manufacturing together and creating a smart factory (Grieco et al., 2017; Jermsittiparsert and Boonratanakittiphumi, 2019b). T. H. S. Li et al. (2017) also refer to increased flexibility in production and a reduction of resource waste as some of the end benefits of the fourth industrial revolution. I4.0 can be divided into four main components: the physical (or devices) layer, networks layer, cloud/BD layer, and the application layer as seen in Fig. 1.

The physical (or devices) layer includes entities that perform mechanical tasks or acquire and compute data, such as machines, robots, mobile devices, and automated guided vehicles. The networks layer consists of the different types of networks that have the objective of transmitting real-time data between devices that are part of the system, such as wireless, wired, or cellular networks. The communication happening in these networks can be machine to machine (M2M), operator to device, or communication between networks and servers or industrial clouds. The cloud/BD layer is where all handling of data happens, such as mining, cleaning, and storage of data, and it is what bridges the network layer and application layer together. Finally, the application layer includes smart services, users, smart enterprises, and smart city (X. Li et al., 2017).

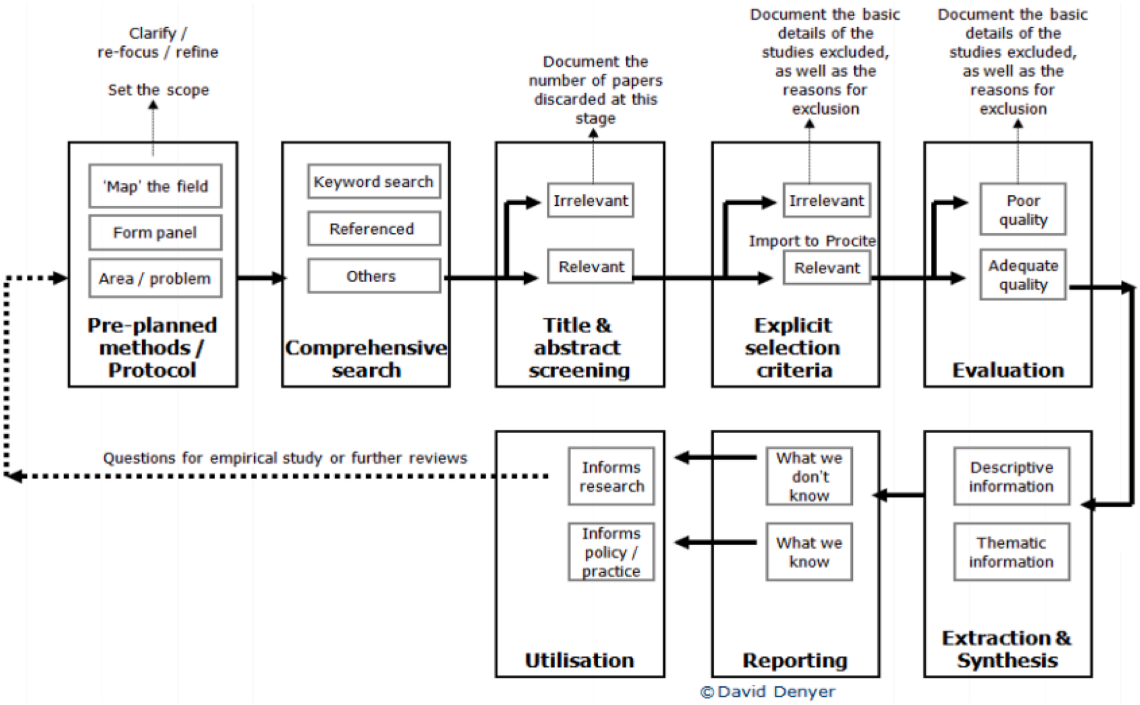

Fig. 2. 8 Key steps for conducting SLR- Source: Reproduced (Denyer & Pilbeam, 2013).

4. Methodology

Within the methodology section, the underlying methodological choices are discussed and presented. The topic of I4.0 is still an emerging and underdeveloped topic, so the application of more exploratory research methods is suitable to give first directions instead of a final answer (Schüter & Hetterscheid, 2017). According to Saunders et al. (2007), there are three principal ways of conducting exploratory research: conducting literature review, interviewing experts within the area of research, and conducting focus group interviews.

The first step of this paper was to conduct a literature review to develop a better understanding of the topic and to find a gap in the existing literature. According to Seuring et al. (2005), a literature review serves as a foundation for any research. The authors further state that a literature review is an integral part of any research, and therefore it is a necessary step towards structuring a field of research. It contributes to developing theory, and it is a method for identifying the conceptual content of the research area.

The two standard types of reviews are:

- Non-systematic or narrative review.
- Systematic Literature Review.

Narrative reviews are useful for avoiding duplication, and they focus on summarizing previously published findings, thus locating new areas of study that have not yet been addressed in the literature. Furthermore, in a narrative review, it is not necessary to explicitly specify the criteria for inclusion of articles. The main weakness of the narrative review is subjectivity in the selection of studies, which can lead to biases (Ferrari, 2015).

A Systematic Literature Review is a specific type of literature review which detects the necessary data. It assesses their value and, after a profound analysis, returns manageable results for further consideration and final conclusions about the objective of the study (Denyer & Tranfield, 2009; Demartini et al., 2022). A systematic literature review is different from the traditional narrative review in that the systematic review uses a detailed, scientific, and transparent method, which is replicable. Furthermore, it seeks to minimize bias by providing documentation of the reviewer's procedures, decisions, and conclusions of a comprehensive search of both published and unpublished studies (Tranfield et al., 2003). The objectivity of the results is higher, and issues related to bias or errors are eliminated when a systematic literature review is used (Kilubi & Haasis, 2016). Based on the comparison of the narrative and the systematic literature review, the systematic literature review has been selected as the most suitable method for this work. Although the systematic literature review sometimes takes considerably more time to conduct compared to the narrative review, it is argued to be the most efficient method for reviewing extensive literatures, while maintaining the highest quality (Tranfield et al., 2003).

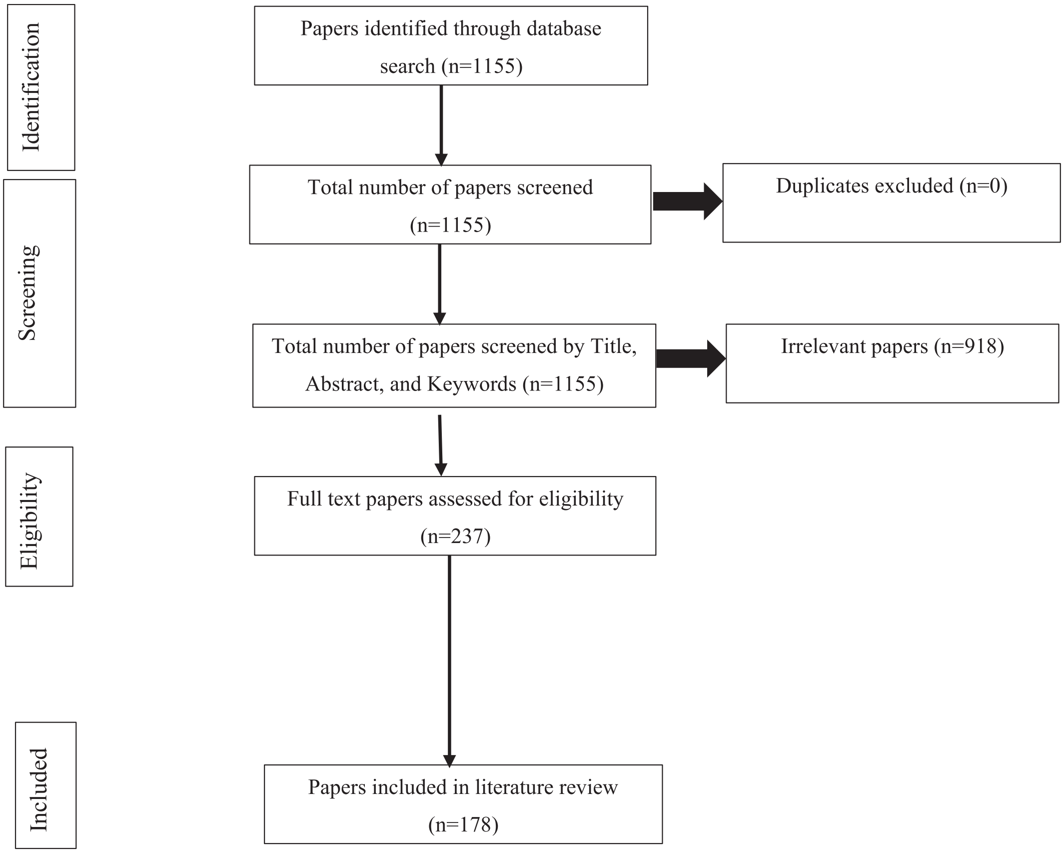

Fig. 3. Literature Screening

4.1. Research process

This section describes the different steps of the research process in detail and explains how they were executed. The aim of the literature review is to create a broad understanding of I4.0 Technologies and concepts, of SC Performance, and to identify a gap in the existing literature. This systematic literature review is conducted to find the linkages between I4.0 technologies and concepts and SC performance measures. The systematic literature review in this paper follows the systematic literature review approach by Denyer & Pilbeam (2013) to answer the research questions. The authors defined eight stages for conducting a systematic literature review, as seen in Fig. 2.

Step 1 – Pre-planned methods/protocol: Prior to beginning the review, a review panel was formed with four experts, each fluent in the areas of both methodology and theory.

In order to get a grasp of the current literature and to map the field of current literature, the literature review started with an explorative phase, where the keywords "I4.0" and "SC Performance" were used to gather literature reviews on the topics I4.0 and SC performance from the online bibliographic database SCOPUS, noted in Section 2.1. This database was accessed through the University of Southern Denmark's online library. These articles were then used to elicit new keywords and key phrases that were used to create a new and narrower search for relevant literature. The keywords used are presented later in Table 4.

According to Tranfield et al. (2003), the outcome of systematic review is captured through a review and evaluation protocol. The protocols were made to protect objectivity by providing explicit descriptions of the steps to be taken. The protocol contains the criteria for inclusion and exclusion of studies in the review during the full text reading. The aim of the protocol is to ensure the reviews are less open to researcher bias (Tranfield et al., 2003). The protocol is displayed in Appendix A with the inclusion and exclusion criteria for Title, Keyword, and Abstract reading.

The development of review questions is critical to the systematic review so other aspects of the process flow from it. The research questions and sub-research questions are as follows:

RQ How can Industry 4.0 technologies improve supply chain performance?

- *SRQ 1: What are the state-of-the-art technologies in Industry 4.0?*
- *SRQ 2: What supply chain performance measures can be enhanced by Industry 4.0 technologies?*

Table 5
Key enabling I4.0 technologies and concepts in relation to SC.

Technology/ Concept	Source
T_1: Internet of Things	(Majeed & Rupasinghe 2017)(Lianguang 2014)(Trappey et al., 2017b)(Waibel et al. 2017) (D. Li et al. 2017)(Krugh et al. 2017)(Tuptuk & Hailes 2018)(Tang et al. 2017)(Lin et al. 2017)(Maslarić et al. 2016)(Reddy et al. 2016)(Trappey et al., 2017a)(Bisio et al. 2018)(C. Wang et al. 2017)(Kusiak, 2018)(Tang et al. 2018)(Haverkort & Zimmermann 2017)(Schütze et al. 2018)(Moghaddam & Nof 2018)(Gruzauskas et al. 2018)(Ma et al. 2017)(Y. Wang et al. 2017)(T. H. S. Li et al. 2017)(Dossou & Nachidi 2017)(Trstenjak & Cosic 2017)(Oku et al. 2015)(Weyer et al., 2015a)(Albini & Rajnai 2018)(Ruppert & Abonyi 2018)(Caggiano & Teti 2018)(Rodič 2017)(Wang et al. 2016)(Reed 2018)(Dallasega et al. 2018)(Tupa et al. 2017)(Fernández-Miranda et al., 2017)(Cohen et al. 2017)(Pagoropoulos et al. 2017)(Yan et al. 2017)(Rakyta et al. 2016)(Moradlou et al. 2018)(Zheng & Wu 2017)(Ahuett-Garza & Kurfess 2018)(Barata et al. 2018)(Kaur & Kaur 2018)(Dallasega et al. 2017)(Tjahjono et al., 2017a,b)(Zhong et al. 2017)(Bocken 2016)(Chen & Lin 2017)(Molka-Danielsen et al. 2018)(Fernández-Caramés et al. 2018) (Garrido-Hidalgo et al., 2019) (Mostafa et al., 2019) (Kalsoom et al., 2020) (Esmaeilian et al., 2020) (Adhitya et al., 2020) (Mastos et al., 2020) (Khan et al., 2020) (Wang et al., 2020) (Kalsoom et al., 2020) (Esmaeilian et al., 2020) (Mastos et al., 2020) (Gorecki et al., 2020) (Attaran, 2020) (Khan et al., 2020) (Ratna, 2020) (Garrido-Hidalgo et al., 2019) (Nascimento et al., 2019) (Molka-Danielsen et al., 2018) (Seyedghorban et al., 2020) (Hahn, 2020) (Dobrescu et al., 2021) (De Vass et al., 2021) (Zahedi et al., 2021) (Dobrowolski, 2021) (Ahmed et al., 2021) (Ekren et al., 2021) (Cifone et al., 2021) (Nandi et al., 2021) (Tibazarwa, 2021) (He et al., 2021) (Ada et al., 2021) (Pyun and Rha, 2021) (Shayganmehr et al., 2021) (Bamakan et al., 2021) (Brandín and Abrishami, 2021) (Stanisławski and Szymonik, 2021) (Mustafee et al., 2021) (Sawangwong and Chaopaisarn, 2021) (Mrugalska and Ahmed, 2021) (Bhattacharya and Chatterjee, 2021) (Rajput and Singh, 2021) (Ud Din et al., 2021) (Tran-Dang and Kim, 2021) (Shen et al., 2021) (Dev et al., 2021)
T_2: Cyber-Physical Systems	(Weyer et al., 2015b)(Albini & Rajnai 2018)(Rodič 2017)(Dallasega et al. 2018)(Majeed & Rupasinghe 2017)(Tupa et al. 2017)(Fernández-Miranda et al., 2017)(Cohen et al. 2017)(Haverkort & Zimmermann 2017)(Krugh et al. 2017)(Yan et al. 2017)(Moradlou et al. 2018)(Reitze et al. 2018)(Zheng & Wu 2017)(Ahuett-Garza & Kurfess 2018)(Barata et al. 2018)(T. H. S. Li et al. 2017)(Kaur & Kaur 2018)(Dallasega et al. 2017)(Tjahjono et al., 2017a,b)(Zhong et al. 2017)(Asakura 2016)(Long et al. 2018)(Trappey et al., 2017a) (Bocken 2016)(Chen & Lin 2017)(Molka-Danielsen et al. 2018)(Bisio et al. 2018)(Moghaddam & Nof 2018)(Ruppert & Abonyi 2018)(Caggiano & Teti 2018)(Wang et al. 2016)(Trappey et al., 2017b)(Kusiak, 2018)(Bodrow 2017)(Waibel et al. 2017)(Tang et al. 2018)(Y. Wang et al. 2017)(D. Li et al. 2017)(Tuptuk & Hailes 2018)(Tang et al. 2017)(Lin et al. 2017)(Reddy et al. 2016)(Ivanov et al. 2016)(Trstenjak & Cosic 2017)(Rødseth et al. 2017)(Gruzauskas et al. 2018)(Harrison et al. 2016)(Ma et al. 2017)(Siafara et al. 2018)(Maslarić et al. 2016)(Maslarić et al. 2016) (Jermsittiparsert and Boonratanakittiphumi, 2019a) (Pandey et al., 2020) (Morella et al., 2020) (Gruzauskas et al., 2018) (Spieske and Birkel, 2021) (Raji et al., 2021) (Lyu et al., 2021) (Ud Din et al., 2021) (Bhattacharya and Chatterjee, 2021) (Mrugalska and Ahmed, 2021)
T_3: Augmented reality	(Weyer et al., 2015b)(Rodič 2017)(Dallasega et al. 2018)(Kusiak, 2018)(Cohen et al. 2017)(Contents 2017)(Barata et al. 2018)(Tjahjono et al., 2017a,b)(Zhong et al. 2017) (Fernández-Caramés et al. 2018) (Rejeb et al., 2020) (Rejeb et al., 2021) (Cagliano et al., 2021) (Bhattacharya and Chatterjee, 2021)
T_4: Cloud Computing	(Zhu et al., 2014) (Subramanian et al., 2014) (Bodrow 2017) (Zhong et al. 2017) (Trappey et al., 2017a) (Ding 2018) (Trstenjak & Cosic 2017) (Bienhaus & Haddud 2018) (Moradlou et al. 2018) (Tuptuk & Hailes 2018) (Dallasega et al. 2017) (Ma et al. 2017) (Haverkort & Zimmermann 2017) (Kusiak, 2018) (Kamble et al. 2018) (Fernández-Miranda et al., 2017) (J. W. Strandhagen et al., 2017) (Sundarakani et al., 2019) (Li et al., 2020) (Attaran, 2020) (Oncioiu et al., 2019) (Gruzauskas et al., 2018) (Tran-Dang and Kim, 2021) (Raji et al., 2021) (Stanisławski and Szymonik, 2021) (Mustafee et al., 2021) (Sawangwong and Chaopaisarn, 2021) (Gunduz et al., 2021)
T_5: Internet of Services	(Cohen et al. 2017)(Xue et al., 2013a)(Maslarić et al. 2016)(Moghaddam & Nof 2018)(Dallasega et al. 2018)(Waibel et al. 2017)(Tupa et al. 2017)(Moghaddam & Nof 2018)(Long et al. 2018)(Bocken 2016)(Y. Wang et al. 2017)
T_6: Big Data & Analytic	(Bodrow 2017) (Yan et al. 2017) (Y. Wang et al. 2017) (Zhong et al. 2017) (Molka-Danielsen et al. 2018) (J. W. Strandhagen et al., 2017) (Fernández-Miranda et al., 2017) (Kamble et al. 2018) (Bocken 2016) (Reddy et al. 2016) (Zheng & Wu 2017) (Haverkort & Zimmermann 2017) (Xue et al., 2013b) (Long et al. 2018) (Bienhaus & Haddud 2018) (Trstenjak & Cosic 2017) (Ding 2018) (Oku et al. 2015)(Bisio et al. 2018) (Ahuett-Garza & Kurfess 2018) (Dallasega et al. 2018) (Govindan et al., 2018) (Oncioiu et al., 2019) (Fernández-Caramés et al., 2019) (Li et al., 2020) (Bag et al., 2020) (Gupta et al., 2020) (Li et al., 2020) (Jha et al., 2020) (Bag et al., 2020) (Gupta et al., 2020) (Oncioiu et al., 2019) (Zheng et al., 2020) (Molka-Danielsen et al., 2018) (Gruzauskas et al., 2018) Bag et al., 2021a,b) Romero-Silva and de Leeuw, 2021) (Kazancoglu et al., 2021) (Spieske and Birkel, 2021) (Tran-Dang and Kim, 2021) (Rai et al., 2021) (Tuzkaya and Şahin, 2021) (Cagliano et al., 2021) (Raji et al., 2021) (Ada et al., 2021) (Pyun and Rha, 2021) (Shayganmehr et al., 2021) (Bamakan et al., 2021) (Brandín and Abrishami, 2021), (Sawangwong and Chaopaisarn, 2021) (Mrugalska and Ahmed, 2021) (Bhattacharya and Chatterjee, 2021) (Gunduz et al., 2021)
T_7: Artificial Intelligence	(J. W. Strandhagen et al., 2017) (Kusiak, 2018) (Bienhaus & Haddud 2018) (Dossou & Nachidi 2017) (Ding 2018) (Schütze et al. 2018) (Asakura 2016) (Tjahjono et al., 2017a,b) (Albini & Rajnai 2018)(Ahuett-Garza & Kurfess 2018) (Rødseth et al. 2017) (Bag et al., 2020 (Kriebitz and Lutge, 2020) (Sanders et al., 2019) (Oh, 2019) (Radanliev et al., 2020) (Reyes et al., 2020) (Bag et al., 2020) (Mahroof, 2019) Cagliano et al., 2021)
T_8: Digital Twin	((Zhong et al. 2017) (Ahuett-Garza & Kurfess 2018) (Reitze et al. 2018) (Geissbauer et al. 2018) (Vanderroost et al., 2017a) (Fernández-Miranda et al., 2017) (Kamble et al. 2018) (Kusiak, 2018) (Bienhaus & Haddud 2018)(Ahuett-Garza & Kurfess 2018) (Chen & Lin 2017)(L. Li et al. 2017) (Zhong et al. 2017)(Zheng & Wu 2017) (Long et al. 2018) (Caggiano & Teti 2018) (Dallasega et al. 2017) (Ivanov and Dolgui, 2021) (Kaivo-Oja et al., 2020) (Ivanov and Dolgui, 2021) (Ho et al., 2021) (Lugaresi and Matta, 2021) (Serrano-Ruiz et al., 2021) (Bamunuarachchi et al., 2021)
T_9: Additive Manufacturing	(Srai et al. 2016) (Murmura & Bravi 2018) (Durão et al. 2017) (Chen & Lin 2017) (J. W. Strandhagen et al., 2017) (Vanderroost et al., 2017a) (Kamble et al. 2018) (Kusiak, 2018) (Moradlou et al. 2018) (Bienhaus & Haddud 2018) (Bocken 2016) (Tuptuk & Hailes 2018) (Ding 2018) (Jermsittiparsert and Boonratanakittiphumi, 2019b) (Sun et al., 2020) (Nica, 2019) (Franco et al., 2020) (Attaran, 2020) (Dev et al., 2020) (Gupta et al., 2020) (Nascimento et al., 2019) (Dev et al., 2020); Shen et al., 2021) (Dev et al., 2021); (Sawangwong and Chaopaisarn, 2021) (Spieske and Birkel, 2021) (He et al., 2021)
T_{10}: Industrial Robotics	(Rodič 2017)(Wang et al. 2016)(Dallasega et al. 2018)(Majeed & Rupasinghe 2017)(Tupa et al. 2017)(Kusiak, 2018)(Cohen et al. 2017)(Waibel et al. 2017)(D. Li et al. 2017)(Moradlou et al. 2018)(Contents 2017)(Tjahjono et al., 2017a,b)(Zhong et al. 2017)(Asakura 2016)(Kovacs & Kot 2016)(Gruzauskas et al. 2018)(Oku et al. 2015)(T. H. S. Li et al. 2017)(Dossou & Nachidi 2017)(Müller et al. 2017)(Caggiano & Teti 2018) Strandhagen et al. 2017) (Kamble et al. 2018) (Ma et al. 2017) (Ding 2018) (Liu and De Giovanni, 2019) (Duong et al., 2020) (Attaran, 2020) (Shen et al., 2021) (Dev et al., 2021)

(continued on next page)

Table 5 (*continued*)

Technology/ Concept	Source
T_{11}: Flexible Automation	(Rodič 2017)(Wang et al. 2016)(Dallasega et al. 2018)(Majeed & Rupasinghe 2017)(Tupa et al. 2017)(Kusiak, 2018)(Cohen et al. 2017)(Waibel et al. 2017)(D. Li et al. 2017)(Moradlou et al. 2018)(Contents 2017)(Tjahjono et al., 2017a,b)(Zhong et al. 2017)(Asakura 2016)(Kovacs & Kot 2016)(Gruzauskas et al. 2018)(Oku et al. 2015)(T. H. S. Li et al. 2017)(Dossou & Nachidi 2017)(Müller et al. 2017)(Caggiano & Teti 2018) Strandhagen et al. 2017) (Kamble et al. 2018) (Ma et al. 2017) (Ding 2018) (Simchi-Levi and Wu, 2018) (Molka-Danielsen et al., 2018) (Duong et al., 2020) (Mastos et al., 2020)
T_{12}: Horizontal Integration	(Ding 2018) (Reitze et al. 2018) (Zheng & Wu 2017) (Bocken 2016) (Kamble et al. 2018) (J. W. Strandhagen et al., 2017) (Tsuchiya et al. 2018a)(Kovacs & Kot 2016)(Barreto et al. 2017)(Ma et al. 2017)(Maslarić et al. 2016)(Kusiak, 2018)(Tupa et al. 2017)(Barata et al. 2018)(Xue et al., 2013a) (Weyer et al., 2015a) (Cozmiuc and Petrisor, 2018) (Sun et al., 2020)
T_{13}: Vertical Integration	(Ding 2018) (Reitze et al. 2018) (Zheng & Wu 2017) (Bocken 2016) (Kamble et al. 2018) (J. W. Strandhagen et al., 2017) (Tsuchiya et al. 2018a)(Kovacs & Kot 2016)(Barreto et al. 2017)(Ma et al. 2017)(Maslarić et al. 2016)(Kusiak, 2018)(Tupa et al. 2017)(Barata et al. 2018)(Xue et al., 2013a) (Weyer et al., 2015a) (Halaška and Šperka, 2019) (Cozmiuc and Petrisor, 2018)
T_{14}: Cyber security	(Weyer et al., 2015b)(Albini & Rajnai 2018)(Tupa et al. 2017)(Fernández-Miranda et al., 2017) (Haverkort & Zimmermann 2017)(Zhong et al. 2017)(Asakura 2016)(Maslarić et al. 2016)(Bocken 2016)(Fernández-Caramés et al. 2018)(Tuptuk & Hailes 2018) (Pandey et al., 2020)

Step 2 – Comprehensive search: The comprehensive search begins with an identification of the keywords and search terms to be used for the literature review. These were found in the first step where the scope of the review was determined. Next, a keyword search was conducted, resulting in a full list of articles and reviews on which this review is based. Only publications that meet the inclusion criteria described in the review protocol and, at the same time, do not manifest any exclusion criteria, were included in the review (Tranfield et al., 2003).

To define the search terms for the literature search, a brainstorming session was held to create as many keywords as possible in relation to I4.0 and SC performance. The results of the brainstorm were combined with the findings from the review of the previous review in Section 2.1 This created a list of key words, which is displayed in Table 4.

The keywords from Table 4 were chosen to gather as much literature as possible regarding I4.0 technologies and concepts in relation to SC performance.

The keywords were separated into three sections connected by the logical operator “AND”. In each of the three sections the keywords are connected with the logical operator “OR”; this ensures that at least one of the keywords is found in the resulting literature. Since the research topic is I4.0, the identified synonyms of I4.0 must occur in the abstract, keyword, or title of the examined articles. The second section of the keywords consists of technologies and concepts related to I4.0, and these keywords also need to appear in the title, abstract, and keywords of the potential literature. The third section of keywords consists of the SC performance metrics and synonyms, which were included to identify the SC performance benefits related to I4.0 and I4.0 technologies.

In order to avoid neglecting the plural and other versions of keywords, the “*” sign was used. As an example, the keyword “manufacturing” is changed to “manufactur*”. The usage of a large number of synonyms for I4.0 and SC performance measurements increases the likelihood of including more relevant papers.

The literature search has been conducted only in the Scopus database (https://www.scopus.com) which is a database containing numerous articles, and which provides greater ease for the researcher to search articles forward and backward in time (Burnham, 2006). The research was restricted to include formal literature, such as articles, reviews, and conference reviews, and to exclude informal literature such as books. The first search on Scopus was conducted in August 2018 generating 378 papers, a second search was conducted in October 2018 generating 430 papers, a third search was conducted in September 2020, and a fourth search was conducted in Jan 2022 generating a total of 1155 papers.

Step 3 – Title & abstract screening: Appendix presents the review protocol used during the procedure of the systematic literature review (see in Appendix A).

In this step, the 1155 papers were evaluated based on their Title and Abstract in relation to I4.0 and SC performance. During that evaluation, papers which were irrelevant according to the review protocol and the scope of the study were excluded. As a result, the evaluation procedure has provided 237 papers to be considered for further examination.

Step 4 – Explicit selection criteria: The 237 articles were further evaluated by a thorough reading of each article, using the Inclusion and Exclusion protocol from Appendix A, resulting in 178 articles that are included in the review. The evaluation process and number of discarded papers due to their irrelevance to this study is displayed in Fig. 3.

Step 5 – Evaluation: Only peer reviewed articles are used in this systematic literature review, thus evaluating the quality of the articles did not result in the exclusion of any articles.

Step 6 – Extraction and synthesis: This section synthesizes the research papers with the ‘thematic analysis’, derived through an interpretative approach, outlining findings from the literature (Tranfield et al., 2003). These are presented in the “Findings” section.

Step 7 – Reporting: Conclusions regarding what was found and what was not found in the systematic literature review are drawn.

Step 8 – Utilization: How the findings can be utilized in the future is explained, after which new questions for empirical study or further reviews can be developed.

5. Findings

In this section, the thematic findings from the literature review are presented. The findings comprise descriptions of each of the

Table 6
I4.0 Terms classified in Technology and Concept.

Technology	Concept
– Additive Manufacturing	– Cloud Computing
Augmented Reality	– Horizontal Integration
– Artificial Intelligence	– Internet of Service
– Big Data Analytics	– Internet of Things
– Industrial Robotics	– Vertical Integration
– Digital Twin	– Cyber Security
– Cyber Physical Systems	
– Flexible automation	

technologies and concepts identified, as well as related SC performance benefits.

5.1. *Thematic findings*

An analysis of the content of the selected samples was initiated. The methodology of the content analysis aims to divide long texts into smaller meaningful content divisions (Oesterreich & Teuteberg, 2016). The following subsection screens the literature regarding I4.0 technologies and concepts and SC Performance. A thorough research has been performed to identify key technologies and concepts of I4.0. By screening the literature, phenomena related to I4.0 and SC were identified. The discovered I4.0 related topics were divided between I4.0 technologies and I4.0 concepts. The following definition will be used to distinguish between I4.0 technologies and concepts. Schüter & Hetterscheid (2017) define an I4.0 technology as a “directly recognizable object and real existing physical hardware or logical software which is financially activatable and supports or realizes the principles and ideas of I4.0”.

A variety of terms of I4.0 technologies and concepts emerged during the examination of the literature. 14 key technologies and concepts that represent I4.0 were identified and are listed in Table 5.[1] This has been considered as a limitation of this present study and the same has been addressed in an forthcoming study by the author with the specific focus on reviewing the relationship between the blockchain technology and its impact on supply chain management benefits / performance.

Based on the definition of I4.0 technologies provided by Schüter & Hetterscheid (2017), the I4.0 related subjects were divided into technologies and concepts in Table 6. The I4.0 concepts are more abstract principles, which can be enabled by using the technologies. The technologies are tangible through certain hardware or software (ibid.). A mix of the I4.0 technologies on the left and the concepts on the right side of Table 6 is used for the later framework.

In the following subsections the findings regarding I4.0 technologies and concepts are presented.

5.1.1. *Internet of Things*

The Internet of Things (IoT) is defined as a network of different physical objects that are embedded with digital devices such as sensors, actuators, etc. These elements are connected in order to collect and exchange data. Furthermore, communication is enabled between objects or ‘things’, systems, and services in the network that allows for data sharing (Zhong et al., 2017; Kalsoom et al., 2020). Krugh et al. (2017) refer to the Industrial Internet of Things (IIoT) as a connected manufacturing ecosystem that leverages BD and includes sensor data, machine learning, machine-to-machine communication, human-to-machine communication, and automation technologies. The purpose of the IIoT is to facilitate root cause analysis, identify inefficiencies, and support business intelligence. According to Bisio et al. (2018), the main enabling technology for realizing the fourth industrial revolution is the IoT. The advanced connectivity of electronic devices at any time in any place is the main objective of the IoT. Furthermore, the different devices and objects in the system gain intelligence from a common understanding protocol, allowing them to make decisions. All of this is enabled by technologies such as CC and the IPv6 protocol that has nearly unlimited addressing capacity (Majeed & Rupasinghe, 2017; Mostafa et al., 2019). Bisio et al. (2018) further explain that IoT is the result of many technological developments complementing each other and allowing for the gap between the physical and virtual worlds to be bridged. The capabilities from the different developments include sensing, actuation, communication, cooperation, addressability, identification, embedded information processing, localization, and user interfaces. The network infrastructure created by the IoT that connects the virtual systems and physical objects allows for more efficient, accurate, and intelligent operations performance (Trappey et al., 2017a; Adhitya et al., 2020). The IoT is further seen as a convergence of other technologies such as machine learning, data analytics, and ubiquitous wireless standards (Zhong et al., 2017; Li et al., 2020; Sim and Cho, 2021).

5.1.1.1. Internet of Things Benefits. The purpose of the IoT concept is to allow ‘things’ in a system to perform tasks with greater accuracy, improve responsiveness, increase collaboration between entities in the system, and enable learning at the same time. This is done by giving the ‘things’ in the system the ability to see, hear, smell, touch, and speak. IoT can benefit companies in many different

[1] Recently, blockchain technology was applied in various supply chain related issues (Choi et al., 2020; Yang, 2019; Choi et al., 2019; Choi, 2019; Kouhizadeh et al., 2021) and the authors of the paper explored the relationship between the blockchain and supply chain management in another specific review study which leads to excluding this technology in the current work.

areas, such as increasing product delivery speed, reducing costs, improving customer relationships, and tracking tools. If Moore's law is applied, the cost of IoT sensors can be expected to decrease further over time (Trappey et al., 2017b). Remote control and sensing of objects using IoT throughout the network infrastructure in place increases the integration between the virtual world and the physical world, and that integration brings the benefits of improved efficiency, accuracy, and potentially reduced costs (Bisio et al., 2018; Mastos et al., 2020; De Vass et al., 2021). Further benefits related to the implementation of IoT are shorter production cycles, real-time incorporation of customer needs, automatic maintenance, automatic filling, shipping and dispatching of orders (Barreto et al., 2017; Adhitya et al., 2020; Zahedi et al., 2021; Cifone et al., 2021).

There are many ways that IoT can influence the entire SC, of which four stand out. First, IoT can help develop SC reliability through real-time information exchange and object visibility. Second, IoT can reduce costs and improve the responsiveness of the SC, using real-time optimization. Third, through real-time resource tracking, IoT can enhance SC assets' management. Finally, IoT can increase the speed of information flow process, thus improving SC agility. With all of this in mind, IoT has great potential of addressing SC challenges related to controllability, traceability, and visibility (Dweekat et al., 2017; Kalsoom et al., 2020; Brandín and Abrishami, 2021; Pyun and Rha, 2021).

5.1.1.2. Architecture. Trappey et al. (2017b) describe an architecture for IoT, which is divided into four layers: the perception, transmission, computation, and application layers. The perception layer includes components such as circuits, sensors, actuators, controllers, etc. giving the object the ability to perceive. The inputs gathered at the perception layer are used in consecutive layers and end in the application layer where the object gains micro intelligence. The transmission layer is the next layer in the IoT architecture, which takes information gathered in the perception layer and transmits it to the next layers. Power, range, and storage capacity are some of the factors to be considered in this layer. The computation layer is concerned with data receiving and processing, as well as decision-making and delivery of decisions to the application layer. Different hardware, software, algorithms, cloud platforms, and encryption need to be considered in this layer. Finally, the application layer aggregates the information received from lower levels, giving a tactical understanding, and it allows for actions to be taken based on decisions made in the computation layer. Applications can be business-related, focusing on categories such as manufacturing, retail, public services, or they can be consumer-related, made for home, lifestyle, health care, transport, etc.

5.1.1.3. IoT in factory. In the context of future factories, IoT will allow for greater connection and communication between physical beings and machines, and humans are going to work in complex environments with networks of processes, robotics, machines, sensors, and other devices. Competitive advantage will be gained through intelligent, quick and self-adaptive production processes, which requires development of novel operating concepts for human–machine interaction (Majeed & Rupasinghe, 2017).

5.1.1.4. IoT in Smart logistics. In a logistics context, IoT is considered the critical enabler for smart logistics services. Smart logistics management of objects and information flows cannot be facilitated without the IoT tracking and connecting the status of moving objects in the SC, such as containers, trucks, goods, and storage capacity. Immediate collection and efficient monitoring of data associated with the physical objects is what enables smart logistics (Trappey et al., 2017a).

As the amount of bar codes, sensors, and RFID tags equipped to physical objects increases, so too will logistics and transportation companies' ability to monitor the movement of these objects in real time throughout the SC. Transportation management systems and IoT will be a core part of transportation and logistics industries in the future, and the IoT will heavily affect automobile services and transportation systems. An example includes improved sharing of under-utilized resources among vehicles through enhanced sensing, data processing, networking, and communication capabilities by tracking and monitoring the location of each vehicle and its movement and predicting the future location of the vehicle (Barreto et al., 2017).

5.1.1.5. Sensor technology. Sensor technology is becoming smarter every year; devices are created with the ability to share information on the internet with no human intervention. The performance and accuracy of these sensors is increasing incredibly fast, making a future with almost pervasive communication between sensors without human contact becoming a reality very quickly. With such a sensor system in place in manufacturing, it would be possible for workers to be warned and told the right course of action in case of issues in the process (Wang et al., 2017).

5.1.1.6. RFId. IoT enables control and automation of machining, lighting, heating, remote monitoring, and robotic vacuums. A key IoT technology is automatic identification technology, which turns objects into smart object (Zhong et al., 2017; Corches et al., 2021). One such technology is Radio-Frequency Identification (RFID), which is a wireless communications technology. RFID is a combination of sensors and tags that use wireless radio signals to identify objects with the purpose of enabling real-time monitoring through information exchange (Biswal et al., 2018; Ustundag and Tanyas, 2009). Examples include SC, logistics, warehouses, finished goods, work in progress, and raw materials, which can be tracked using the RFID technology (Trappey et al., 2017a). RFID enables full process and inventory transparency by tracking material flows in real time (Zhong et al., 2017). Production floors, distribution centers, retailers, and disposal/recycle stages are additional examples where RFID has been used to track different objects. The objects that are equipped with sensors gain smart sensing abilities, allowing them to interact and connect with other objects, which in turn generates loads of data (Zhong et al., 2017).

5.1.2. Cyber-Physical systems

Cyber-Physical Systems (CPS) can be defined as physical systems that are integrated by a computing and communication system, and such systems can monitor, coordinate, and control the operations of the physical system. CPS comprises a variety of networked agents that include control processing units, sensors, actuators, and communication devices (Barreto et al., 2017; Morella et al., 2020; Dafflon et al., 2021). CPS is considered a key component of the I4.0 paradigm, which serves to bridge the gap between the virtual and physical worlds (Y. Wang et al., 2017). As physical objects and software get intertwined in the CPS, interaction and information exchange between various components is facilitated, which is enabled by embedded systems, resulting in improved coordination between the physical objects and their associated computational elements or services. Furthermore, sensors are a big part of CPS, which is developed to include both physical inputs and outputs in the networked interactions, as well as computation capabilities and control algorithms (Zhong et al., 2017; Pandey et al., 2020; Bagula et al., 2021). Maslarić, Nikoličić and Mirčetić (2016) describe CPS as a network of social machines, in which electronic and mechanical components are linked with IT, allowing them to communicate within the network similarly to how social networks function.

As the availability and use of industrial CPS devices increases, new developments for better self-configuring automation systems with higher effectiveness could appear. These new developments have the ability to make radical changes to the manufacturing environment. In order to realize CPS for industrial automation, focus must be shifted towards integration of cloud technology, and IoSs that can support distributed systems rather than the traditional focus on specialism-based and monolithic methods (Harrison et al., 2016). CPS development over time has been through three phases. The first phase included RFID technologies that had the ability to identify individual objects. In the second phase, sensors and actuators had few additional functions available. The third phase of CPS includes sensors and actuators that, in addition to their normal functions, are able to store and analyze data while being compatible in the network (Y. Wang et al., 2017).

5.1.2.1. CPS Benefits. One of the functionalities provided by CPS include optimization and validation of designs using CAD or Virtual Reality (VR) by creating and analyzing, for example, the geometry and appearance of a system. Another example is CPS's ability to predict and analyze performance, behavior, and process efficiency in production with the purpose of finding the optimal parameters in the production process (Vanderroost et al., 2017b; Raji et al., 2021; Spieske and Birkel, 2021).

Tsuchiya et al. (2018a,b) mention several benefits associated with the implementation of CPS in manufacturing, such as reductions in waste and work in lean manufacturing, as well as improved maintenance through advanced fault detection, all of which makes CPS a key component of the I4.0 paradigm. The authors further explain that CPS is a facilitator for the implementation of vertical integration, allowing for real-time information sharing across various hierarchical levels in a way that far exceeds what current traditional Manufacturing Execution Systems can achieve. Dallasega et al. (2017) refer to high responsiveness, mass customization, and time efficient production system with reconfigurability as some of the main benefits of CPS, and IoT as well. Ding (2018) mentions increased robustness and flexibility of linkages in manufacturing, which helps in achieving cost reductions and energy savings through optimization of value chains. Furthermore, load time, delivery responsiveness, and counterfeit product detection can be improved by the CPS system through increased traceability and transparency in the distribution process.

5.1.2.2. Case with benefits. Fernández-Caramés et al. (2018) present the design and implementation of a cyber-physical system that was developed to automate different tasks in a workshop making pipes for ships. The goal was to improve the output of the production processes in the pipe workshop. Many of the processes were normally done manually by the operators of the case company, including paper forms that had to be filled and then later uploaded to the system. The proposed cyber-physical system could remove errors and bottlenecks in the process of filling and uploading paper forms manually by storing and modifying information using digital devices, clearly increasing productivity of the pipe workshop.

5.1.3. Augmented reality

Augmented Reality (AR) has potential to provide benefits to industrial companies in the fields of manufacturing, logistics, maintenance, and training. AR is described as information and work instructions displayed on wearable devices to support the workers in executing process steps. AR within logistics shows great potential in pick-by-vision, which can increase the effectiveness and speed of the picking processes for parts and products. Furthermore, AR can be utilized for integrating information directly into the work environment, thus supporting workers by reducing their cognitive load and improving performance of different operations (J. W. Strandhagen et al., 2017; Rejeb et al., 2020). Unlike I4.0-related technologies such as modularization, mobile computing, and CC that have matured in the market, AR is still maturing (Kamble et al., 2018; Bai et al., 2021). Through integration of other SC systems, the implementation of AR has the potential of improving inventory velocity or customization by enabling the SC systems to take orders and create supplier orders, picking, and shipping instructions immediately (Druehl et al., 2018; Cagliano et al., 2021).

5.1.4. Cloud computing

CC refers to the delivery of computational services via the internet through resources that are both scalable and visualized (Zhong et al., 2017; Li et al., 2020; Shukri et al., 2021). Toka (2013) defines CC as "an IT service model where computing services (both hardware and software) are delivered on-demand to customers over a self-service fashion, independent of device and location.".

5.1.4.1. Architectures. According to Toka (2013), cloud-based application can be accessed by customers through a browser, and all of the data can be stored on servers that are either located remotely or in-house. CC is composed of four deployment models, namely the

Table 7
Perceived Benefits of Cloud Computing.

Benefits	Source
Operational cost reduction	(Zhong et al. 2017) (Kamble et al. 2018) (Haverkort & Zimmermann 2017) (Fernández-Miranda et al., 2017) (Toka 2013) (Mustafee et al., 2021) Gunduz et al., 2021)
Elasticity	(Zhong et al. 2017)
Optimal resource utilization	(Zhong et al. 2017) (Toka 2013)
On demand manufacturing	(J. W. Strandhagen et al., 2017) (Dallasega et al. 2017) (Kaur & Kaur 2018) (Moradlou et al. 2018) (Toka 2013)
Optimize logistics	(J. W. Strandhagen et al., 2017) (Toka 2013)
Accessibility	(Kamble et al. 2018) (Toka 2013)
Agility and flexibility	(Kamble et al. 2018) (Haverkort & Zimmermann 2017) (Toka 2013) (Zhong et al. 2017) (Raji et al., 2021)
Improve system performance	(Kamble et al. 2018) (Toka 2013)
Increase efficiency	(Haverkort & Zimmermann 2017) (Toka 2013) (Tran-Dang and Kim, 2021)
Decentralized production	(Ma et al. 2017) (Bienhaus & Haddud 2018) (Ma et al. 2017) (Toka 2013)
Virtual inventory	(Moradlou et al. 2018) (Toka 2013)
Reduce Inventory	(Moradlou et al. 2018) (Toka 2013)
Traceability	(Ding 2018) (Toka 2013)
Forecasting and planning	(Toka 2013)

public cloud, private cloud, hybrid cloud, or community cloud. (Toka, 2013; Zhong et al., 2017; Sundarakani et al., 2019). A public cloud is designed for open use by the general public. This can be managed by a company and its partners and it is provided by an external cloud provider. A public cloud creates a comparative advantage compared to in-house systems, because companies will not have to handle maintenance or system setup. The costs of set-up when companies use a public cloud are low because of the application costs being covered by the third-party provider. Additionally, the cost of a public cloud is low, due to the pay per use principle (Toka, 2013). The private cloud is created by the individual organization and might be based on resources and infrastructure already present in the organization's local data center or on a new, separate infrastructure (Toka, 2013; Zhong et al., 2017). In both cases, the organization itself owns and operates the private cloud. Companies that need lower risk and higher security levels can use a private cloud instead (Toka, 2013). The hybrid cloud combines aspects of the private and public clouds (Zhong et al., 2017). These clouds are connected by either technology that is standardized or proprietary, which provides portability for data and applications. It is possible for companies to keep their private cloud and then use capacity from a public cloud when their own is fully used. This offers the companies greater flexibility and more data deployment options (Toka, 2013). Finally, the community cloud is when a group has similar needs and thus can use private clouds and work together in order to reach the same business goals. Management of the cloud can be done by one representative, or several cloud community members, or by a third party (Toka, 2013).

A number of different cloud service models can be used for communication, namely Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS) (Zhong et al., 2017). Data travels from one node to another through networking. Numerous production units, warehouses, stores, and customers are able to subscribe to these service models (Kaur & Kaur, 2018). IaaS is a platform that companies can use to rent servers, hardware, and/or storage space at a pay-per-use basis. The cloud provider offers raw storage, load balancers, firewalls, virtual or physical machines, and networks (Toka, 2013; Kaur & Kaur, 2018). PaaS is used for the development, testing, delivery, and management of software application, which is provided by on-demand services on the cloud such as a programming language execution environment, operating system, and data base (Kaur & Kaur, 2018). It is possible for companies to avoid the acquisition and management of hardware and software, and instead rent servers for using applications or developing new ones (Toka, 2013). SaaS provides software applications, typically via subscription on the internet and on demand (Kaur & Kaur, 2018). The cloud providers take care of security and software upgrading of the application and underlying infrastructure. While the users of the cloud are not responsible for the management of the cloud infrastructure and platform, they are able to control the deployed application and access the software on a browser or program interface (Toka, 2013).

According to Ding (2018), traceability and connection can be provided at a high level for both physical flows and information flows. This is enabled by embedded sensors that collect and record product process data and environmental data, allowing for real-time traceability and monitoring within the SC (Kaur & Kaur, 2018).

5.1.4.2. Cloud Computing Benefits. Some aspects that drive firms to use CC can be found in the literature. Toka (2013) confirms that CC facilitates collaboration between stakeholders in the SC, which suggests that CC can be an effective tool the SCM field. The author further presents different scenarios where CC can be applied in SCM, more specifically in forecasting and planning, sourcing and procurement, and logistics. According to Toka (2013), cloud-based platforms can improve the service levels of companies by coordinating retailers, suppliers, and distributors, and that improved service provides a great impact on demand forecasting. The entire SC is able to access cloud-based applications in real time. This means that the cloud platform can serve as a basis for creating accurate demand forecasts for SC partners based on analytics of sales data, which is collected via the internet, and, in turn, it has the potential to reduce bullwhip effects (Moreira et al., 2018).

Cloud-based platforms can also serve as a database that keeps data about suppliers, which will be a significant advantage for companies dealing with several suppliers. This database makes it possible for companies to better select suppliers based on their ability to satisfy customer requirements in terms of product specifications, delivery time, etc. (Toka, 2013; Moradlou et al., 2018; Raji et al., 2021). CC can also benefit companies' inventory, warehouse, and transportation management, due to its logistics tracking of multiple SC partners. An integrated cloud platform has the potential to streamline transportation and reduce inventory, leading to transportation cost savings. Cloud services do not need investment for software or hardware ownership, unlike common Enterprise Resource Planning (ERP) systems, because they are provided by public clouds through external providers. Hence, companies are able to reduce their operating costs. Moreover, the companies only have to pay per use when they use CC services, which minimizes their cost (Zhong et al., 2017). The cloud-based systems simplify the supply chain, since every part of the SC may be accessible through the same platform. That level of accessibility eliminates compatibility problems, provides easy connection, and enables SC information sharing among SC partners. This makes it possible for companies to reduce response time (ibid.).

Bodrow (2017) describes the cloud applications as being location-independent, thus providing agility to the entire SC, which allows companies to quickly enter new markets with new products and services, and thereby improve the companies' flexibility (Trappey et al., 2017a; Gunduz et al., 2021). Visibility and traceability will be improved by CC as it enables companies to observe SC events as they occur, thereby helping companies to coordinate their operations and manage different customers, while granting transparency of the system to the customer network (Bodrow, 2017). The author further states that real-time visibility of shipments and inventory can be provided by cloud-based systems and inventory routes can be optimized. CC has the potential to improve SC stakeholders' control and accuracy of their capacity (Zhong et al., 2017). To meet the demand of customers during peak periods, companies require enough capacity. Cloud technology makes it possible for companies to adjust their capacity to comply with the needs of customers, while scaling computing power depending on the fluctuations of demand (Toka, 2013). A CC platform provides flexibility that permits dynamic resource allocation in complex logistic systems and has the benefit of decreased delivery times and rapid response to customers (Trappey et al., 2017a; Zhong et al., 2017). The perceived benefits of CC found in the literature are presented in Table 7.

In SCs, CC is a low cost concept that can help facilitate I4.0 and upgrade provided services and technologies (Moreira et al., 2018).

5.1.5. Internet of Services

Using the Internet of Services (IoS), vendors can provide their services through the internet, which makes it possible for companies and private users to create and offer new kinds of value-added services or to combine already existing services (Hofmann & Rüsch, 2017). The authors give a different, broader definition of the term service as "a commercial transaction where one party grants temporary access to the resources of another party in order to perform a prescribed function and a related benefit. Resources may be human workforce and skills, technical systems, information, consumables, land and others." The IoS consists of four different parts: services, business models, participants, and infrastructure. The IoT gives customers access to different value-added services that are integrated and provided by several suppliers (Y. Wang et al., 2017; Cozmiuc and Petrisor, 2018). Maslarić, Nikoličić, and Mirčetić (2016) refer to IoS as both internal and cross-organizational services that are driven by CC and BD, with the users being different actors in the value chain. The rapid technological development of IoS is considered one of the main drivers for the fourth industrial revolution along with other technologies such as IoT, CPS, smart objects, and BD (J. W. Strandhagen et al., 2017). Furthermore, IoS is one of the technologies that will facilitate smart logistics processes and smart manufacturing (Bocken, 2016).

5.1.6. Big data analytics

The big data analytics (BDA) is an activity of managing a large amount of information. This technology is used when the amount of data can't be analyzed by one computer alone, when there is a continuous flow of information entering the system, and when the rate in which information is received is fast and variable (Bag et al., 2020; Ranjan, and Foropon, 2021). According to Bodrow (2017), Big Data (BD) is one of the primary enablers of I4.0. Furthermore, Fernández-Miranda et al. (2017) state that BD, in an I4.0 context, deals with the collection and comprehensive evaluation of data from a large variety of sources, such as customers, operations, and sales, and over time it will become a standard to support decision making and to coordinate operations at optimal cost and performance.

Data accessibility is increasing for many industries as the IoT is being pushed aggressively, which results in the BD issue. The data comes from a variety of channels, such as sensors, devices, networks, video files, audio files, log files, transactional applications, social media feeds, and the web (Zhong et al., 2017; Gupta et al., 2020). From these sources, data is gathered constantly and stored in a data warehouse. After being stored, the data is analyzed in order to discover patterns and to obtain knowledge to aid real-time decision making (Bienhaus & Haddud, 2018; Y. Wang et al., 2017; Oncioiu et al., 2019; Novak et al., 2021). Data can be characterized by the "5V"s, namely volume, velocity (speed of the data), variety (number of data types or sources), veracity (data source quality), and variability (data source inconsistency) (Molka-Danielsen et al., 2018).

New business opportunities will be opened up in the BD field because of the importance of information in I4.0 where each part of the value chain is connected (Bocken, 2016). Using data mining (DM), BDA is able to provide information that is both systematic and comprehensive, depending on the features of the 5Vs. DM is used extracting knowledge from BD that is collected from a variety of sources, and for identifying and analyzing patterns and rules in the data, which improves decision making (Y. Wang et al., 2017). According to Yan et al. (2017), defects in equipment design, product design, production processing, as well as health conditions of equipment, work habits of employees, habits and demands of customer, etc. are some of the information that DM can discover. Data collected can usually be referred to as either quantitative data, which is numeric data that can be measured and used for predictive models, or qualitative data, such as videos, pictures, or texts that are non-numeric (Fernández-Miranda, et al., 2017).

BD can be generated continuously from many sources, which increases the number of datasets and improves the quality of data and precision of analytics. The continuous gathering of data requires large scalable storage. Preservation of BD is very complicated due to the high velocity feature, which makes it impossible for those datasets to be analyzed with the traditional methods; therefore, new methodologies have been invented for analysis, capture, search, storage, sharing, visualization, and transfer to interpret the datasets

Table 8
Big Data Analytics benefits.

Perceived Benefits	Source
Increase competitiveness	(Xue et al., 2013b) (Bienhaus & Haddud 2018)
Improve productivity/ efficiency	(Fernández-Miranda et al., 2017) (Bocken 2016)(Haverkort & Zimmermann 2017) (Long et al. 2018) (Ding 2018) (Tran-Dang and Kim, 2021) (Brandín and Abrishami, 2021)
Drive agility	(Kamble et al. 2018) (Ding 2018) (Raji et al., 2021) (Bamakan et al., 2021) (Mrugalska and Ahmed, 2021) (Bhattacharya and Chatterjee, 2021)
Improve quality	(Oku et al. 2015)(Kamble et al. 2018) (Rai et al., 2021)
Reduce production cost	(Oku et al. 2015)(Fernández-Miranda et al., 2017)(Zheng & Wu 2017) (Kazancoglu et al., 2021) (Cagliano et al., 2021) (Gunduz et al., 2021)
Efficient decision-making	(J. W. Strandhagen et al., 2017)(Zheng & Wu 2017)(Bienhaus & Haddud 2018)(Ding 2018)(Molka-Danielsen et al. 2018) (Dallasega et al. 2018)
Improve demand forecasting	(J. W. Strandhagen et al., 2017)(Zheng & Wu 2017)(Long et al. 2018) (Ding 2018) (Ada et al., 2021)
Improve supply chain planning	(J. W. Strandhagen et al., 2017)(Trstenjak & Cosic 2017)
Improve transparency	(Zheng & Wu 2017)(Bienhaus & Haddud 2018)(Ding 2018) (Shayganmehr et al., 2021) (Brandín and Abrishami, 2021)
Improve traceability	(Bienhaus & Haddud 2018)(Ding 2018)
Increase flexibility	(Zheng & Wu 2017)(Ding 2018) (Bag et al., 2021a,b)
Real-time data	(Zheng & Wu 2017)(Bienhaus & Haddud 2018)(Trstenjak & Cosic 2017)(Ding 2018)(Y. Wang et al. 2017)
Predictive maintenance	(Haverkort & Zimmermann 2017) (Zheng & Wu 2017) (Long et al. 2018) (Ding 2018)(Fernández-Miranda et al., 2017)
Improve monitoring performance	(Ding 2018)
Identify and reduce waste	(Ding 2018)
Supplier evaluation	(Ding 2018)
Reduce safety stock	(Ding 2018)
Improve risk management	(Romero-Silva and de Leeuw, 2021) (Spieske and Birkel, 2021) (Pyun and Rha, 2021)

into actionable insights (Kang et al., 2016; Yan et al., 2017).

Data goes through a number of processing methods before it can be put to use. Some of those methods include analytics, management, visualization, and sharing. In analytics, hidden information is extracted from the data. Management refers the maintenance and management of the data. Visualization is the easy access of data. Sharing relates to the sharing of BD, while taking privacy and security into account (Fernández-Miranda, et al., 2017).

It is essential for manufacturing with plenty of data from operations and the shop floor to use advanced BDA to extract unknown correlations, patterns, customer preferences, and/or trends in the market (Zhong et al., 2017). Integration of the SC network can be facilitated by new methods in visualization and geo-analytics, which makes use of data generated externally to the company (Molka-Danielsen et al., 2018). The authors further point out that using the presentation of data for decision making and analysis is one of the greatest prospects of BD, in addition to the well-known fact that it refers to managing larger quantities of data from various sources.

5.1.6.1. Big Data Analytics Benefits. Big data and analytics have a range of benefits that can benefit the SC positively. An example includes the use of information regarding traffic, weather, and driver characteristics in order to improve logistics. BDA can also be used on manufacturing information from the company and each of its suppliers to improve delivery information that customers receive and to evaluate the performance of the suppliers (J. W. Strandhagen et al., 2017; Ding, 2018; Rai et al., 2021). Predictions can be made to facilitate production process and systems optimization based on experience and BD (Long et al., 2018). Another aspect of the predictive function of BDA is the support of predictive maintenance. Yan et al. (2017) confirms that BDA can enhance predictive maintenance, leading to benefits such as improved system performance and near zero downtime. Fernández-Miranda, et al. (2017) claim that factory floor machine failures can be avoided through the use of predictive maintenance with BDA, while reducing downtime by approximately 50% and increasing productivity by 20%. In their article, Zhong et al. (2017) state that customer satisfaction and engagement can be enhanced effectively by applying analytics to data regarding customer relationship management.

To summarize, BDA touches many SCM functions, such as demand forecasting, risk management, logistics planning, customer service, network optimization, supplier collaboration, and inventory management (Long et al., 2018; Zheng & Wu, 2017; Romero-Silva and de Leeuw, 2021). All of the perceived benefits of BD and BDA are presented in Table 8.

5.1.7. Artificial intelligence

Artificial intelligence (AI) can be described as intelligence for machines that are able to mimic, approximate, replicate, automate, and at some point improve upon human thinking (G. Li et al., 2017; Bag et al., 2020; Thiebes et al., 2021). AI has an essential role in I4.0 and supply chains by providing learning, reasoning, and acting (Asakura, 2016). Using AI technology, it is possible to minimize human involvement, since it enables data gathering from machines and products without human interference (J. W. Strandhagen et al., 2017; Kriebitz and Lutge, 2020). AI is able to support decision-making of complex processes through the analysis of large amounts of real-time data, highlighting possibilities, predicting lead times, and increasing profitability (Dossou & Nachidi, 2017; Bienhaus & Haddud, 2018; Sanders et al., 2019). AI technologies also enable automatic arrangement of production compositions, as well as real-time monitoring and control of manufacturing operations and production processes (Zhong et al., 2017; Oh, 2019). A branch of AI is Machine Learning (ML), which is used for making predictions based on large data sets. With its ability to recognize patterns, ML can draw knowledge from data independently. ML makes it possible to discover patterns in SC data by using algorithms to identify the most

Table 9
Perceived benefits of the DT.

Perceived Benefits of the DT	Source
Increased efficiency	(Andaluz 2017) (Rodič 2017)
Reduced downtimes	(Andaluz 2017) (Rodič 2017)
Increased productivity	(Andaluz 2017) (Rodič 2017) (Lugaresi and Matta, 2021)
Improved quality	(Andaluz 2017)(Ahuett-Garza & Kurfess 2018)
Improved training	(Rodič 2017) (Serrano-Ruiz et al., 2021)
Improved accuracy and capabilities	(Ahuett-Garza & Kurfess 2018)
Predictive maintenance	(Ahuett-Garza & Kurfess 2018) (Andaluz 2017) (Rodič 2017) Ivanov and Dolgui (2021)

influential factors to a supply network's success, while constantly learning in the process (Ahuett-Garza & Kurfess, 2018; Schütze et al., 2018). ML is used for gaining insights, finding solutions, and optimizing processes based on BD. Deep Learning (DL), is a recent trend of ML (Rødseth et al., 2017), which uses raw signals as input for the detection of patterns in simultaneous or complex processes. Some of the potential applications of DL include fault detection after failure occurrences, classification and pattern detection for health monitoring systems, and predictions of remaining useful life and future working conditions (Ahuett-Garza & Kurfess, 2018; Schütze et al., 2018).

5.1.7.1. Artificial Intelligence Benefits. Using sensors, it is possible for companies to use ML for support services and maintenance. Furthermore, machine data regarding energy consumption can be collected, while the AI technology is used for analysis of maintenance cycles, allowing for optimization in the following stage. Companies can also use machine learning to analyze operating data to discover when parts should be replaced, and the likelihood of part defects. Proactive maintenance can be conducted for preventing machine failures after the ML algorithms have been trained by BD (Ding, 2018; Radanliev et al., 2020). Applications of AI have the potential to have a great impact on both quality and productivity (J. W. Strandhagen et al., 2017; Cagliano et al., 2021).

5.1.8. Digital Twin

The Digital Twin (DT) concept uses simulation modelling for all product life cycle phases. When products are developed, they are first tested in a virtual environment in full detail, and in the following phases, information gathered from previous life cycle phases is used for optimization. Accurate predictions of maintenance and productivity can be made based on realistic data, combined with simulation models from design (Rodič, 2017). The author further defines DT as "the digital representation of a unique asset (product, machine, service, product service system or other intangible asset), that alters its properties, condition and behavior by means of models, information and data." In other words, DT creates virtual models to simulate the functionality of the physical objects. The sensor system provides the DT with data regarding the physical objects (Zhong et al., 2017; Ivanov and Dolgui, 2021; Aheleroff et al., 2021). Hence, DTs analyze, predict, and simulate various changes to get implications of the physical entities' correspondence and in that way achieve optimization throughout the whole production line and SC (Qi & Tao, 2018; Kaivo-Oja et al., 2020).

According to Rodič, (2017) the DT of a process has several potentials in an organization. The first is the in-line DT, which can help develop the skills of an operator through training on a virtual machine, thus removing the need for a dedicated training simulator. The second potential is for the DT to identify issues of its real machine counterpart through the use of advanced machine-learning, optimal control, and model-predictive control techniques. Such information allows for quick service of the machine, or it could be used for planning to compensate for performance decreases without the need to stop or slow down production.

5.1.8.1. Digital Twin Benefits. Process DT enhance the benefits of a Product DT as well as enable advanced scenarios in the area of SC (Andaluz, 2017; Ivanov and Dolgui, 2021; Ivanov and Dolgui 2021). A list of these benefits is shown in Table 9.

5.1.9. Additive manufacturing

Today, manufacturers are pursuing the production of customized products for each customer in order to augment their competitiveness. In the pursuit of producing mass customized products in lot sizes of one with the same unit cost as mass production, additive manufacturing (AM), also known as three-dimensional printing (3D Printing), is able to provide cost-efficiency, short lead times, and flexibility (Durão et al., 2017; Jermsittiparsert and Boonratanakittiphumi, 2019b; Gu et al., 2021). The term AM covers "a range of manufacturing processes that create three-dimensional objects through layer-by-layer deposition of material. The first of these processes originated in the 1980 s and was applied in rapid prototyping" (Srai et al., 2016; Sun et al., 2020). According to Moradlou et al. (2018), most manufacturers prefer to move or build their factories in regions that either have cheap labor, or are closer to markets, due to rapid changes in customer demand. Using a 3D printer is a simple and low-cost solution to this problem (Moradlou et al., 2018). Maslarić, Nikoličić, and Mirčetić, (2016) argue that it is possible to decentralize manufacturing facilities at any place with a demand for 3D printers, which is a major step toward further globalization. According to Kamble, Gunasekaran, and Gawankar (2018) and Moradlou et al. (2018), AM technology is one of the enablers of I4.0 due to its ability to produce customized products, and its ability to offer construction advantages, such as complex, lightweight designs. Furthermore, Chhetri et al. (2017) point out that it is in decentralized and flexible manufacturing that seeks to mass produce customized products that the value of AM manifests itself. Furthermore, it can result in reduced product lifecycle with just-in-place manufacturing, as well as energy optimization.

The current literature defines AM as "a digital technology for producing physical objects layer by layer from a three-dimensional

Table 10
Perceived Benefits of AM.

Perceived Benefits of AM	Source
Reduction in time to define technical specifications of products	(Murmura & Bravi 2018)(Moradlou et al. 2018)
Reduction in prototyping time	(Murmura & Bravi 2018)(Moradlou et al. 2018)
Reduction in production time	(Murmura & Bravi 2018)(Kamble et al. 2018)(Moradlou et al. 2018) (Srai et al. 2016)
Reduction in time to market	(Murmura & Bravi 2018) (Durão et al. 2017)
Reduction in lead time	(Kamble et al. 2018)(Moradlou et al. 2018) (Durão et al. 2017)
Reduction in cost of materials	(Murmura & Bravi 2018)(Durão et al. 2017)(Dallasega et al. 2018)
Reduction of inventory and unsold costs	(Murmura & Bravi 2018)(Kamble et al. 2018)(Moradlou et al. 2018) (Ding 2018) (Durão et al. 2017)
Reduction of cost	(Kusiak, 2018)(Moradlou et al. 2018) (Murmura & Bravi 2018) Durão et al. 2017) (He et al., 2021) (Bhattacharya and Chatterjee, 2021)
Reduction of labor costs	(Murmura & Bravi 2018)
Reduction in transportation	(Kamble et al. 2018)(Moradlou et al. 2018) (Bocken 2016)
Reduce waste	(Kamble et al. 2018)(Ding 2018)(Murmura & Bravi 2018)(Durão et al. 2017)(Chen & Lin 2017)(Ford & Despeisse 2016)(Dallasega et al. 2018)
Decentralized production	(Moradlou et al. 2018) (Murmura & Bravi 2018) (Durão et al. 2017) (Srai et al. 2016)
Energy saving	(Murmura & Bravi 2018)(Tuptuk & Hailes 2018) (Ding 2018)
Increased responsiveness	(Moradlou et al. 2018) (Durão et al. 2017) (Dev et al., 2021)
Increased flexibility	(Ding 2018)(Durão et al. 2017)
Creation of new business model: offer a virtual model – virtual inventory	(Murmura & Bravi 2018)(Moradlou et al. 2018) (Srai et al. 2016)
Creation of new products with complex geometries, increased performance and quality	(Murmura & Bravi 2018)(J. W. Strandhagen et al., 2017) (Kamble et al. 2018) (Kusiak, 2018) (Moradlou et al. 2018) (Ding 2018) (Durão et al. 2017) (Srai et al. 2016) (Shen et al., 2021)
Greater chance of internationalization	(Murmura & Bravi 2018)
Product customization	(Murmura & Bravi 2018)(J. W. Strandhagen et al., 2017)(Kamble et al. 2018)(Moradlou et al. 2018) (Bienhaus & Haddud 2018) (Ding 2018) (Durão et al. 2017) (Srai et al. 2016)(Dallasega et al. 2018)
Batch reduction	(J. W. Strandhagen et al., 2017) (Kamble et al. 2018) (Moradlou et al. 2018) (Ding 2018) (Durão et al. 2017)
On demand manufacturing	(Srai et al. 2016)
Reduction of environmental impact	(Murmura & Bravi 2018)(Ding 2018)(Murmura & Bravi 2018)(Srai et al. 2016) (Chen & Lin 2017)(Dallasega et al. 2018)

(3D) computer aided design (CAD) file rather than using traditional subtractive techniques, such as machining" (Moradlou et al., 2018). Chen and Lin (2017) describe the process of AM beginning with "the creation of a 3D CAD model of the product. The 3D CAD model is then transformed into an STL format file, which can be directly processed by the AM printing machine. Each slice of the STL file represents a two-dimensional (2D) layer of the product to be produced. These 2D layers are then sent to the AM machine one layer at a time.".

In the literature, AM and 3D printing are used as umbrella terms to reflect a range of related technologies (Nica, 2019) including direct metal laser sintering, selective laser sintering, stereolithography, fused deposition modelling, laminated object manufacturing, and inkjet bioprinting. All of these technologies produce the product one layer at a time, each layer on top of the previous, until the final product is complete, and then avoiding the need for parts and component assembly (Srai et al., 2016), which can provide benefits in the form of reduced costs, time, and quality issues related to the assembly process (Murmura & Bravi, 2018; Kamble et al., 2018; Moradlou et al., 2018; Ahuett-Garza & Kurfess, 2018; Chen & Lin, 2017). The AM technology also enables companies to create products from a variety of materials including plastics, metals, ceramics, glass etc. with input materials in the forms of either powders, filaments, liquids, or sheets (Chen & Lin, 2017; J. W. Strandhagen et al., 2017; Kamble et al., 2018).

5.1.9.1. Additive Manufacturing Benefits. The current literature highlights some general advantages in relation to the use of AM Technologies in the SC, as seen in Table 10. According to the majority of the literature, the AM technology has advantages superior to traditional manufacturing. Ford and Despeisse (2016), Chen and Lin (2017), Kamble, Gunasekaran, and Gawankar (2018) argue that the use of AM can reduce the amount of wasted material. Approximately 40% of the waste from traditional subtraction methods can be recycled, while 95% – 98% of waste material can be recycled using AM. Moreover, J. W. Strandhagen et al. (2017), Kamble, Gunasekaran, and Gawankar (2018), Moradlou et al. (2018), and Murmura and Bravi (2018) state that the use of AM working, according the pull principle, is able to produce customized products with reduced lead times, reduce the inventory levels of raw materials, eliminate finished goods inventory, and utilize the capacity more efficiently. Furthermore, Srai et al. (2016), and Dallasega et al. (2018) argue that customers and suppliers can join forces to design and manufacture exactly what the customer requires with low lead times and reduced material usage, leading to a more sustainable way of creating mass customized products through AM. Another sustainable effect of AM is extended product life, increased resource efficiency, and reconfigured value chain (Murmura & Bravi, 2018; Srai et al., 2016; Shen et al., 2021). Beyca et al. (2018) argue that AM can produce prototypes significantly faster than conventional techniques, while also being able to produce almost any shape that can be designed in a CAD software. However, the authors further argue that AM is limited in terms of dimensions when materials with low strength are used, such as powder materials and liquid polymers. That generally means large parts cannot be produced and the surface finish is not great, so post-production is needed. Finally, AM is not yet suited for mass production due to its low production speed compared to conventional production methods.

5.1.9.2. Decentralized production. One of the characteristics of I4.0 is decentralization. Decentralized production is also referred to as distributed manufacturing, and it can be described as specific facilities equipped with AM equipment/3D printers, located near the customers. According to Kamble, Gunasekaran, and Gawankar (2018) and Murmura and Bravi (2018), distributed manufacturing enables customers and companies to print products on demand from files sent across the globe, or they can print from a nearby supplier that provides the needed capabilities.

Decentralized production enables companies to print parts and components when they are needed, where they are needed, thus creating the potential for significant transportation and warehouse cost reductions. Among the benefits of reduced transportation is a reduction in the carbon footprint (Chen & Lin, 2017).

Durão et al. (2017) state that decentralized AM production creates essential advantages: improved decision making based on more accurate information from local conditions, greater responsiveness and flexibility, and improved efficiency and higher SC reliability. Moreover, demand unpredictability becomes much easier for the system to handle, and companies can have lower capital investment in each facility, lower shipping costs, and lower inventory-related costs (Kamble et al., 2018). Along with these benefits the production cost per unit is lower when using AM compared to traditional subtractive production methods, due to the fact that the traditional manufacturing methods have to produce utilizing economies of scale to reduce unit costs, while AM can produce single units with a lower overall production cost (Moradlou et al., 2018; Kamble et al., 2018). As a final result, the overall SC costs will be lower than those of traditional manufacturing SCs, from the reduced inventory costs and the reduced material use and waste of outdated products (Murmura & Bravi, 2018). Reduced inventory, cost efficiency, and shorter delivery times are some of the benefits that AM can provide low-volume manufacturers (Kamble et al., 2018).

5.1.10. Industrial robotics

Automation within factories will be enhanced, following the introduction of the new generations of low-cost industrial robots. Industrial robotics is the equipment used for automation in various industrial contexts. The equipment within manufacturing will become smarter through integration of sensors and software capabilities, while improving its communication both inside and outside of the factory (Kusiak, 2018). Industrial robots are becoming more advanced in the I4.0 context. This happens through improved communication between system entities, which benefits the production system in terms of improved responsiveness to robot failures, demand variability, etc. In general, some of the benefits associated with the implementation of robots are labor cost reductions, quality improvements, increased flexibility, cycle time reduction, and increased throughput rate (Müller et al., 2017).

5.1.11. Flexible automation

Robots that are able to perform tasks intelligently, while at the same time being flexible, versatile, collaborative, and safe, are referred to as flexible automation in the context of I4.0. It is not necessary for such robots to be isolated; therefore, workers can be integrated into the same workspace with the robot. With the help of smart sensors and human–machine interfaces, operators are able to collaborate with the robots (Bahrin et al., 2016). The automated guided vehicle (AGV) is an example of flexible automation in the form of flexible robotic vehicle that can improve operation efficiency (Ma et al., 2017). Furthermore, autonomy and sharing will be increased in manufacturing transportation both internally and externally to the factory through future developments in these autonomous vehicles and robotics, which could reduce costs and improve quality in production (Kusiak, 2018). Automation equipment such as robots, AGVs, and warehousing automation equipment are used in many industries for their ability to provide improved operation efficiency and quality control. While the equipment can provide those benefits, it is still limited to fairly simple tasks, leaving the more complex operations, such as assembly, to human operators. Furthermore, the adoption of robots can be risky due to the high investment costs, coupled with potentially low investment returns and risk of investment transformation failure (Ma et al., 2017). Similar to industrial robotics, some of the general benefits that can be gained through flexible automation are increased throughput rate, reduction in cycle time, improved quality, and higher flexibility (Müller et al., 2017).

5.1.12. Horizontal & vertical integration

The implementation of I4.0 requires both horizontal and vertical integration (Kamble et al., 2018; Bocken, 2016; Cozmiuc and Petrisor, 2018) and in a manufacturing world characterized by complete connectivity and digitization, manufacturers now have the option to integrate both vertically and horizontally.

According to a study by J. W. Strandhagen et al. (2017), one of the main features of I4.0 is vertical integration, which refers to in-factory integration of different IT systems at various hierarchical levels of the automation pyramid (Reitze et al., 2018; Halaška and Šperka, 2019). The integration starts at the shop floor level with sensors and actuators, goes through the manufacturing execution system, and further up to the enterprise resource planning level (Tsuchiya et al., 2018a).

The integration of several companies through the value networks that appear across and within the different companies is referred to as horizontal integration (Kamble et al., 2018). This will facilitate collaboration between corporations, allowing for more fluent flow of materials (J. W. Strandhagen et al., 2017; Reitze et al., 2018). Zheng & Wu (2017) argue that for companies to achieve horizontal integration, they need to establish a new generation of global value chain networks that are real-time optimized and enable transparency, offer a high level of flexibility to respond to problems immediately, and facilitate better optimization globally.

5.1.12.1. Horizontal and Vertical Integration Benefits. A smart SC in the horizontal integration of I4.0 creates greater transparency between manufacturers and suppliers through information sharing and improved forecasting (Zheng & Wu, 2017; Sun et al., 2020). Within I4.0, vertical integration will turn production plants into "reconfigurable factories" with highly flexible production lines that

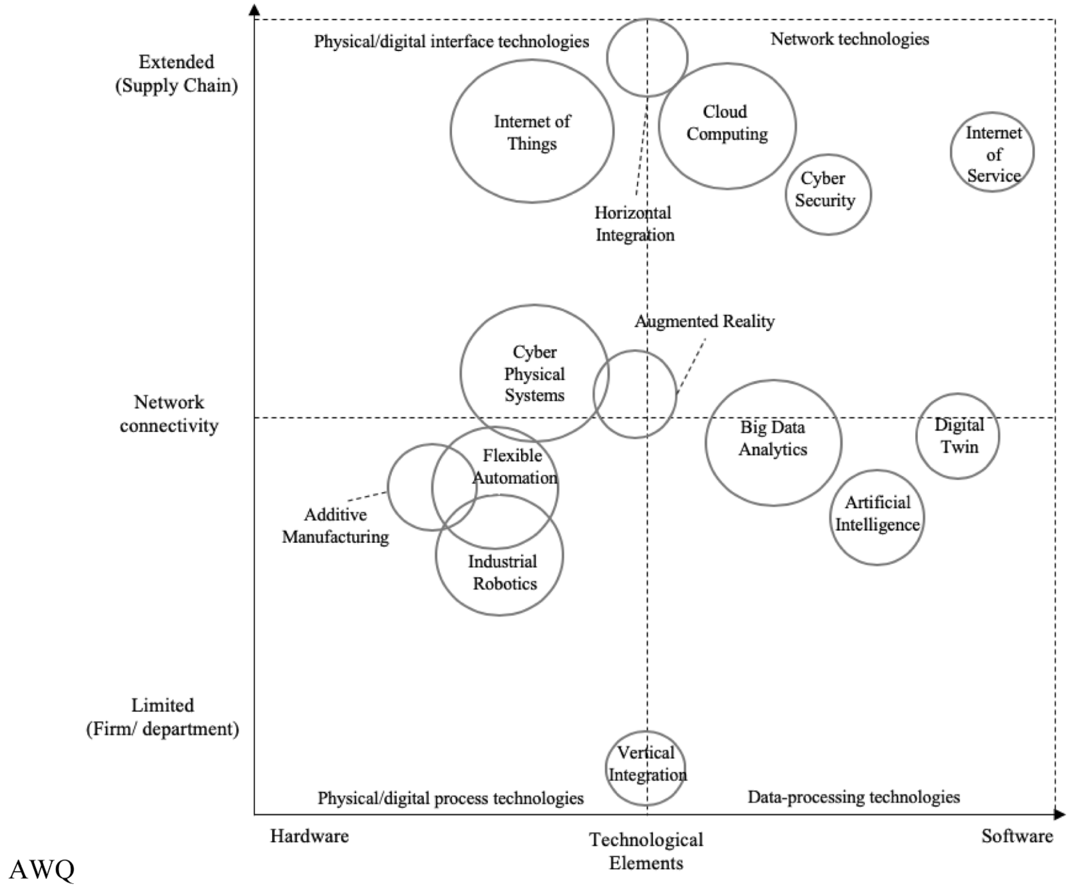

Fig. 4. Key enabling technologies clustered by the nature of their technological elements and network connectivity - Source: Adapted from (Govindan et al., 2018).

enable mass customization of personalized products for different demands (Ding, 2018). While the horizontal integration along the entire value creation network means that manufacturers provide access to companies' systems and databases resulting in greater efficiency in terms of costs and greater innovation, the advances in velocity and flexibility of product design can significantly improve all SC actors' responsiveness to personalized customer demands (Ding, 2018).

5.1.13. Cybersecurity

Cyberattacks can be a significant threat to future manufacturing companies as they can result in huge losses for cases in which operations in manufacturing must shut down. Furthermore, these attacks pose a serious threat to operator safety when the systems that monitor safety operation requirements are targeted. As a result of these threats, cybersecurity is required when implementing I4.0 technologies and concepts (Tsuchiya et al., 2018b; Pandey et al., 2020; Lallie et al., 2021). A common misconception of cybersecurity, one that has resulted in insecure systems, is that it is regarded as a characteristic instead of a design principle. Cybersecurity is not simply an add-on to the system that you can buy separately. Cybersecurity is a principle that must be taken into consideration in every single aspect of a system, and the security should be able to adapt to new threats. With increasing complexity of a system, as well as the ability to add or remove different subsystem modules, comes increased difficulty of having a secure system (Tuptuk & Hailes, 2018). In order to secure SCs from external threats, it is imperative that security developments and systems are based on a common approach that includes all members of the SC (Bienhaus & Haddud, 2018).

The digital network of the entire SC and the IT infrastructure internal to the company are taken into consideration in cybersecurity to guarantee that the data is safe. A number of procedures can be implemented to remove some cybersecurity-related uncertainty in I4.0 applications. Some examples of practices that can remove uncertainty include: having devices connected to the network only when necessary, keeping the industrial production network updated regularly, and using the private network of the company to store critical information. Furthermore, system failures and breaches can be prevented by giving device users and manufacturers security responsibility (Dalmarco & Barros, 2018).

These different technologies and concepts are divided into four major clusters, which will be discussed in the following subsection.

Table 11
Literature Findings.

	Physical/digital interface technologies			Network Technologies		Data-processing technologies			Physical/digital process technologies			Other	
Potential Benefits	Internet of Things	Cyber Physical Systems	Augmented reality	Cloud Computing	Internet of Service	Big Data Analytics	Artificial Intelligence	Digital Twin	Additive Manufacturing	Industrial robotics	Flexible Automation	Horizontal Integration	Vertical Integration
Improved risk management	X			X		X						X	X
Increased flexibility		X		X		X			X		X	X	X
Improved operator performance	X		X					X					
Improved productivity	X	X	X			X	X	X		X			
Enable products with complex geometrics									X				
Improved aftersales	X				X	X	X	X					
Improve demand forecasting	X			X		X						X	X
Improved traceability	X	X		X		X							
Improved maintenance	X	X			X	X	X	X					
Improved quality and robustness	X	X				X	X	X	X	X			
Reduced downtime	X	X		X		X							
Improved supplier evaluation						X							
Improved end to end visibility	X			X									
Improved customer satisfaction	X					X		X					
Reduced transportation lead time	X								X				
Improved responsiveness	X	X		X		X			X			X	X
Enhanced mass customization		X				X			X		X		
Reduced time to market	X	X	X					X	X				
Improved inventory picking process	X		X	X				X	X	X			
Improved decision making	X	X		X		X							
Improved efficiency	X	X				X		X		X			
Reduced logistics costs			X	X						X		X	X
Reduced inventory costs								X	X				
Reduced waste		X				X			X				
Reduced maintenance costs	X	X				X		X					
Reduced production costs			X			X		X	X	X			
Reduced energy consumption		X					X		X				
Reduced materials costs								X	X				
Increased sales	X				X	X							
Reduced inventory volume	X			X					X				
Reduced safety stock	X			X		X			X				
Improved utilization of resources	X			X			X						

5.1.14. *Key enabling technologies and concepts*

The technologies and concepts are a fundamental part of I4.0. Based on the reviewed articles there are two common trends characterizing these 14 enabling technologies and concepts. A clear trend in the literature is the integration between the digital and the physical world. The integration is possible due to improved performances and falling cost of hardware components due to Moore's law. On the other hand, the digital world is increasingly moving online, allowing network connectivity. This has allowed for the development of a chart, based on the dimensions of "technological elements" and "network connectivity" (Fig. 4). The x-axis maps the technologies regarding hardware and software, while the y-axis considers the connectivity of each technology, ranging from limited/local to extended/global, which is the potential of each technology to be applied at the SC level.

To get a better understanding of the relevance of these two dimensions shaping I4.0, a qualitative assessment of how the technologies would be located in the matrix has been made, based on definitions from the literature review.

From the matrix in Fig. 4, four different clusters can be identified:

1. **Physical/digital interface technologies:** Technologies/concepts that make it possible to gather information from the clients and suppliers in the supply chain.
2. **Network technologies:** Technologies/concepts that allow humans to gather data or connect other components.
3. **Data processing technologies:** Technologies/concepts that enable a better understanding of data.
4. **Physical/digital process technologies:** Automation Technologies/concepts that can improve the automation of a process.

Physical/digital interface technologies connect the reality of machines, products, and people with cyber space. This connection can be two-way in the sense that the physical world gets visualized in the digital world, which in turn provides feedback to the physical world. On the other hand, the connection might be a one-way connection as seen with visualization technologies, where the digital information is converted into a visual experience by using Augmented or Virtual reality.

Network technologies support the functionalities of other technologies online. CC (or the IoT) are economically effective ways of increasing on-site computational capabilities and storage capacity. Cybersecurity solutions guarantee a secure digital flow and integration across the production system and supply chain.

Data processing technologies are used to analyze data and provide information-driven input for decision making. Artificial intelligence provide insight into future system behavior based on existing datasets while learning to adapt to changes. Additionally, BDA can be performed in real time. All the technologies in the data processing cluster can both be operated locally or on a CC platform.

Physical/digital process technologies are technologies such as industrial robotics which are robots that are reprogrammable and collaborative with their human counterpart. Another technology is AM (also known as 3D printing), which has evolved from only being used in rapid prototyping to be used in the manufacturing of a wide array of products.

5.1.15. *Summary of findings*

In order to answer the first research question, the technologies are assigned according to their impact on different SC performance

Table 12
Responding companies.

No.	Company	Job Title
1	Company A	CEO
2	Company B	3D Production Specialist
3	Company C	Business Developer
4	Company D	Head of Corporate Logistics
5	Company E	Manufacturing manager
6	Company F	Chief Technology Architect
7	Company G	Senior Program Manager
8	Company H	Lead of IoT and I4.0
9	Company I	Director, Global Manufacturing Technology
10	Company J	Industrial PhD Student

measures found in the literature. The results in Table 11 present the mapping of I4.0 concepts on the four identified clusters of I4.0 technologies and concepts from Fig. 4. Based on the findings of the content analysis of all publications in the SLR, links between I4.0 technologies and concepts, and SC performance benefits were identified. Cybersecurity is not added to the matrix because it has no direct impact on supply chain performance.

From Table 11, it can be observed that both IoT and Big Data Analytics have mapped the highest number of potential benefits over other considered industry 4.0 technologies. In contrast, flexible automation and internet of services mapped the fewest number of potential benefits over other considered I4.0 technologies. Further, the physical/digital interface technologies are observed to present more potential benefits than other considered groupings. After reviewing the literature, the next section aims to present a synthesis of the data collected from the industry, followed by a framework development based on findings from literature and the industry.

6. Validation and framework development

The conducted SLR has demonstrated that a large number of publications examining I4.0 technologies and concepts and SC improvements have been produced by researchers and companies over the past seven years. Collectively, these articles may be viewed as having a number of strengths and limitations, many of which are relevant to future I4.0 technology and SC performance framework development.

6.1. Method

To assign I4.0 technologies and concepts to the proposed framework, the authors chose interviews with I4.0 experts as an appropriate method. This method is useful for exploring people's knowledge and experiences within the field of I4.0 and SC performance (Kitzinger, 1995).

Data triangulation has been used in order to reduce bias in data sources. As a result, datasets were collected at different times and from a variety of sources, including I4.0 specialists from different companies and industries and findings from the literature review (Karlsson, 2016). In practice, data triangulation means inputs from the Danish industry with experience in using I4.0 are used to validate and reinforce the concepts and findings from the literature review. Interviews and questionnaires, in some cases, act as a complement to the literature in those topics in which literature provided scarce information.

An abductive study method was used due to the difficulty of knowing how the companies would respond to the findings from the literature. The abductive method is used to build theory based on the literature and empirical findings and to avoid tunnel vision. Empirical data were collected to construct and validate the framework in the concept of I4.0 and SC performance. It was not possible to create a valid framework solely based on theory without comparing it to practical findings.

6.1.1. Pre-data collection

Before contacting I4.0 experts from the industry, one group discussion took place. At the group discussion, an expert on the topics of I4.0 and SCM was selected, who was an employee at a consulting company and university. The I4.0 technologies, concepts, and potential SC performance benefits identified in the literature were briefly explained to the expert. The objective of the meeting was for the expert to assign the technologies to the various SC performance benefits to gain a preemptive validation of the framework before contacting the industry for validation. The expert was allowed to talk about the task and to communicate his respective opinions with the two students facilitating the meeting. The results were afterwards integrated in the framework draft.

6.1.2. Data collection

After creating the framework draft, 58 I4.0 experts and company representatives from 43 different Danish companies were contacted to sign up for an interview to verify and provide input to the framework.

Interviews were held with selected companies in order to confirm or refute the connections between I4.0 technologies and concepts and potential SC performance benefits identified in the literature review. The selected companies are all working with I4.0 and are considered experienced within I4.0. The interviews with the company ranged from 30 min to 1 h, where open questions provided an insight into their company and technological maturity regarding manufacturing. These interviews were semi-structured with some

Table 13
Validated Matrix.

	Physical/digital interface technologies			Network Technologies		Data-processing technologies			Physical/digital process technologies			Other	
Potential Benefits	Internet of Things	Cyber Physical Systems	Augmented reality	Cloud Computing	Internet of Service	Big Data Analytics	Artificial Intelligence	Digital Twin	Additive Manufacturing	Industrial robotics	Flexible Automation	Horizontal Integration	Vertical Integration
Improved risk management	3.6			4.5	4.0	4.0		4.7			4.0	2.0	2.0
Increased flexibility		3.0		5.0	5.0	4.2	5.0	5.0	4.8		3.8	2.0	2.0
Improved operator performance	3.0		3.8					3.0		5.0	4.5		5.0
Improved productivity	3.2	2.0	3.3			3.3	3.5	4.0	4.7	3.8	4.7		
Enable products with complex geometrics			4.0	5.0	4.0	5.0	4.3		4.4				4.0
Improved aftersales	3.6			5.0	2.5	2.8	3.0	3.3				4.0	
Improve demand forecasting	3.8			5.0	4.0	4.6	4.3	5.0				4.0	
Improved traceability	4.3	3.5		5.0	5.0	1.3							
Improved maintenance	4.7	4.0		5.0	3.0	3.6	4.0	5.0				5.0	5.0
Improved quality and robustness	3.2	2.5		5.0	5.0	2.8	3.5	3.0	2.7	3.8			
Reduced downtime	4.3	3.5		3.5	4.0	3.6	4.5	5.0	5.0				
Improved supplier evaluation					4.0	4.2		4.5					
Improved end to end visibility	4.5			3.5	4.0	4.0	5.0	5.0				4.5	
Improved customer satisfaction	3.2		5.0	4.0		3.6	4.0	2.7					
Reduced transportation lead time	3.4						4.0		4.0			5.0	5.0
Improved responsiveness	3.8	3.5		3.0		3.0			3.8	5.0	5.0	5.0	5.0
Enhanced mass customization		2.5		5.0		3.0	5.0	5.0	3.7		2.5		
Reduced time to market	1.0	3.0	3.5	4.0	4.0		5.0	4.7	4.4		5.0	5.0	5.0
Improved inventory picking process	3.6		3.8	4.0		4.0	4.0	4.5	4.0	4.0	5.0		5.0
Improved decision making	4.2	3.5		3.0	5.0	4.2	4.0	4.7					
Improved efficiency	3.6	4.5	5.0	5.0	5.0	3.6	5.0	4.0		4.3			
Reduced logistics costs			2.5	2.5		4.0	4.0	4.5	4.0	3.0	4.0	4.0	4.0
Reduced inventory costs				5.0		4.5	5.0	3.3	3.8		4.0		
Reduced waste		1.5				2.5		5.0	4.3				
Reduced maintenance costs	2.8	3.0			5.0	3.5	5.0	3.7				4.0	
Reduced production costs	4.5		2.3	5.0	5.0	2.5		3.3	1.7	4.7	4.5		
Reduced energy consumption		2.5		5.0	5.0	5.0	5.0	5.0	3.0				
Reduced materials costs	4.0	4.0		5.0		4.0	4.0	3.3	2.0	4.0	4.0	4.0	
Increased sales	2.7			5.0	4.0	3.5	5.0	5.0	4.0		4.0		
Reduced inventory volume	3.3		4.0	3.0			5.0	4.5	4.5	4.0	4.0		
Reduced safety stock	3.3		4.0	3.0		3.4	5.0	4.5	4.0	4.0	4.0		
Improved utilization of resources	3.4			3.0		4.5	3.5	4.0	4.0	4.0	4.5	4.0	4.0

fixed questions and some customized. The respondents' companies are from Danish manufacturing industries, including Consulting, Industrial Communication, Manufacturing, Wind power, Pharmaceutical, and Logistics. A list of the responding companies is displayed in Table 12.

The interviews validated the findings from the literature review. An interview guide, including the matrix from Table 11 and relevant questions that should be covered, was developed. However, during the interview it was possible for participants to digress and open up for new ideas to be discussed.

The semi-structured interview had some fixed questions that allowed each technology and concept to have sufficient background to give a proper qualitative score. The companies and I4.0 experts were asked to select whether or not they agreed with the identified connections between technologies and concepts, and SC performance improvements, and to rate the impact of the technologies and concepts on the related SC benefits. The preferred outcome of the interviews was to get an overview of the industries and what SC benefits they believe I4.0 technologies and concepts can bring to a supply chain. Because no rigid definition of I4.0 exists, interviewees had different perceptions of its meaning. Hence, to overcome this problem, questions regarding the concept of I4.0 were not asked; rather, the focus was placed on the specific I4.0 technologies and concepts identified in the literature. It was important that the respondents understood the meaning of the interview; therefore, a short description of the purpose of the work was always included.

Most of the contacted companies did not have the time for an interview, and to make sure to get as many answers as possible to increase the validity of the framework, a survey containing the findings from the literature was made. The companies had to answer if they had any experience within the identified technologies and concepts and to rate their impact on the identified SC performance benefits.

After the companies gave feedback to the matrix, their answers were collected, and an average company rating was calculated for each I4.0 technology and SC benefit link. All links that received an average rating of less than 4, and those that were not found in the literature, were removed from the final validated matrix as depicted in Table 13.

6.2. Company answers

Due to a Non-Disclosure Agreement (NDA), some of the companies did not want to share how they were using I4.0, but companies A, B, D, and E have provided some examples of how they benefit from I4.0.

6.2.1. Company D

Company D, a worldwide logistics company, has tested the use of AR. Their warehouse employees have been equipped with AR smart glasses, which allows them to identify the ideal path for order collection. This is enabled by a real-time identification feature and it reduces inventory time. Furthermore, the smart glasses are able to scan the packages, so it is no longer necessary for the workers to scan the barcodes on packages. Employees can also be supported by image recognition software, which allows them to see if they are picking from the right location. Additionally, Company D states that enhanced image recognition has enabled them to monitor every step in the process, improve their quality control, and improve the assembly process through more efficient fault detection. The use of

AR as an interactive guide has reduced training costs in addition to the average time it takes employees to perform a task. AR has replaced the need for a physical bill of material (BOM) or picking list because it allows the employees to see the BOM or picking list on a heads-up display with step-by-step instructions on how to most efficiently execute a certain task.

Company D uses BDA for a variety of reasons, including optimization of resource consumption, improved decision making, and improved performance and quality of processes. Furthermore, the planning reliability can be improved through BD techniques, which improves the ability for DHL to match demand with the resources that are available. Company D also uses BDA for precise segmentation of customers, increasing the loyalty of customers, and improving customer service.

6.2.2. Company B

Company B is a 3D printing company located in Kolding. An interview was conducted with their 3D production specialist. Company B described AM technology as a complementary manufacturing method, which is useful only in very specific contexts; hence, they do not consider it to be a substitute for traditional manufacturing methods. This is because it simply is not economical to produce all products on a 3D printer. In terms of quality, Company B states that parts produced using AM have almost the same quality as those made through conventional means; however, when very tight tolerances are required, traditional manufacturing outcompetes AM. Furthermore, they consider it inevitable that 3D printing will become a go-to method for on-demand spare part manufacturing as the 3D printing costs decrease over time. Company B also highlighted the advantage of AM for creating highly customized and complex products, and how, most likely, it will be used in the future instead of conventional techniques. While Company B noted that the cost of materials can be reduced when using AM, resulting in less material waste in production, they also made it clear that in many cases the materials used specifically for AM are extremely expensive.

6.2.3. Company E

With the purpose of reducing costly downtime of their products, Company E includes a way to implement predictive maintenance into their products. Companies that offer products with a predictive maintenance strategy are able to utilize their most important machines to the fullest, extending their service life. This is done through the detection of condition variation in the operating fluid at an early stage, and it serves as a basis for removing or minimizing unplanned downtime of the system, thus significantly lowering costs. It functions in a way where estimations of the remaining service life of a product sold by Company E can be estimated immediately after variations in the condition is detected, after which more controlled production can continue. At the same time, orders can be sent for spare parts, and maintenance can be scheduled for the product at low cost.

6.2.4. Company A

Company A provides IoT solutions to companies. Companies can improve the visibility of their SC by using the cloud-based management solutions and IoT products from trusted providers. The improved visibility increases the efficiency of the companies, and, by having assets available without any delays, these companies will be able to complete even more jobs.

6.3. Validity and reliability

With the purpose of improving the confidence in the findings and reducing method variance, triangulation was used in the form of multiple measurement methods, including both qualitative and quantitative methods (Karlsson, 2016). The methods used include interviews conducted with different industry experts, as well as a survey. The validity of the work and proposed framework is ensured through a continuous review of the connection between the purpose, research questions, and methodology. Most interviews were recorded, and notes were taken during all interviews.

This study considers the effect of identified I4.0 components on SC performance in selected companies and the literature, and to some extent, the results are in a framework that can be generalizable to other companies. In order to create a fully generalizable framework, more and smaller firms within the industry need to be studied. Due to the time constraint, it was difficult to reach a wider set of companies. But it can be argued that the company respondents to the interviews and questionnaires are sufficient because they are advanced with their use of I4.0 technologies and concepts.

6.4. Discussion of validation

In this subsection, the identified benefits related to the use of different I4.0 technologies and concepts are discussed. The results of the SLR are compared with the findings of the questionnaires and interviews that were conducted with different companies, and short examples of how some of the I4.0 technologies or concepts are related to the different benefits are given.

6.4.1. Improved risk management

The technologies and concepts that have been identified to improve risk management are the IoT, BDA, CC, and vertical and horizontal integration. The increased transparency in the SC that can be gained from implementing all of these technologies and concepts can improve risk management. According to the industry responses, CC, IoS, BDA, DT, and flexible automation were all rated at or higher than 4 on average.

6.4.2. Increased flexibility

CPS, CC, BDA, AM, flexible automation, and horizontal and vertical integration all have an influence on flexibility according to the literature. As an example, AM can increase the flexibility of production due to the fact that it can produce almost any product designed in a CAD file (Moradlou et al., 2018). CC can also improve flexibility due to its feature of location-independency, which provides agility and flexibility to the SC (Bodrow, 2017; Raji et al., 2021). CC, IoS, BDA, AI, DT, and AM, were all rated 4 or higher on average.

6.4.3. Improved operator performance

In the literature, IoT, AR, and DT have the capacity to improve operator performance. As an example, AR can be utilized for integrating information directly into the work environment, thus supporting workers by reducing their cognitive load and improving performance of different operations (J. W. Strandhagen et al., 2017). Using the IoT and RFID, incoming products or raw materials can send assembly instructions and other useful information directly to an operator, improving their performance, and enabling highly individualized mass production (Weyer et al., 2015a; Brandín and Abrishami, 2021). Using an in-line DT, an operator can receive training on a virtual machine without the need for a dedicated trainer or simulator (Rodič, 2017). The results from the industry responses show that, DT, industrial robotics, flexible automation, and vertical integration have average or above connection with the improved operator performance benefit with average scores above 4.

6.4.4. Improved productivity

IoT, CPS, AR, BDA, AI, DT, and industrial robotics all have the potential to impact productivity positively according to the literature. Examples include AR that can display information in the visual field of employees, or BDA, where manufacturers can find new information and identify patterns that can help them improve processes and identify variables that affect production (Consoli, 2018). The industry rated DT, AM, and flexible automation at or above 4.

6.4.5. Enable products with complex geometrics

The AM technology is the only technology mentioned in the literature that enables the production of products with complex geometrics. Due to the way that AM produces products, it has more freedom in terms of geometry and shape, and it allows for the development of products that require more simple assemblies and a smaller number of different parts and materials. The entire life cycle of the product and its required materials benefit from AM's ability to produce more complex products (Ford & Despeisse, 2016). The industry, however, gave average scores at or above 4 to AR, CC, IoS, BDA, AI, AM, and vertical integration.

6.4.6. Improved aftersales

IoT, IoS, BDA, AI, and DT are all able to improve aftersales according to the literature. An example here is the use of IoT, BD, and AI that can make products smart enough to predict user needs and usage patterns. This is relevant in terms of aftersales where these products can be used for predictive maintenance (Anon, 2018). According to the industry, CC and horizontal integration have high impacts aftersales with scores at or above 4.

6.4.7. Improved demand forecasting

According to the literature, IoT, CC, BDA, horizontal integration, and vertical integration can have the related benefit of improved demand forecasting. The increased collection of data from customers and the analytics of these data can help improve the accuracy of demand forecasting (Strandhagen et al., 2017; Long et al., 2018; Ding, 2018; Ada et al., 2021). With cloud-based platforms, coordination in the SC can be improved, which will have a positive impact on demand forecasting. The cloud platform can collect sales data and perform basic analytics in order to make statistical demand forecasts with high accuracy (Toka, 2013). The findings from the industry show that, CC, IoS, BDA, AI, DT, and horizontal integration have high impacts on improving demand forecasting, all of which were rated 4 or higher.

6.4.8. Improved traceability

When traceability in the SC is improved it is possible to detect and remove unnecessary steps, while increasing efficiency of practices in the supply chain. IoT, CPS, CC, and BDA have the potential to improve traceability according to the literature. Common for all of the technologies and concepts is how embedded sensors collect relevant production process data, as well as environmental data, which allows for real-time traceability within the SC (Kaur & Kaur, 2018). The following technologies and concepts were given average scores at or above 4 by the industry: IoT, CC, and IoS.

6.4.9. Improved maintenance

In relation to I4.0, maintenance is mainly improved through predictive and automatic maintenance. The technologies and concepts that were identified in the literature to improve maintenance are IoT, CPS, IoS, BDA, AI, and DT. Following are some examples of how different technologies and concepts improve maintenance: In CPS, advanced fault detection can improve maintenance (Tsuchiya et al., 2018a,b). In relation to BD, when advanced analytics are used in predictive maintenance programs, it is possible to avoid machine failures (Fernández-Miranda, et al., 2017). In relation to DT, when simulation models from design are combined with real life data, it is possible to accurately predict productivity and maintenance based on realistic data (Rodič, 2017). AI can be used in conjunction with sensors to analyze maintenance cycles in order to optimize them in the following stage (Ding, 2018). The industry rated IoT, CPS, CC, AI, DT, horizontal integration, and vertical integration 4 or higher.

6.4.10. Improved quality and robustness

IoT, CPS, BDA, AI, DT, AM, and industrial robotics were found in the literature to improve quality and robustness. Using IoT and applying analytics to the sensor data allows manufacturers to sense and predict variation in output. In a networked manufacturing environment such as a CPS, the output variation of a machine can be communicated to downstream equipment, which is able to automatically adjust itself (Hitmar, 2014). Another example is the DT which, through sensors that are embedded into a machine, collects information that it analyzes in order to continuously improve the future quality of products (Rodič, 2017). According to industry, CC, IoS, have impacts, all with scores at or above 4.

6.4.11. Reduced downtime

According to the literature, IoT, CPS, CC, and BDA have the potential to reduce downtime. For example, it is possible to reduce downtime by approximately 50% through the use of advanced analytics, which makes it possible for companies to avoid factory floor machine failures (Fernández-Miranda et al., 2017). The industry rated IoT, IoS, AI, DT, and AM, 4 or higher.

6.4.12. Improved supplier evaluation

BDA is the only technology found in the literature that can improve supplier evaluation. When BD is collected from the suppliers, it can be analyzed in order to better evaluate the performance of the suppliers (Ding, 2018). The industry, however, rated IoS, BDA, and DT, above 4, and thus consider these to have a high impact on supplier evaluation.

6.4.13. Improved end to end visibility

According to the literature, IoT, CC, and BDA (Pyun and Rha, 2021) can improve end-to-end visibility. A good example of improved end-to-end visibility using I4.0 technology, is IoT, which can provide object visibility using real-time resource tracking, where a resource can be tracked throughout the SC using sensor equipment (Dweekat et al., 2017). CC makes the information accessible in real-time to the company (Bodrow, 2017), and along with IoT, this enables end-to-end visibility. The industry rated IoT, IoS, BDA, AI, DT, and horizontal integration 4 or higher.

6.4.14. Improved customer satisfaction

IoT, BDA, and DT can improve customer satisfaction according to the literature. IoT can improve customer relationships and allow for real-time incorporation of customer needs (Trappey et al., 2017b; Barreto et al., 2017). Regarding BD, if customer relationship management data is included in the BDA, customer engagement and satisfaction can be enhanced (Fernández-Miranda et al., 2017). The industry rated AR, CC, and AI 4 or higher.

6.4.15. Reduced transportation lead time

In the literature, IoT and AM have the capacity to reduce transportation lead time. As an example, the AM technology allows for decentralized production, which brings companies closer to the customers. This is especially useful for the production of spare parts or tools, which can benefit from the significantly shorter transportation lead time (Chen & Lin, 2017). According to industry responses, AI, AM, horizontal integration, and vertical integration all have a large impact on reducing transportation lead time, being rated at 4 or above on average.

6.4.16. Improved responsiveness

Responsiveness refers to the ability of a SC to respond to shifting market demands or to specific customer demands in a timely manner. Improving responsiveness requires a flexibility that often comes at the cost of reduced efficiency. IoT, CPS, CC, BDA, AM, horizontal integration, and vertical integration were found to improve responsiveness in the literature. The increased traceability and transparency that IoT and CPS provide can improve responsiveness (Dallasega et al., 2017); Ding, 2018; Zahedi et al., 2021). Another example is AM, which, when used in decentralized production, can improve responsiveness simply by being closer to the customers (Durão et al., 2017). The industry rated industrial robots, flexible automation, horizontal integration, and vertical integration at or higher than 4.

6.4.17. Enhanced mass customization

According to the literature, CPS, BDA, AM, and flexible automation can enhance mass customization. As an example, using BDA it is possible for manufacturers to deeply analyze their processes in order to identify areas where production can be postponed, enabling greater customization in the manufacturing process (Consoli, 2018). The industry rated CC, AI, and DT 4 or higher.

6.4.18. Reduced time to market

The technologies and concepts that have been identified to reduce the time to market are IoT, CPS, AR, DT, and AM. Using AR validation techniques, it has been possible for some companies to reduce their time to market by reducing the amount of physical prototypes needed for production planning (Steinhaeusser & Reinhart, 2017). AM can also reduce time to define technical specifications of products, and reduce prototyping time, thus reducing time to market (Ford & Despeisse, 2016; Sawangwong and Chaopaisarn, 2021). CC, IoS, AI, DT, AM, flexible automation, horizontal integration, and vertical integration were rated 4 or higher by the industry.

6.4.19. Improved inventory picking process

In the literature, IoT, AR, CC, DT, AM, and industrial robotics can improve the inventory picking process. AR has the potential to improve the inventory picking process, using pick-by-vision eyewear, which stimulates the operator's senses in a way that can increase the speed and effectiveness of picking parts and products (J. W. Strandhagen et al., 2017). AM can reduce the need for a picking process entirely when used as on-demand production that utilizes a virtual inventory instead of an actual inventory. According to the industry, CC, BDA, AI, DT, AM, industrial robotics, flexible automation, and vertical integration can improve the inventory picking process, rating them at least 4 or higher on average.

6.4.20. Improved decision making

The technologies and concepts that have been identified in the literature to improve decision making are IoT, CPS, CC, and BDA. These technologies and concepts can improve decision making by providing real-time information accessibility, sharing, and monitoring. When real-time information is provided, issues can be detected as they happen and decisions can be made very quickly (Trappey et al., 2017a; Strandhagen et al., 2017; Bienhaus & Haddud, 2018; Ding, 2018; Molka-Danielsen et al., 2018; Dallasega et al., 2018). IoT, IoS, BDA, AI, and DT, were rated 4 or higher on average by the industry.

6.4.21. Improved efficiency

IoT, CPS, BDA, DT, and industrial robotics were identified in the literature to improve efficiency. D. Li et al. (2017) present a framework for smart manufacturing that includes machines, conveyors, or AGVs, smart products and the cloud, all of which communicate through networks. By using BD feedback for intelligent evaluation and control algorithms, global coordination can be facilitated with the purpose of increasing efficiency and load-balance that are at risk of being impaired by differing performances of agents in the system. According to the responses from the industry, CPS, AR, CC, IoS, AI, DT, and industrial robotics, were all rated 4 or higher on average.

6.4.22. Reduced logistics costs

According to the literature, AR, CC, industrial robotics, horizontal integration, and vertical integration can all help in reducing logistics costs. Industrial robots can improve operation efficiency at a warehouse, for example, by using AGVs and other robotic warehousing equipment (Ma et al., 2017). CC can reduce inventory and costs of transportation through the implementation of an integrated cloud platform. Overall, the management of inventory, warehouse, and transportation can be improved through tracking the logistics of SC partners (Zhong et al., 2017). BDA, AI, DT, AM, flexible automation, horizontal integration, and vertical integration were rated 4 or higher by the industry.

6.4.23. Reduced inventory costs

In the literature, it was found that DT and AM can reduce inventory costs. AM can reduce the costs of inventory by reducing the overall inventory levels through decentralized production (Moradlou et al., 2018; Kamble et al., 2018; J. W. Strandhagen et al., 2017; Murmura & Bravi, 2018; Ho et al., 2021). DT can optimize spare part inventory and reduce the related costs by tracking the life cycles of machines in a digital journal and determining when there is a need for spare parts (Deloitte, 2017). The industry rated CC, BDA, AI, and flexible automation at 4 or higher on average.

6.4.24. Reduced waste

It was identified in the literature that CPS, BDA, and AM can reduce waste. An example is how AM, as the name suggests, only adds material and does not subtract material from a workpiece, which reduces material waste. Furthermore, 95% − 98% of waste material can be reused for AM (Chen & Lin, 2017; Ford & Despeisse, 2016; Kamble et al., 2018). According to the industry, DT and AM can have a high impact on reducing waste, and they were both rated at 4 or higher.

6.4.25. Reduced maintenance costs

IoT, CPS, CC, BDA, and DT can reduce maintenance costs according to the literature. IoT is able to reduce maintenance costs and improve reliability through continuous monitoring and analysis. BDA can drive predictive analytics as well as analysis of historical data, which can be utilized by manufacturers for scheduling predictive maintenance, and in turn reduce costs of maintenance (Manyika et al., 2013; Kazancoglu et al., 2021). The industry rated IoS, AI, and horizontal integration at 4 or higher.

6.4.26. Reduced production costs

According to the literature, AR, BDA, DT, AM, and industrial robotics can reduce production costs. An example is how DT can

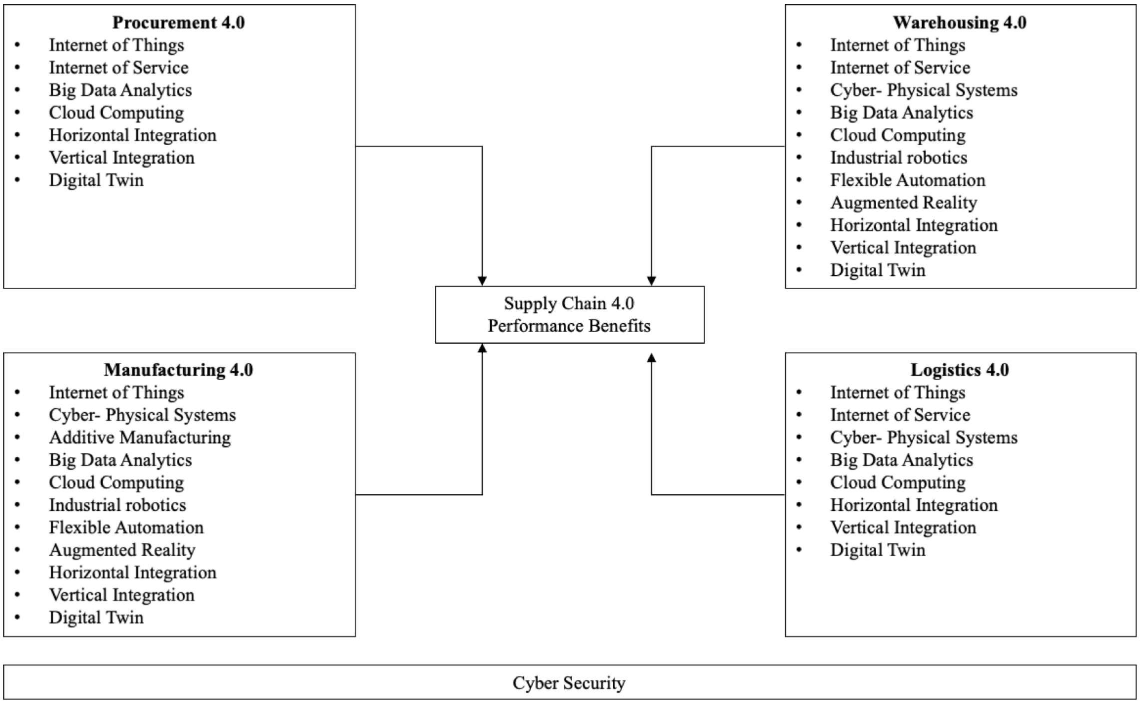

Fig. 5. Supply Chain 4.0 Performance Framework.

reduce production costs by improving product design and engineering change execution, and performance of manufacturing equipment, and by reducing operations and process variability (Deloitte, 2017; Bamunuarachchi et al., 2021). CC, IoS, and flexible automation were rated 4 or higher on average by the industry.

6.4.27. *Reduced energy consumption*

The technologies and concepts that have been identified in the literature to reduce energy consumption are CPS, AI, and AM. CPS increases robustness and flexibility of linkages in production, which in turn can facilitate energy consumption reduction through optimization of value chains. Furthermore, AI can be used in conjunction with sensors measure the energy consumption of individual machines, and then optimize in the following stage (Ding, 2018). CC, IoS, BDA, AI, and DT were rated 4 or higher on average by the industry.

6.4.28. *Reduced materials costs*

According to the literature, DT and AM can reduce materials costs. The cost of materials can be reduced using AM already in the design phase, due to the fact that AM can produce almost any shape, potentially reducing material usage (Srai et al., 2016; Dallasega et al., 2018; Murmura & Bravi, 2018; Sawangwong and Chaopaisarn, 2021). The industry rated IoT, CPS, CC, BDA, AI, industrial robotics, flexible automation, and horizontal integration at 4 or higher. One of the interviewed companies noted that some of the materials used for AM were significantly more expensive than materials used for conventional production methods, so while the material usage may be lower when using AM, the total material cost may be higher, depending on what material is used.

6.4.29. *Increased sales*

IoT, IoS, and BDA were identified in the literature to increase sales. IoT allows for real-time incorporation of customer needs, which can increase sales when, for example, the company provides a selection of products that is more in line with the requirements of the customers (Barreto et al., 2017). BD collection and analytics are some of the prerequisites for the real-time incorporation of customer needs that can increase sales (Zhong et al., 2017). The technologies and concepts that were rated 4 or higher by the industry are CC, IoS, AI, DT, AM, and flexible automation.

6.4.30. *Reduced inventory volume*

In the literature, IoT, CC, and AM have been identified to reduce inventory volume. An example of reduced inventory volume from the industry is apparent in the case of Wal-Mart and Procter & Gamble. These companies were able to reduce their inventory levels by 70% using RFID technologies, which can be used in an IoT (Majeed & Rupasinghe, 2017; Ekren et al., 2021). According to the pull principle, using AM allows for the production of customized products with reduced raw materials inventory, and it reduces or eliminates finished goods inventory (J. W. Strandhagen et al., 2017; Kamble, Gunasekaran, and Gawankar, 2018; Moradlou et al., 2018; Murmura and Bravi, 2018). The industry, however, rated AR, AI, DT, AM, industrial robotics, and flexible automation 4 or higher.

6.4.31. Reduced safety stock

IoT, CC, BDA, and AM can facilitate reduction of safety stock according to the literature. CC can reduce safety stock levels through improved coordination of retailers, suppliers, and distributors. This can reduce bullwhip effects, leading to reduced inventory levels, including reduced safety stock levels (Toka, 2013). Another example is AM, which can reduce safety stock levels when used as decentralized production (Moradlou et al., 2018; J. W. Strandhagen et al., 2017; Kamble et al., 2018; Murmura & Bravi, 2018). The industry rated AR, AI, DT, AM, industrial robotics, and flexible automation 4 or higher on average.

6.4.32. Improved utilization of resources

According to the literature, IoT, CC, and AI can improve utilization of resource. An example includes using IoT for improved sharing of underutilized resources among vehicles through enhanced sensing, data processing, networking, and communication capabilities by tracking and monitoring the location of each vehicle and its movement and predicting the future location of the vehicle (Barreto et al., 2017). BDA, DT, AM, industrial robotics, flexible automation, horizontal integration, and vertical integration were all rated 4 or higher by the industry.

6.4.33. Validation summary

When the literature findings are compared with the industry answers, a huge gap is found. In many cases, a link identified in the literature receives a low rating by the industry, while in other cases, the industry finds a large impact by a technology/concept on a SC benefit, which the literature has not discussed. Many benefits were identified in the literature that the industry gave low scores on average, mainly from IoT, BDA, CPS, and CC. This can in part be explained by the fact that the companies may not have experience in gaining these benefits from the implementation of said technologies and concepts. Furthermore, for a number of the technologies and concepts, only a few related SC benefits were identified in the literature, while the industry noted large impacts on many additional SC benefits. This was especially evident for AI, DT, flexible automation, and IoS.

7. Framework and discussion

The following framework is the result of a systematic literature review, a group discussion, followed by a validation from 10 companies. The proposed I4.0 and SC performance framework answers the first RQ, and it can be used within supply optimization activities as a supportive tool for those companies who wish to implement I4.0 technologies and concepts, but who do not yet know the potential benefits that the different technologies and concepts may have on their SC performance.

I4.0 technologies and concepts with impact on SC performance are grouped into a comprehensive framework. The framework in Fig. 5 gives an overview of I4.0 technologies and concepts that can be used to improve different functions of the SC, namely procurement, manufacturing, warehousing, and logistics, allowing practitioners to better decide what I4.0 technologies and concepts to focus on implementing.

Regardless of the sector, cooperation between the different functions involved in the SC is necessary. When each function is digitalized through I4.0 technologies and concepts, they are transformed into 4.0. The procurement function, which is in charge of all processes related to the purchase of goods or services from suppliers, is transformed into the Procurement 4.0 dimension in the framework. The manufacturing function refers to the creation of goods or services through the transformation of inputs, such as raw materials, resources, and information, into outputs that customers receive. In the framework, it is referred to as the Manufacturing 4.0 dimension. The warehousing function refers to all warehouse operations and inventory management and is referred to as Warehousing 4.0 in the framework. The logistics function is concerned with all transportation and delivery of products and is transformed into Logistics 4.0 through digitization in the framework.

In the following, I4.0 technologies and concepts are discussed for each of the respective SC dimensions, explaining how SC performance can be increased. To show the practicability of the proposed framework depicted in Fig. 5, the description of each dimension includes examples of the practical applications of the different technologies and concepts, based on literature and the empirical findings from the interviewed companies. Cybersecurity is added as an underlying dimension to the proposed framework in Fig. 5 because it has no direct impact on supply chain performance. However, it is still necessary in a I4.0 environment.

7.1. Procurement 4.0

One important organizational function of the SC is procurement. The procurement division is the initial owner of the supplier interface (Geissbauer et al., 2016), which makes it important for a production network in the digital era (Glas & Kleemann, 2016).

Companies can enhance their competitiveness by applying I4.0 technologies and concepts in the procurement functions to reduce cost and increase product quality by selecting the most appropriate suppliers for raw material. In Procurement 4.0, valuable customer data can be used with the purpose of better managing inventories, transportation flows, quality inspection, warehouse requirement, and so forth (Geissbauer et al., 2016). The technological solutions suited for Procurement 4.0 are AI, BDA, CC, IoT, horizontal and vertical Integration and cybersecurity. These technologies and concepts can be used within Procurement 4.0 for real-time integration of data from suppliers, production, distributors, and customers in order to reduce inventory costs, lead times, and supplier performance (Glas & Kleemann, 2016).

AI is important for procurement, and it can analyze BD in real time to find possibilities and improve decision-making. To improve the relationship between buyers and suppliers and increase trust, companies can enable access to information in real time, which is leveraged by increased visibility within the SC. As a result, competitive advantages will be gained by companies that have highly transparent SCs in the future. Technologies and concepts used in Procurement 4.0 to enable real-time access and observations include IoT and CC. A digital solution enabled by cloud services is the real-time collection, accessing, sharing, and processing of information via a digital platform, which is available to all parties in the SC. A standard user interface is used, which can increase efficiency and effectiveness by enabling remote accessibility. Sensor technologies from IoT are required for real-time information flow, and they are essential for companies that seek to improve traceability and transparency. Using BDA, CC, and IoT, it is possible for collaborating buyers and suppliers to reduce supply risk from the improved information flow transparency. When markets demand shorter product time to market, it is necessary for the procurement process to be agile by following the demand volatility. This can be done by using BD collection, which can support predictive analytical tools and deliver more accurate forecasts. These benefits improve a company's ability to respond to the market.

The horizontal integration of suppliers can be achieved by integrating cloud systems resulting in cost-efficiency, less inventory, and shorter lead times. The systems of the manufacturer and its suppliers can be integrated in a way that allows for automatic recognition of demand for raw materials, which enables the manufacturer to automatically send orders without human interference (Glas & Kleemann, 2016). Integration with suppliers can increase the flow of virtual information, which further increases the importance of cybersecurity. It is important for companies to handle cybersecurity issues, and it should be done cross-functionally by including all parties in the SC in order to prevent external violence (Bienhaus & Haddud, 2018). BDA is a significant enabler for Procurement 4.0. It can automatically drive decisions regarding procurement and, in general, improve decision-making of employers (Geissbauer et al., 2016). BDA will make sure that procurement identifies and exploits all possible opportunities, benefitting both the company and its suppliers.

7.2. Manufacturing 4.0

It is clear that I4.0 addresses the manufacturing part of the value chain. The reduction of product life cycles and the fact that customers demand customized products with shorter lead times force companies to accelerate the product time-to-market to stay competitive, while also providing high quality products.

In companies, I4.0 is driven by top management's vison and strategy to digitize manufacturing. Production managers strive to achieve high efficiency, effectiveness, process optimization, and shorter lead times with less inventory and reduced cost. This can be done by applying some of the I4.0 technologies and concepts, such as IoT, BDA, CPS, AM, flexible automation, and industrial robotics which are key technologies and concepts in I4.0. CPS unifies the physical entities with the cyber world, and IoT provides seamless connectivity along the value chain. Industrial robots contribute to process optimization as well, and the use of AM enables production managers to achieve mass customization producing lot sizes of one. The BD collected through IoT can facilitate resource utilization optimization, improved quality, increased decision-making transparency and speed. Furthermore, when AI is used for BDA, self-learning capabilities can be developed, and predictive maintenance can be facilitated. As with procurement 4.0, the issue of CS also needs to be considered when implementing I4.0 technologies and concepts in manufacturing. IoS offers value-added services over the internet that are made available by different suppliers. It forms a network of virtual production capabilities and technologies through the combination of individual services.

7.3. Logistics 4.0

I4.0 affects SC dimensions and it creates the contemporary Logistics 4.0. The purpose of manufacturers is to deliver the right product to the right customer, at the right time with an objective of sustaining high customer satisfaction. There are several technologies and concepts fostering Logistics 4.0, such as IoT, which is very significant for logistics with its ability to sense, identify, locate, process and act. With the virtual and physical worlds moving closer, actions can rarely be taken for items that have not been identified in the SC. RFID can be used to ensure that items 'exist' in the system, and it offers a convenient way of identifying the right objects at the right time and at the right place. In transportation and logistics, IoT can provide an almost perfect order, shipping, receiving, and inventory accuracy, as well as faster order processing. The IoT improves the visibility across the SC, and it enables companies to share information in real time, connect all SC functions, and optimize and augment the transparency of the logistics processes. In a CPS, physical reality operations are connected with computing and communication structures. It makes use of IoT for identifying and locating items, while BDA extracts relevant information, which is later shared through CC in real time. This improves coordination of processes and logistics, increases agility, and facilitates both horizontal and vertical integration. The CPS makes it possible for the items to track themselves without human intervention. At the same time, the CPS can communicate with other CPSs via the internet, thus forming a network.

Horizontal integration of end-to-end monitoring creates integration networks among the suppliers, manufacturers and customers (Strandhagen et al., 2017). Horizontal integration enables data to be shared in real time and reduce the differences between companies in the supply chain. The real-time exchange of data among the connected actors, reduces the consequences of the bullwhip effect. The information sharing through BD accessibility in the cloud also enables inventories and related costs to be reduced. The use of IoT in logistics calls for the implementation of cyber security making sure that data is protected.

Agility is necessary for a company to respond to changing market demand, and within logistics, shorter lead times and greater reliability are some of the main contributors to agility in the supply chain. IoSs should connect the IT systems of the integrated stakeholders, and analytics on the data regarding products, vehicles, and facilities locations can provide optimal delivery routes for transportation of material and products, as well as real time optimization using CC (Strandhagen et al., 2017). Investments in flexible automation, such as autonomous guided vehicles, can reduce the cost of logistics service.

7.4. Warehousing 4.0

The warehouse management or in terms of I4.0, Warehousing 4.0, is an important component of the SC. Production, warehouse transportation technologies, warehouse management systems, and production all have to be considered simultaneously in the Warehousing 4.0 concept (Lerher, 2018). I4.0 technologies and concepts, such as IoT, AI, AR, CPS, BD, CC and autonomous vehicles, are key technologies and concepts of Warehousing 4.0. The adoption of these technologies and concepts contributes towards the optimum control of inventory levels at a lower cost.

Manufacturers need to be agile to customers' needs, so their inventories should be ready and should contain the necessary raw materials and finished goods to satisfy consumer needs. The horizontal integration with customers and suppliers provides more accurate information to utilize warehouse resources in the best way. AR provides a real-time user interface capability with objects and digital devices and can be used within warehousing operations. AR can enable warehouse employees to find objects faster and more accurately, reducing costs and lowering inefficiencies. AR also offers digital picking lists, and AR-enabled glasses can be used to show the best route for completing the task, thus reducing total travel time. Additionally, flexible automation such as AGVs are used to transport goods throughout the warehouse, while a CPS for tracking and decision-making can be implemented for keeping control over inventory management and material handling (Strandhagen et al., 2017). These tracking and decision-making systems are supported by sensors used by IoT applications to gather data about operating conditions. These data points are then analyzed to proactively manage buildings to better ensure efficiency. The adoption of technologies and concepts such as IoT, CPS, and BDA have the potential to reduce inventory and optimize the warehousing operations, which can result in a high return of investment.

8. Scope for future research directions

This section intends to provide various research directions that were derived from the findings of the study for future researchers. The future scope has been categorized into four themes (Procurement 4.0, Manufacturing 4.0, Logistics 4.0 and Warehousing 4.0) as mentioned earlier in the proposed supply chain 4.0 performance framework. The detailed descriptions on the future possibility of each theme are as follows.

8.1. Procurement 4.0

Decisions from the procurement front have made a severe impact on the overall cost of industrial operations, and major capital has been associated with the procurement of raw materials. Under procurement, there are several sub themes to address with Industry 4.0 concerns to make the existing system more effective. Several research initiatives could be encouraged in the themes to include supplier selection, supplier relationship management, and agile procurement.

8.1.1. Supplier selection

Supplier selection is a multi-criteria task in which several elements are involved. Globalization and communication open markets to everyone. Regardless of the size and level of the organization, anyone can join in the competition of being a supplier for multi-brand companies. This broad playing field increases the complexity among sourcing organizations to select their most suitable supplier. Recent industry 4.0 technologies could help make supplier selection decisions easier, especially because studies have started to explore various opportunities on I4.0-based supplier selections. However, existing studies (Ghadimi et al., 2019; Sachdeva et al., 2021) emphasize that several research gaps still exist with this phenomenon that are worthy of further investigation. Adding to the perspectives of this study, here are some potential research propositions to explore in future studies.

- What are the challenges and opportunities caused and provided by Industry 4.0 in supplier selection even with the consensus of various necessary inclusions (for instance, sustainable supplier selection)?
- What are the impacts of smart technologies on supplier selection performance under the concern of labor force?

8.1.2. Supplier relationship management

Recent global issues have increased the complexity of forecasting demand, and those complications may, in turn, disrupt the whole supply chain. To manage such disruptions, manufacturers must be aware of their suppliers' capacities, which serve a key role. In fact, the success of the manufacturing organization largely depends on the suppliers' dynamic capability and that they are well-equipped and flexible enough to handle market uncertainty. Accordingly, capacity and flexibility should be more explored under supplier relationship management, in which the manufacturing organization could assist the supplier firm to more easily adapt to global business uncertainty. Concerning the significance, the following proposition could be useful for further research strengthening.

- What is the role of Industry 4.0 in improving capacity and flexibility among suppliers within the topic of supplier relationship management?
- How can Industry 4.0 be a viable solution for managing uncertainty among supplier firms under supplier relationship management?

8.1.3. Agile procurement

Agile procurement is a primary function under 'Procurement 4.0′. According to CPO rising report (2015), agility in procurement has been defined as "The procurement teams that adeptly connect their tools, resources, and expertise to support the evolving needs of the business will succeed above all others. Agility will define the next wave of procurement success." The agility flavors the procurement by increasing the ability of problems at the source (suppliers' end), meanwhile being as flexible and identifying new opportunities within the system. Industry 4.0 could assist this agile procurement process to a greater extent. For instance, Industry 4.0 tools could make the agile procurement better by providing support to negotiate the contract with their suppliers and assuring the manufacturers that the essentials have been assessed. Such discussion brings some interesting research propositions as future scope.

- How could the supply chain finance and its related contract be improved through I4.0 tools (specifically blockchain) under procurement 4.0?
- How should the current procurement operations be reassessed with the focus of lean and agile parameters under procurement 4.0?

8.2. Manufacturing 4.0

According to several studies (Koh et al., 2019; Ivanov et al., 2020; Guo et al., 2021), insufficient findings have been evident in the literature on the integration of Industry 4.0 in manufacturing. The urge and significance of integrating Industry 4.0 technologies in manufacturing has resulted in a major literature gap. As a future scope of the study, three key themes have been highlighted for further extension of applications of Industry 4.0 in manufacturing systems.

8.2.1. Process optimization

Process optimization depends upon identifying the process inefficiencies and trying to minimize them. Recent technological advancements are believed to be useful in minimizing these process inefficiencies. This includes leveraging real time data to understand the root cause of process inefficiencies and to predict the time of the process that displays inefficiency. Concerning the fact, the following propositions is worth investigating to improve process optimization through Industry 4.0 technologies.

- What is the role of IoT connectivity for real time data for process optimization?
- How can be a root cause analysis be effectively evaluated through Artificial intelligence for process optimization?
- How might process inefficacies of process optimization be predicted using machine learning algorithms?
- What is a suitable way to identify a better fit to avoid process inefficiencies for effective process optimization through simulation?

8.2.2. Mass customization

Mass customization is a recent key term in contemporary manufacturing business environments. Mass customization provides an advantage for manufacturers by improving their ability to cater to their customers' specific demands with no loss of productivity and increased profitability. This customer-oriented approach of manufacturing increases the business competitiveness and helps the manufacturing companies to sustain. Flexible manufacturing principles are used to adapt to achieve mass customization. Industry 4.0 technologies can be used to improve the mass customization phenomenon through flexible manufacturing. Recently, some studies (Guo et al., 2022; James and Mondal, 2019) explored the various options under this context, and scholars admit that there is need for more studies. Industry 4.0 tools such as sensors and communication technologies interact with different streams of manufacturing operations (including business units and supply and distribution chains) through collected data. With the recent advent of digital twin, these collected datasets were used to help the customers in the real world. However, the role of this digital twin is still distinct within the literature. Hence, the following proposition has been made for further research investigation.

- What is the role of digital twin/digital replica of the product or processes and how might it improve flexible manufacturing for achieving mass customization through real world data?

- How might the efficiency of mass customization culture be improved through effective interaction among different streams of manufacturing operations through Industry 4.0 tools?

8.2.3. Predictive maintenance

A maximum of 60% of manufacturing cost has been spent towards predictive maintenance (Haarman et al., 2017). This amount even be on the higher side in some cases due to the uncertain business environments. Industry 4.0 provides a better edge for such predictive maintenance by using the data to predict the remaining life of the assets. Industry 4.0 technologies also tends to assist the manufacturers through patterns and correlations for effective decision making on the periodic assets replacement. In line with other studies (Zonta et al., 2020) on predictive maintenance, there are some propositions can be explored further to strengthen the implication of Industry 4.0 technologies regarding predictive maintenance.

- What role do Industry 4.0 technologies in predictive maintenance play other than simple alert monitoring?
- What are the effects of challenging factors on intelligent maintenance processes?

8.3. Logistics 4.0

As claimed by several studies, Logistics 4.0 can improve the process through speed and flexibility by eliminating the imprecision involved. It assists the firm to explore the real time information on both forward and reverse logistics. Under logistics, inventory decision making is a difficult task; it involves several risks of being either over stock or under stock. Hence, recent studies focus on the different impacts of Industry 4.0 technologies in the aspects of inventory decision making (process, classification, system parameters, and system review). Optimizing such inventory aspects through Industry 4.0 technologies can balance the supply and demand on both end (suppliers and customers). Many studies (Dev et al., 2021; Ding et al., 2021) urged that there is room to explore the digital inventory options under the concern of Logistics 4.0. By combining the findings of the study and knowledge from existing studies, the following propositions have been made as future scope for continued research.

- What are the roles of Industry 4.0 in predictive analytics to eliminate over and under stocking through effective inventory decision making?
- What is the best way to understand and improve the cross functional interactions between logistics (transport), production planning, and inventory decision making through Industry 4.0 technologies?
- How can digital connectivity and agility be improved for the most effective inventory decision making?

8.4. Warehousing 4.0

Owing to customer requirements and business revolutions, conventional warehousing is being updated with smart features. Smart warehouses display many advantages over conventional ones, including the ability to optimize capabilities, to be responsive, agile, and extensible, while being user friendly. Technologies such as automated vehicles, IoT, sensors, COBOTS, and augmented reality push the concept of Warehousing 4.0 to greater heights than ever before. To reap the benefits of Industry 4.0 in warehousing, it is necessary to reduce overall operating costs, while simultaneously improving quality, service, and productivity. These benefits are highly dependent on two key operations under warehousing, tracking and optimization, which are discussed in detail.

8.4.1. Process and logistics coordination and tracking

Warehousing involves several entities of business: suppliers, manufacturers, and customers. Hence, it is necessary to be precise in the process and logistics coordination. Precision improves the connectivity among the entities. In addition, it is necessary to be track and update real time information to understand the market dynamics which further helps in inventory decisions. To make precise coordination and tracking, it is necessary to design and build a warehouse with smart focus. With the support of these discussions, the following propositions can be suggested for future research explorations.

- What are the impacts of Industry 4.0 integrated warehousing design and its key parameters in the overall productivity of an organization's supply chain?
- What are the effects of automation priority in existing warehouse in the transformation to Warehousing 4.0?

8.4.2. Transport optimization

Fundamental warehousing involves several operations, including receiving the goods, stocking, storage, picking, and shipping. These entities relate to both in-house and to external movement; hence, these movements must be effective. Optimizing transportation is a central objective of a successful warehouse. In the era of Industry 4.0, under Warehousing 4.0, this optimization has become more effective. Real time economy under Industry 4.0 increases the speed and accuracy of transportation which, in turn, optimizes the overall system by connecting the human and business systems more effectively. Further, these optimizations happen based on accurate data being collected and processed. This objective brings new opportunities to explore as follows.

- What are the impacts of data driven warehousing as it relates to transport optimization?
- What roles do digital technologies play in transport optimization under Warehousing 4.0?

9. Conclusion

As I4.0 is emerging, this work sheds light on the technologies and concepts of I4.0. From previous literature reviews, it became clear that there was a lack of reviews on the impact of I4.0 on SC performance. To address this concern, this work is aimed at exploring the current state of the art within the technologies and concepts of I4.0 through an SLR on selected publications by using the 8-step method proposed by Denyer & Pilbeam (2013). 832 articles were narrowed down to 137 articles, and those were thoroughly analyzed. The lack of literature reviews on I4.0 and SC performance was apparent, so this work contributes to the literature with an SLR in the field of I4.0 and SC performance. The result of the descriptive analysis indicates that the interest of I4.0 is growing with an increase in the number of publications over the past seven years. From the descriptive findings it appears that 14 technologies and concepts, such as IoT, CC, AM, BDA, Industrial Robotics, DT, horizontal and vertical integration, among others contribute to a new paradigm in SC. The thematic findings describe all the identified technologies and concepts and their effect on SC performance. The identified I4.0 technologies and concepts provide merely a holistic view of the most common technologies and concepts and their impact on SC performance. The identified I4.0 technologies and concepts were then divided into four clusters: physical/digital interface technologies; network technologies; data processing technologies; and physical/digital process technologies. These divisions are determined by whether their network connectivity is extended or limited, and it explores how many of the technological elements are either software or hardware. Based on the four technology clusters and SC performance benefits found in the SLR, combined with a validation from the industry, an I4.0 and SC performance framework is proposed. The validation of the findings from the SLR was done by ten companies from Danish industries working with I4.0. The companies assessed the impact of the 13 out of the 14 identified technologies and concepts on the potential benefits found in the literature by giving them a score from 0 to 5; these results were used to finalize the framework. The 14th technology, cybersecurity, was not considered, since it does not have a direct impact on SC performance. The proposed framework identifies the impact of different I4.0 technologies and concepts on SC performance and serves as one of the initial efforts to contribute to the theory of I4.0 and the relationships between technologies, concepts, and SC performance improvement.

The framework proposes that I4.0 technologies and concepts in the procurement, manufacturing, warehousing, and logistics functions can unlock certain SC performance benefits. The proposed framework can therefore act as a guide for companies to decide where they should start looking at I4.0 in order to improve their SC performance. With the proposed framework showing the general potential for SC performance improvement using I4.0 technologies and concepts, it does not deal with the implementation of said technologies and concepts.

10. Limitations

Selecting the Scopus database may be one of the limitations of this SLR, as there may be articles outside of Scopus that are relevant to the scope of the study that have remained unconsidered. Review studies in the future may include other popular databases, like Web of Science. The scoring of the I4.0 technologies and concepts impact on the potential benefits depended solely on the qualification and number of experts included in the validation. The experts participating in the validation of the findings from the SLR are mainly experienced representatives from the industry and familiar with I4.0 technologies and concepts as well as SCM. The limited number of participating experts has limited the reliability of the framework to their experience. To improve the proposed framework, a broader survey or set of workshops might be set up to get more inputs and to reduce the standard deviation in the technology scoring. This work has not considered how the technologies and concepts are interrelated, and that focus may have an impact on a company's decision to try to improve its SC performance through I4.0.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

See Table 14.

Table 14
Review protocol.

	Description
Boolean Operators	OR between keywords; AND between Database search fields
Search Fields	Title; Abstract; Keywords
Inclusion and Exclusion Criteria’s when reading Title, keywords and Abstract.	Include technologies in the context of I4.0 Description of a use case in the context of I4.0 Description of Supply Chain performance optimization based on technologies in the context of I4.0
Language	English
Publication Type	Articles and Reviews
Time Window	January 2011 to Dec 2021
▪ Scientific Database	Scopus
Search string	**TITLE-ABS-KEY** (“Industry 4.0″ OR ”Industrie 4.0″ OR “I4.0″ OR ”I4″ OR “Fourth industrial revolution” OR “digitization” OR “4th industrial revolution” OR “4IR” OR “Digital operations” OR “Digital industry” OR “smart factor*” OR “manufacturing 4.0″ OR ”smart manufactu*“ OR ”Smart Product*“ OR ”smart industry“ OR ”Calm system“ OR ”Cyber-physical system*“ OR ”Cyber physical system*“ OR ”CPS“ OR ”smart analytics“ OR ”Human-machine interaction“ OR ”Big Data“ OR ”big data analytics“ OR ”additive manufacturing“ OR ”3D print*“ OR ”3D scanning“ OR ”Cloud computing“ OR ”cloud manufactur*“ OR ”vertical integration“ OR ”horizontal integration“ OR ”decentralized intelligence“ OR ”Cybersecurity“ OR ”Augmented reality“ OR ”digital twin“ OR ”Internet of Things“ OR ”IoT“ OR ”industrial internet of thing*“ OR ”IIOT“ OR ”Industrial Internet“ OR ”Near field communication“ OR ”internet of service*“ OR ”IoS“ OR ”digital supply chain*“ OR ”supply chain 4.0″ OR “digital supply chain networks” OR “DSN” OR “digital logistics” OR “logistic* 4.0″ OR ”smart logistics“ OR ”cobot*“ OR ”M2M“ OR ”Machine-to Machine“ OR ”predictive maintenance“ OR ”Smart warehousing“ OR ”iBin“ OR ”AIDC“ OR ”automatic identification and data collection“ OR ”RFID“ OR ”visual computing“ OR ”procurement 4.0″ OR “sourcing 4.0″) AND **TITLE-ABS-KEY** (”supply chain*“ OR ”supply chain performance*“ OR ”performance measure*“ OR ”performance metric*“ OR ”Order lead time“ OR ”Receiving time“ OR ”Order picking time“ OR ”Delivery Lead Time“ OR ”Queuing time“ OR ”Putaway time“ OR ”Shipping time“ OR ”Dock-to-stock time“ OR ”Equipment downtime“ OR ”Manufacturing lead time“ OR ”Throughput time“ OR ”Customer response time“ OR ”Cycle time“ OR ”Lead time“ OR ”On-time delivery“ OR ”Customer satisfaction“ OR ”Order fill rate“ OR ”Physical inventory accuracy“ OR ”Stock-out rate“ OR ”Storage accuracy“ OR ”Picking accuracy“ OR ”Shipping accuracy“ OR ”Delivery accuracy“ OR ”Perfect orders“ OR ”Scrap rate“ OR ”Orders shipped on time“ OR ”Cargo damage rate“ OR ”Stockout probability“ OR ”Product lateness“ OR ”Average lateness of orders“ OR ”Average earliness of orders“ OR ”Stockout probability“ OR ”Number of backorders“ OR ”Number of stockouts“ OR ”Average backorder level“ OR ”Shipping errors“ OR ”Customer complaints“ OR ”Information accuracy“ OR ”Information timeliness“ OR ”Delivery performance“ OR ”Design revision time“ OR ”Prototyping time“ OR ”Level of technology support in process design and engineering“ OR ”Safety stock level“ OR ”Inventory cost“ OR ”Order processing cost“ OR ”Cost as a percentage of sales“ OR ”Labour cost“ OR ”Labor cost“ OR ”Distribution cost“ OR ”Maintenance cost“ OR ”Manufacturing cost“ OR ”Operating cost“ OR ”Obsolescence“ OR ”Rework“ OR ”Total supply chain cost“ OR ”Transportation cost“ OR ”Work-in-process cost“ OR ”Finished goods inventory cost“ OR ”Return on investment“ OR ”Total revenue“ OR ”Profit“ OR ”Recovery cost“ OR ”Market share gain“ OR ”demand gain“ OR ”Set-up cost“ OR ”Cost of defective parts“ OR ”Shortage cost“ OR ”Material handling cost“ OR ”Cost of goods sold“ OR ”Labour productivity“ OR ”Labor productivity“ OR ”Throughput“ OR ”Shipping productivity“ OR ”Transport utilization“ OR ”Warehouse utilization“ OR ”Picking productivity“ OR ”Inventory space utilization“ OR ”Outbound space utilization“ OR ”Receiving productivity“ OR ”Turnover“ OR ”Inventory level“ OR ”Equipment utilization“ OR ”Component Standardization“ OR ”Energy usage“ OR ”Pollution effect“ OR ”Solid waste“ OR ”Air emission“ OR ”Water waste“ OR ”Chemical waste“ OR ”Thermal pollution“ OR ”Transport distance“ OR ”Possibility of reuse/refurbish/remanufacture“ OR ”Material usage“ OR ”Transportation greenness“ OR ”Demand forecasting“ OR ”Demand management“ OR ”Flexibility“ OR ”Customer satisfaction“ OR ”Information flow“ OR ”Supplier performance“ OR ”Risk management“ OR ”Personnel requirements“ OR ”Real-time monitoring“ OR ”Production process control“ OR ”Forecast horizon“ OR ”Forecast error“ OR ”Forecast frequency of update“ OR ”agil*“ OR ”responsiv*“ OR ”organisational performance*“ OR “Delivery Performance to Customer Commit Date” OR “Documentation Accuracy” OR “Perfect Condition” OR “Perfect Order Fulfillment” OR “Order Fulfillment Cycle Time” OR “Upside Supply Chain Adaptability” OR “Downside Supply Chain Adaptability” OR “Value at Risk” OR “Cost to Return” OR “Cost to Deliver” OR “Cost to Make” OR “Cost to Plan” OR “Inventory days of supply” OR “Cash to cash cycle time”)

References

Abidi, H., De Leeuw, S. and Klumpp, M., 2014. Humanitarian supply chain performance management: a systematic literature review. Supply Chain Manage.: Int. J.

Ada, N., Kazancoglu, Y., Sezer, M.D., Ede-Senturk, C., Ozer, I., Ram, M., 2021. Analyzing barriers of circular food supply chains and proposing industry 4.0 solutions. Sustainability 13 (12), 6812.

Adhitya, Y., Prakosa, S.W., Köppen, M., Leu, J.S., 2020. Feature Extraction for Cocoa Bean Digital Image Classification Prediction for Smart Farming Application. Agronomy 10 (11), 1642.

Agrawal, R., Wankhede, V.A., Kumar, A., Luthra, S. and Huisingh, D., 2021. Progress and trends in integrating Industry 4.0 within Circular Economy: A comprehensive literature review and future research propositions. Business Strategy and the Environment.

Aheleroff, S., Xu, X., Zhong, R.Y., Lu, Y., 2021. Digital twin as a service (DTaaS) in industry 4.0: an architecture reference model. Adv. Eng. Inf. 47, 101225.

Ahmed, S., Kalsoom, T., Ramzan, N., Pervez, Z., Azmat, M., Zeb, B., Ur Rehman, M., 2021. Towards supply chain visibility using internet of things: A dyadic analysis review. Sensors 21 (12), 4158.

Ahuett-Garza, H., Kurfess, T., 2018. A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart manufacturing. Manuf. Lett. 15, 60–63. Available at: https://doi.org/10.1016/j.mfglet.2018.02.011.

Albini, A., Rajnai, Z., 2018. General Architecture of Cloud Costing models for capacity optimization in Industry 4.0: Trade-off between used capacity and operational efficiency General Architecture of Cloud. Procedia Manuf., 22, 485–490. Available at: https://doi.org/10.1016/j.promfg.2018.03.074.

Andaluz, E., 2017. The Process Digital Twin: A step toward operational excellence.

Anon, 2018. Industry 4.0 | LeanKit. Available at: https://leankit.com/learn/lean/industry-four-point-0/ [Accessed October 10, 2018].

Aoun, A., Ilinca, A., Ghandour, M., Ibrahim, H., 2021. A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology. Comput. Ind. Eng. 162, 107746.

Asakura, T., 2016. Industrial operations supporting industry 4.0. NEC Tech. J. 11 (1), 31–34.

Attaran, M., 2020, July. Digital technology enablers and their implications for supply chain management. In: Supply Chain Forum: An International Journal, Vol. 21, No. 3. Taylor & Francis, pp. 158–172.

Awan, U., Sroufe, R., Shahbaz, M., 2021. Industry 4.0 and the circular economy: A literature review and recommendations for future research. Bus. Strategy Environ. 30 (4), 2038–2060.

Bag, S., Pretorius, J.H.C., Gupta, S., Dwivedi, Y.K., 2020. Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities. Technol. Forecast. Soc. Chang., 120420

Bag, S., Gupta, S., Kumar, S., 2021a. Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. Int. J. Prod. Econ. 231, 107844.

Bag, S., Pretorius, J.H.C., Gupta, S., Dwivedi, Y.K., 2021b. Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities. Technol. Forecast. Soc. Chang. 163, 120420.

Bagula, A., Ajayi, O., Maluleke, H., 2021. Cyber physical systems dependability using cps-iot monitoring. Sensors 21 (8), 2761.

Bahrin, M.A.K., et al., 2016. Industry 4.0: A review on industrial automation and robotic. Jurnal Teknologi 78 (6–13), 137–143.

Bai, H., Li, S., Shepherd, R.F., 2021. Elastomeric Haptic Devices for Virtual and Augmented Reality. Adv. Funct. Mater. 31 (39), 2009364.

Balfaqih, H., Nopiah, Z.M., Saibani, N., Al-Nory, M.T., 2016. Review of supply chain performance measurement systems: 1998–2015. Comput. Ind. 82, 135–150.

Bamakan, S.M.H., Faregh, N., ZareRavasan, A., 2021. Di-ANFIS: an integrated blockchain–IoT–big data-enabled framework for evaluating service supply chain performance. J. Comput. Des. Eng. 8 (2), 676–690.

Bamunuarachchi, D., Georgakopoulos, D., Banerjee, A., Jayaraman, P.P., 2021. Digital Twins Supporting Efficient Digital Industrial Transformation. Sensors 21 (20), 6829.

Banomyong, R., Varadejsatitwong, P., Oloruntoba, R., 2019. A systematic review of humanitarian operations, humanitarian logistics and humanitarian supply chain performance literature 2005 to 2016. Ann. Oper. Res. 283 (1–2), 71–86.

Barata, J., Rupino Da Cuncha, P., Stal, J., 2018. Mobile supply chain management in the Industry 4.0 era: An annotated bibliography and guide for future research. J. Enterprise Inform. Manage. 31 (1), 173–192.

Barreto, L., Amaral, A. & Pereira, T., 2017. Industry 4.0 implications in logistics: an overview. Procedia Manuf. 13, pp.1245–1252. Available at: https://doi.org/10.1016/j.promfg.2017.09.045.

Beyca, O.F., Hancerliogullari, G., Yazici, I., 2018. Additive Manufacturing Technologies and Applications. In Industry 4.0: Managing The Digital Transformation. pp. 217–234.

Bhattacharya, S. and Chatterjee, A., 2021. Digital project driven supply chains: a new paradigm. Supply Chain Manage.: Int. J.

Bienhaus, F., Haddud, A., 2018. Procurement 4.0: factors influencing the digitisation of procurement and supply chains. Bus. Process Manage. J.

Birkel, H., Müller, J.M., 2021. Potentials of industry 4.0 for supply chain management within the triple bottom line of sustainability–A systematic literature review. J. Cleaner Prod. 289, 125612.

Bisio, I., et al., 2018. Exploiting context-aware capabilities over the internet of things for industry 4.0 applications. IEEE Network 32 (3), 108–114.

Biswal, A.K., Jenamani, M., Kumar, S.K., 2018. Warehouse efficiency improvement using RFID in a humanitarian supply chain: Implications for Indian food security system. Transport. Res. Part E: Logist. Transport. Rev. 109, 205–224.

Bocken, N.M.P., 2016. Sustainable business models and structures for Industry 4.0. Journal of Security and Sustainability. Issues 2 (April), 1–28.

Bodrow, W., 2017. Impact of Industry 4.0 in service oriented firm. Adv. Manuf. 5 (4), 394–400.

Brandín, R., Abrishami, S., 2021. Information traceability platforms for asset data lifecycle: blockchain-based technologies. Smart Sustain. Built Environ. 10 (3), 364–386. https://doi.org/10.1108/SASBE-03-2021-0042.

Brandín, R., Abrishami, S., 2021. Information traceability platforms for asset data lifecycle: blockchain-based technologies. Smart Sustain. Built Environ.

Burnham, J.F., 2006. Scopus database: A review. Biomed. Digital Libraries 3, 1–8.

Caggiano, A., Teti, R., 2018. Digital factory technologies for robotic automation and enhanced manufacturing cell design. Cogent Eng. 5 (1), 1–14.

Cagliano, A.C., Mangano, G., Rafele, C., 2021, April. Determinants of digital technology adoption in supply chain. An exploratory analysis. In: Supply Chain Forum: An International Journal, Vol. 22, No. 2 Taylor & Francis, pp. 100-114.

Calabrese, A., Levialdi Ghiron, N., Tiburzi, L., 2020. 'Evolutions' and 'revolutions' in manufacturers' implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework. Production Plann. Control 1–15.

Chen, T., Lin, Y.C., 2017. Feasibility Evaluation and Optimization of a Smart Manufacturing System Based on 3D Printing: A Review. Int. J. Intell. Syst. 32 (4), 394–413.

Chhetri, S.R., et al., 2017. Manufacturing Supply Chain and Product Lifecycle Security in the Era of Industry 4.0. Journal of Hardware and Systems. Available at: Security 51–68 http://link.springer.com/10.1007/s41635-017-0031-0.

Choi, T.-M., 2019. Blockchain-technology-supported platforms for diamond authentication and certification in luxury supply chains. Transport. Res. Part E: Logist. Transport. Rev. 128, 17–29.

Choi, T.-M., Guo, S., Luo, S., 2020. When blockchain meets social-media: Will the result benefit social media analytics for supply chain operations management? Transport. Res. Part E: Logist. Transport. Rev. 135, art. no. 101860.

Choi, T.-M., Wen, X., Sun, X., Chung, S.-H., 2019. The mean-variance approach for global supply chain risk analysis with air logistics in the blockchain technology era. Transport. Res. Part E: Logist. Transport. Rev. 127, 178–191.

Chopra, S., Meindl, P., 2001. Strategy, planning, and operation. Supply Chain Manage. 13–17. http://catalogue.pearsoned.ca/assets/hip/ca/hip_ca_pearsonhighered/preface/0134731883.pdf.

Cifone, F.D., Hoberg, K., Holweg, M., Staudacher, A.P., 2021. 'Lean 4.0': How can digital technologies support lean practices? Int. J. Prod. Econ. 241, 108258.

Cohen, Y., et al., 2017. Assembly system configuration through Industry 4.0 principles: Assembly the system. IFAC-PapersOnLine, 50(1), pp.14958–14963. Available at: https://doi.org/10.1016/j.ifacol.2017.08.2550.

Consoli, R., 2018. Using Big Data Analytics To Improve Production. Available at: https://www.manufacturing.net/article/2018/05/using-big-data-analytics-improve-production [Accessed October 17, 2018].

Contents, T.O.F., 2017. A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart manufacturing. Manuf. Lett. 15, 1–10.

Corches, C., Daraban, M., Miclea, L., 2021. Availability of an RFID object-identification system in IoT environments. Sensors 21 (18), 6220.

Cozmiuc, D., Petrisor, I., 2018. Industrie 4.0 by Siemens: steps made next. J. Cases Inform. Technol. (JCIT) 20 (1), 31–45.

Dafflon, B., Moalla, N., Ouzrout, Y., 2021. The challenges, approaches, and used techniques of CPS for manufacturing in Industry 4.0: a literature review. Int. J. Adv. Manuf. Technol. 113 (7), 2395–2412.

Dallasega, P., et al., 2017. Simulation Based Validation of Supply Chain Effects through ICT enabled Real-time-capability in ETO Production Planning. Procedia Manuf. 11 (June), 846–853.

Dallasega, P., Rauch, E. & Linder, C., 2018. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. Comput. Ind. 99 (March), pp.205–225. Available at: https://doi.org/10.1016/j.compind.2018.03.039.
Dalmarco, G. & Barros, A.C., 2018. Adoption of Industry 4.0 Technologies in Supply Chains. In Innovation and Supply Chain Management. pp. 303–319.
De Vass, T., Shee, H., Miah, S.J., 2021. Iot in supply chain management: a narrative on retail sector sustainability. Int. J. Logist. Res. Appl. 24 (6), 605–624.
Deloitte, 2017. Industry 4.0 and the digital twin Manufacturing meets its match A Deloitte series on Industry 4.0, digital manufacturing enterprises, and digital supply networks, Available at: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/cip/deloitte-cn-cip-industry-4-0-digital-twin-technology-en-171215.pdf [Accessed October 17, 2018].
Denyer, D., Pilbeam, C., 2013. Doing a literature review in business and management, (September), pp.1–57.
Denyer, D. & Tranfield, D., 2009. Producing a Systematic Review. The SAGE Handbook of Organizational Research Methods, pp.671–689.
Demartini, M., Tonelli, F., Govindan, K., 2022. An investigation into modelling approaches for industrial symbiosis: A literature review and research agenda. Clean. Logist. Suppl. Chain 100020.
Dev, N.K., Shankar, R., Swami, S., 2020. Diffusion of green products in industry 4.0: Reverse logistics issues during design of inventory and production planning system. Int. J. Prod. Econ. 223, 107519.
Dev, N.K., Shankar, R., Zacharia, Z.G., Swami, S., 2021. Supply chain resilience for managing the ripple effect in Industry 4.0 for green product diffusion. Int. J. Phys. Distrib. Logist. Manageent.
Ding, B., 2018. Pharma Industry 4.0: literature review and research opportunities in sustainable pharmaceutical supply chains. Available at: Process Saf. Environ. Prot. 119, 115–130 https://www.sciencedirect.com/science/article/pii/S0957582018303720.
Ding, Y., Jin, M., Li, S., Feng, D., 2021. Smart logistics based on the internet of things technology: an overview. Int. J. Logist. Res. Appl. 24 (4), 323–345.
Dobrescu, R., Mocanu, S., Chenaru, O., Nicolae, M., Florea, G., 2021. Versatile edge gateway for improving manufacturing supply chain management via collaborative networks. Int. J. Comput. Integr. Manuf. 34 (4), 407–421.
Dobrowolski, Z., 2021. Internet of things and other e-solutions in supply chain management may generate threats in the energy sector—The quest for preventive measures. Energies 14 (17), 5381.
Dossou, P.E. & Nachidi, M., 2017. Modeling Supply Chain Performance. Procedia Manuf. 11(June), pp.838–845.
Druehl, C., Carrillo, J. & Hsuan, J., 2018. Technological Innovations: Impacts on Supply Chains, pp.259–281.
Duong, L.N., Al-Fadhli, M., Jagtap, S., Bader, F., Martindale, W., Swainson, M., Paoli, A., 2020. A review of robotics and autonomous systems in the food industry: From the supply chains perspective. Trends Food Sci. Technol. 106, 355–364.
Durão, L.F.C.S., et al., 2017. Additive manufacturing scenarios for distributed production of spare parts. Int. J. Adv. Manuf. Technol. 93 (1–4), 869–880.
Dweekat, A.J., Hwang, G., Park, J., 2017. A supply chain performance measurement approach using the internet of things. Ind. Manage. Data Syst. 117 (2), 267–286.
Ekren, B.Y., Mangla, S.K., Turhanlar, E.E., Kazancoglu, Y., Li, G., 2021. Lateral inventory share-based models for IoT-enabled E-commerce sustainable food supply networks. Comput. Oper. Res. 130, 105237.
Esmaeilian, B., Sarkis, J., Lewis, K., Behdad, S., 2020. Blockchain for the future of sustainable supply chain management in Industry 4.0. Resour. Conserv. Recycl. 163, 105064.
Fatorachian, H., Kazemi, H., 2021. Impact of Industry 4.0 on supply chain performance. Prod. Plann. Control 32 (1), 63–81.
Fernández-Caramés, T.M., et al., 2018. A fog computing based cyber-physical system for the automation of pipe-related tasks in the industry 4.0 shipyard. Sensors (Switzerland) 18 (6).
Fernández-Caramés, T.M., Blanco-Novoa, O., Froiz-Míguez, I., Fraga-Lamas, P., 2019. Towards an autonomous industry 4.0 warehouse: A UAV and blockchain-based system for inventory and traceability applications in big data-driven supply chain management. Sensors 19 (10), 2394.
Fernández-Miranda, S.S. et al., 2017. The challenge of integrating Industry 4.0 in the degree of Mechanical Engineering. Procedia Manuf., 13, pp.1229–1236. Available at: https://doi.org/10.1016/j.promfg.2017.09.039.
Ferrari, R., 2015. Writing Narrative Style Literature Review. Medical Writing 24 (4), 230–235.
Ford, S., Despeisse, M., 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J. Cleaner Prod. 137, 1573–1587.
Franco, D., Ganga, G.M.D., de Santa-Eulalia, L.A., Godinho Filho, M., 2020. Consolidated and inconclusive effects of additive manufacturing adoption: A systematic literature review. Comput. Ind. Eng. 148, 106713.
Garrido-Hidalgo, C., Olivares, T., Ramirez, F.J., Roda-Sanchez, L., 2019. An end-to-end Internet of Things solution for reverse supply chain management in industry 4.0. Comput. Ind. 112, 103127.
Geissbauer, R., Weissbarth, R., Wetzstein, J., 2016. Procurement 4.0: Are you ready for the digital revolution ? Strategy 1, 1–12.
Geissbauer, R. et al., 2018. Global Digital Operations Study 2018. Digital Champions. How industry leaders build integrated operations ecosystems to deliver end-to-end customer solutions, Available at: https://www.strategyand.pwc.com/industry4-0.
Ghadimi, P., Wang, C., Lim, M.K., Heavey, C., 2019. Intelligent sustainable supplier selection using multi-agent technology: Theory and application for Industry 4.0 supply chains. Comput. Ind. Eng. 127, 588–600.
Ghobakhloo, M., 2020. Industry 4.0, digitization, and opportunities for sustainability. J. Cleaner Prod. 252, 119869.
Ghobakhloo, M., Fathi, M., Iranmanesh, M., Maroufkhani, P., Morales, M.E., 2021. Industry 4.0 ten years on: A bibliometric and systematic review of concepts, sustainability value drivers, and success determinants. J. Cleaner Prod. 302, 127052.
Glas, A.H., Kleemann, F.C., 2016. The Impact of Industry 4.0 on Procurement and Supply Management: A Conceptual and Qualitative Analysis. Int. J. Bus. Manage. Invent. 5 (6), 55–66.
Goetschalckx, M., 2011. Supply Chain Engineering. Springer, US.
Gorecki, S., Possik, J., Zacharewicz, G., Ducq, Y., Perry, N., 2020. A multicomponent distributed framework for smart production system modeling and simulation. Sustainability 12 (17), 6969.
Govindan, K., Cheng, T.E., Mishra, N., Shukla, N., 2018. Big data analytics and application for logistics and supply chain management. Transport. Res. Part E: Logist. Transport. Rev. 114, 343–349.
Govindan, K., et al., 2018. "Defining Industry 4.0: a critical review" – Working paper.
Grieco, A., et al., 2017. An Industry 4.0 Case Study in Fashion Manufacturing. Procedia Manuf. 11 (June), 871–877.
Gruzauskas, V., et al., 2018. Minimizing the trade-off between sustainability and cost effective performance by using autonomous vehicles. Available at: J. Cleaner Prod. 184, 709–717 http://www.sciencedirect.com/science/article/pii/S0959652618306401.
Gu, D., Shi, X., Poprawe, R., Bourell, D.L., Setchi, R., Zhu, J., 2021. Material-structure-performance integrated laser-metal additive manufacturing. Science 372 (6545), p.eabg1487.
Gunasekaran, A. et al., 2015. Performance measures and metrics in outsourcing decisions: A review for research and applications. Int. J. Prod. Econ. 161, pp.153–166. Available at: http://dx.doi.org/10.1016/j.ijpe.2014.12.021.
Gunduz, M.A., Demir, S., Paksoy, T., 2021. Matching functions of supply chain management with smart and sustainable Tools: A novel hybrid BWM-QFD based method. Comput. Ind. Eng. 162, 107676.
Guo, S., Choi, T.M., Chung, S.H., 2022. Self-design fun: Should 3D printing be employed in mass customization operations? Eur. J. Oper. Res. 299 (3), 883–897.
Guo, D., Li, M., Lyu, Z., Kang, K., Wu, W., Zhong, R.Y., Huang, G.Q., 2021. Synchroperation in industry 4.0 manufacturing. Int. J. Prod. Econ. 238, 108171.
Gupta, H., Kumar, S., Kusi-Sarpong, S., Jabbour, C.J.C., Agyemang, M., 2020. Enablers to supply chain performance on the basis of digitization technologies. Ind. Manage. Data Syst.
Haarman, M., Mulders, M., Vassiliadis, C., 2017. Predictive maintenance 4.0: predict the unpredictable. PwC Mainnovation 4.
Hahn, J., 2020. Student Engagement and Smart Spaces: Library Browsing and Internet of Things Technology. In: Emerging Trends and Impacts of the Internet of Things in Libraries. IGI Global, pp. 52–70.
Halaška, M., Šperka, R., 2019. Performance of an automated process model discovery–the logistics process of a manufacturing company. Eng. Manage. Prod. Services 11 (2), 106–118.

Harrison, R., Vera, D., Ahmad, B., 2016. Engineering Methods and Tools for Cyber-Physical Automation Systems, 104(5), pp.973–985.
Haverkort, B.R., Zimmermann, A., 2017. Smart Industry: How ICT Will Change the Game! IEEE Internet Comput. 21 (1), 8–10.
He, P., Li, K., Kumar, P.R., 2021. An enhanced branch-and-price algorithm for the integrated production and transportation scheduling problem. Int. J. Prod. Res. 1–16.
Hitmar, M., 2014. Six Ways the "Internet of Things" Can Boost Quality | IndustryWeek. Available at: https://www.industryweek.com/IoT-boosts-quality [Accessed October 17, 2018].
Ho, G.T.S., Tang, Y.M., Tsang, K.Y., Tang, V., Chau, K.Y., 2021. A blockchain-based system to enhance aircraft parts traceability and trackability for inventory management. Expert Syst. Appl. 179, 115101.
Hofmann, E. & Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Comput. Ind., 89, pp.23–34. Available at: http://dx.doi.org/10.1016/j.compind.2017.04.002.
Huan, S.H., Sheoran, S.K., Wan, G., 2004. A review and analysis of supply chain operations reference (SCOR) model. Supply Chain Manage. 9 (1), 23–29.
Ivanov, D., Dolgui, A., 2021. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Prod. Plann. Control 32 (9), 775–788.
Ivanov, D., Dolgui, A., 2021. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Prod. Plann. Control 32 (9), 775–788.
Ivanov, D., Sokolov, B., Dolgui, A., 2020. Introduction to scheduling in industry 4.0 and cloud manufacturing systems. In: Scheduling in Industry 4.0 and Cloud Manufacturing. Springer, Cham, pp. 1–9.
Ivanov, D., et al., 2016. A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0. Int. J. Prod. Res. 54(2), pp.386–402. Available at: http://dx.doi.org/10.1080/00207543.2014.999958.
James, C.D., Mondal, S., 2019. A review of machine efficiency in mass customization. Benchmarking: Int. J. 26 (2), 638–691. https://doi.org/10.1108/BIJ-05-2018-0120.
Jermsittiparsert and Boonratanakittiphumi, 2019a. The supply chain management, enterprise resource planning systems and the organizational performance of thai manufacturing firms: Does the application of industry 4.0 matter? Int. J. Innov., Creativity Change 8 (8), 82–102.
Jermsittiparsert and Boonratanakittiphumi, 2019b. The role of additive manufacturing and supply chain management in improving the supply chain performance: A case of industry 4.0 in disk Thailand. Int. J. Innov., Creativity Change 8 (8), 103–121.
Jha, A.K., Agi, M.A., Ngai, E.W., 2020. A note on big data analytics capability development in supply chain. Decis. Support Syst. 138, 113382.
Jimeno-Morenilla, A., Azariadis, P., Molina-Carmona, R., Kyratzi, S., Moulianitis, V., 2021. Technology enablers for the implementation of Industry 4.0 to traditional manufacturing sectors: A review. Comput. Ind. 125, 103390.
Kaivo-oja, J., Kuusi, O., Knudsen, M.S., Lauraéus, I.T., 2020. Digital twin: current shifts and their future implications in the conditions of technological disruption. Int. J. Web Eng. Technol. 15 (2), 170–188.
Kalsoom, T., Ramzan, N., Ahmed, S., Ur-Rehman, M., 2020. Advances in Sensor Technologies in the Era of Smart Factory and Industry 4.0. Sensors 20 (23), 6783.
Kamble, S.S., Gunasekaran, A., 2020. Big data-driven supply chain performance measurement system: a review and framework for implementation. Int. J. Prod. Res. 58 (1), 65–86.
Kamble, S.S., Gunasekaran, A., Gawankar, S.A., 2018. Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. Process Saf. Environ. Prot. 117, 408–425.
Kang, H.S., et al., 2016. Smart manufacturing: Past research, present findings, and future directions. Int. J. Precision Eng. Manuf. - Green Technol. 3 (1), 111–128.
Karlsson, C., 2016. Research Methods for Operations Management Second Edi., New York.
Kaur, J., Kaur, P.D., 2018. Electronic Commerce Research and Applications CE-GMS : A cloud IoT-enabled grocery management system, 28, pp.63–72.
Kazancoglu, Y., Ozkan-Ozen, Y.D., Sagnak, M., Kazancoglu, I. and Dora, M., 2021. Framework for a sustainable supply chain to overcome risks in transition to a circular economy through Industry 4.0. Prod. Plann. Control, pp.1-16.
Kerin, M., Pham, D.T., 2019. A review of emerging industry 4.0 technologies in remanufacturing. J. Cleaner Prod. 237, 117805.
Khan, P.W., Byun, Y.C., Park, N., 2020. IoT-Blockchain Enabled Optimized Provenance System for Food Industry 4.0 Using Advanced Deep Learning. Sensors 20 (10), 2990.
Kilubi, I., Haasis, H.D., 2016. Supply chain risk management research: avenues for further studies. Available at: Int. J. Supply Chain Operations Resilience 2 (1), 51 http://www.inderscience.com/link.php?id=75899.
Kitzinger, J., 1995. Qualitative Research: Introducing focus groups. BMJ 311 (7000), 299.
Koh, L., Orzes, G., Jia, F.J., 2019. The fourth industrial revolution (Industry 4.0): technologies disruption on operations and supply chain management. Int. J. Oper. Prod. Manage. 39 (6/7/8), 817–828. https://doi.org/10.1108/IJOPM-08-2019-788.
Kouhizadeh, M., Saberi, S., Sarkis, J., 2021. Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. Int. J. Prod. Econ. 231, 107831.
Kovacs, G., Kot, S., 2016. New Logistics and Production Trends As the Effect of Global Economy Changes. Available at: Polish J. Manage. Stud. 14 (2), 115–126 http://pjms.zim.pcz.pl/files/New-Logistics-and-Production-Trends-as-the-Effect-of-Global-Economy-Changes.pdf.
Kriebitz, A., Lütge, C., 2020. Artificial intelligence and human rights: a business ethical assessment. Bus. Human Rights J. 5 (1), 84–104.
Krugh, M., et al., 2017. Measurement of Operator-machine Interaction on a Chaku-chaku Assembly Line. Procedia Manuf. 10, 123–135.
Kusiak, A., 2018. Smart manufacturing. Int. J. Prod. Res. 56(1–2), pp.508–517. Available at: https://doi.org/10.1080/00207543.2017.1351644.
Kuznaz, T., Pfohl, H.-C., Yahsi, B., 2015. The impact of Industry 4.0 on the Supply Chain. In: Innovations and Strategies for Logistics and Supply Chains, pp. 32–58.
Lallie, H.S., Shepherd, L.A., Nurse, J.R., Erola, A., Epiphaniou, G., Maple, C., Bellekens, X., 2021. Cyber security in the age of COVID-19: A timeline and analysis of cyber-crime and cyber-attacks during the pandemic. Comput. Security 105, 102248.
Lebas, M.J., 1995. Performance measurement and performance management. Int. J. Prod. Econ. 41 (1–3), 23–35.
Lee, C., Lim, C., 2021. From technological development to social advance: A review of Industry 4.0 through machine learning. Technol. Forecast. Soc. Chang. 167, 120653.
Lehyani, F., Zouari, A., Ghorbel, A., Tollenaere, M., 2021. Defining and Measuring Supply Chain Performance: A Systematic Literature Review. Eng. Manage. J. 33 (4), 283–313.
Lerher, T., 2018. Warehousing 4.0 by using shuttlebased storage and retrieval systems. FME Trans. 46 (3), 381–385.
Li, D., et al., 2017a. A big data enabled load-balancing control for smart manufacturing of Industry 4.0. Cluster Comput. 20 (2), 1855–1864.
Li, T.H.S., et al., 2017d. A Three-Dimensional Adaptive PSO-Based Packing Algorithm for an IoT-Based Automated e-Fulfillment Packaging System. IEEE Access 5, 9188–9205.
Li, X., et al., 2017e. A review of industrial wireless networks in the context of Industry 4.0. Wireless Netw. 23 (1), 23–41.
Li, Y., Dai, J., Cui, L., 2020. The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model. Int. J. Prod. Econ., 107777
Li, L. et al., 2017. An improved stochastic programming model for supply chain planning of MRO spare parts. Appl. Math. Modell., 47, pp.189–207. Available at: http://dx.doi.org/10.1016/j.apm.2017.03.031.
Li, G., Hou, Y., Wu, A., 2017b. Fourth Industrial Revolution: technological drivers, impacts and coping methods. Chinese Geograph. Sci. 27 (4), 626–637.
Lianguang, M., 2014. Study on supply-chain of modern agricultural products based on IOT in order to guarantee the quality and safety. Adv. J. Food Sci. Technol. 6 (4), 520–526.
Lim, C.H., Lim, S., How, B.S., Ng, W.P.Q., Ngan, S.L., Leong, W.D., Lam, H.L., 2021. A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach. Renew. Sustain. Energy Rev. 135, 110223.
Lima-Junior, F.R., Carpinetti, L.C.R., 2017. Quantitative models for supply chain performance evaluation: a literature review. Comput. Ind. Eng. 113, 333–346.

Lin, K.C., Shyu, J.Z., Ding, K., 2017. A cross-strait comparison of innovation policy under industry 4.0 and sustainability development transition. Sustainability (Switzerland) 9 (5).
Liu, B., De Giovanni, P., 2019. Green process innovation through Industry 4.0 technologies and supply chain coordination. Ann. Oper. Res. 1–36.
Long, F., Zeiler, P. & Bertsche, B., 2018. Realistic modelling of flexibility and dependence in production systems in Industry 4.0 for analysing their productivity and availability. Proc. Instit. Mech. Eng., Part O: J. Risk Reliab. 232(2), pp.174–184.
Lu, Y., 2017. Industry 4.0: A survey on technologies, applications and open research issues. J. Ind. Inform. Integration 6, pp.1–10. Available at: http://dx.doi.org/10.1016/j.jii.2017.04.005.
Lugaresi, G., Matta, A., 2021. Automated manufacturing system discovery and digital twin generation. J. Manuf. Syst. 59, 51–66.
Lyu, M., Biennier, F., Ghodous, P., 2021. Integration of ontologies to support Control as a Service in an Industry 4.0 context. SOCA 15 (2), 127–140.
Ma, J., Wang, Q., Zhao, Z., 2017. SLAE–CPS: Smart lean automation engine enabled by cyber-physical systems technologies. Sensors (Switzerland) 17 (7).
Maestrini, V. et al., 2017. Supply chain performance measurement systems: A systematic review and research agenda. Int. J. Prod. Econ. 183(November 2016), pp.299–315. Available at: http://dx.doi.org/10.1016/j.ijpe.2016.11.005.
Mahroof, K., 2019. A human-centric perspective exploring the readiness towards smart warehousing: The case of a large retail distribution warehouse. Int. J. Inf. Manage. 45, 176–190.
Majeed, M.A.A., Rupasinghe, T.D., 2017. Internet of things (IoT) embedded future supply chains for industry 4.0: An assessment from an ERP-based fashion apparel and footwear industry. Available at: Int. J. Supply Chain Manage. 6 (1), 25–40 https://www.scopus.com/inward/record.uri?eid=2-s2.0-85016560680&partnerID=40&md5=3777467dbbf669c2f570e02870f3394e.
Manyika, J., et al., 2013. Disruptive technologies: Advances that will transform life, business, and the global economy. Available at: McKinsey Global Insitute May, 163 http://www.mckinsey.com/insights/business_technology/disruptive_technologies%5Cnhttp://www.chrysalixevc.com/pdfs/mckinsey_may2013.pdf.
Maslarić, M., Nikoličić, S., Mirčetić, D., 2016. Logistics Response to the Industry 4.0: The Physical Internet. Open. Engineering 6 (1), 511–517.
Mastos, T.D., Nizamis, A., Vafeiadis, T., Alexopoulos, N., Ntinas, C., Gkortzis, D., Papadopoulos, A., Ioannidis, D., Tzovaras, D., 2020. Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution. J. Cleaner Prod., 122377
Moghaddam, M., Nof, S.Y., 2018. Collaborative service-component integration in cloud manufacturing. Int. J. Prod. Res. 56 (1–2), 677–691.
Molka-Danielsen, J., Engelseth, P., Wang, H., 2018. Large scale integration of wireless sensor network technologies for air quality monitoring at a logistics shipping base. J. Ind. Inform. Integration, 10(November 2017), pp.20–28. Available at: https://doi.org/10.1016/j.jii.2018.02.001.
Moradlou, H. et al., 2018. Reshoring and additive manufacturing. 7(3), pp.241–263.
Moreira, A.C., Ferreira, L.M. & Zimmermann, R., 2018. Innovation and Supply Chain Management: Relationship, Collaboration and Strategies, Available at: https://books.google.nl/books?id=wvhYDwAAQBAJ&pg=PA324&lpg=PA324&dq=The+main+benefit+of+blockchain+is+that+it+allows+significant+simplification+of+interaction+and+reduces+the+noise+in+communication+between+agents,+thus+allowing+them+to+communicate+directl.
Morella, P., Lambán, M.P., Royo, J., Sánchez, J.C., Ng Corrales, L.D.C., 2020. Development of a new green indicator and its implementation in a cyber–physical system for a green supply chain. Sustainability 12 (20), 8629.
Mostafa, N., Hamdy, W., Alawady, H., 2019. Impacts of Internet of Things on supply chains: A framework for warehousing. Social Sci. 8 (3), 84.
Mrugalska, B., Ahmed, J., 2021. Organizational agility in industry 4.0: A systematic literature review. Sustainability 13 (15), 8272.
Müller, C., Grunewald, M., Spengler, T.S., 2017. Redundant configuration of automated flow lines based on "Industry 4.0"-technologies. Journal of. Bus. Econ. 87 (7), 877–898.
Murmura, F., Bravi, L., 2018. Additive manufacturing in the wood-furniture sector: Sustainability of the technology, benefits and limitations of adoption. J. Manuf. Technol. Manage. 29 (2), 350–371.
Mustafee, N., Katsaliaki, K., Taylor, S.J., 2021. Distributed Approaches to Supply Chain Simulation: A Review. ACM Trans. Model. Comput. Simul. (TOMACS) 31 (4), 1–31.
Nandi, S., Hervani, A.A., Helms, M.M., Sarkis, J., 2021. Conceptualising Circular economy performance with non-traditional valuation methods: Lessons for a post-Pandemic recovery. Int. J. Logist. Res. Appl. 1–21.
Nascimento, D.L.M., Alencastro, V., Quelhas, O.L.G., Caiado, R.G.G., Garza-Reyes, J.A., Rocha-Lona, L., Tortorella, G., 2018. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. J. Manuf. Technol. Manage. 30 (3), 607–627.
Neely, A., Gregory, M., Platts, K., 1995. Performance measurement system design: A literature review and research agenda. Int. J. Oper. Prod. Manag. 15 (4), 80–116.
Nia, A.R., Awasthi, A., Bhuiyan, N., 2021. Industry 4.0 and demand forecasting of the energy supply chain: A literature review. Comput. Ind. Eng. 154, 107128.
Nica, E., 2019. Cyber-physical production networks and advanced digitalization in Industry 4.0 manufacturing systems: Sustainable supply chain management, organizational resilience, and data-driven innovation. Journal of Self-Governance and Management. Economics 7 (3), 27–33.
Novak, A., Bennett, D., Kliestik, T., 2021. Product decision-making information systems, real-time sensor networks, and artificial intelligence-driven big data analytics in sustainable Industry 4.0. Economics. Manage. Financial Markets 16 (2), 62–72.
Oesterreich, T.D., Teuteberg, F., 2016. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. Comput. Ind. 83, 121–139.
Oh, A.S., 2019. Development of a Smart Supply-Chain Management Solution Based on Logistics Standards Utilizing Artificial Intelligence and the Internet of Things. J. Inform. Commun. Convergence Eng. 17 (3), 198–204.
Oku, K., Okada, K., Miyatsuji, H., 2015. NEC industrial IoT - Building the foundation for next-generation monozukuri. NEC Tech. J. 10 (1), 23–27.
Oncioiu, I., Bunget, O.C., Türkeș, M.C., Căpușneanu, S., Topor, D.I., Tamaș, A.S., Rakoș, I.S., Hint, M.Ș., 2019. The impact of big data analytics on company performance in supply chain management. Sustainability 11 (18), 4864.
Oztemel, E., Gursev, S., 2020. Literature review of Industry 4.0 and related technologies. J. Intell. Manuf. 31 (1), 127–182.
Pagoropoulos, A., Maier, A., McAloone, T.C., 2017. Assessing transformational change from institutionalising digital capabilities on implementation and development of Product-Service Systems: Learnings from the maritime industry. J. Cleaner Prod. 166, 369–380.
Pandey, S., Singh, R.K., Gunasekaran, A., Kaushik, A., 2020. Cyber security risks in globalized supply chains: conceptual framework. J. Global Oper. Strategic Sourcing.
Piccarozzi, M. & Aquilani, B., 2018. Industry 4 . 0 in Management Studies: A Systematic Literature Review. pp.1–24.
Pivoto, D.G., de Almeida, L.F., da Rosa Righi, R., Rodrigues, J.J., Lugli, A.B., Alberti, A.M., 2021. Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review. J. Manuf. Syst. 58, 176–192.
Pyun, J., Rha, J.S., 2021. Review of Research on Digital Supply Chain Management Using Network Text Analysis. Sustainability 13 (17), 9929.
Qi, Q., Tao, F., 2018. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. IEEE Access 6, 3585–3593.
Radanliev, P., De Roure, D., Page, K., Nurse, J.R., Mantilla Montalvo, R., Santos, O., Maddox, L.T., Burnap, P., 2020. Cyber risk at the edge: current and future trends on cyber risk analytics and artificial intelligence in the industrial internet of things and industry 4.0 supply chains. Cybersecurity 3, 1–21.
Rahman, M., Kamal, M.M., Aydin, E., Haque, A.U., 2022. Impact of Industry 4.0 drivers on the performance of the service sector: comparative study of cargo logistic firms in developed and developing regions. Prod. Plann. Control 33 (2–3), 228–243.
Rai, R., Tiwari, M.K., Ivanov, D., Dolgui, A., 2021. Machine learning in manufacturing and industry 4.0 applications. Int. J. Prod. Res. 59 (16), 4773–4778.
Raji, I.O., Shevtshenko, E., Rossi, T. and Strozzi, F., 2021, October. Modelling the relationship of digital technologies with lean and agile strategies. In Supply Chain Forum: An International Journal (Vol. 22, No. 4, pp. 323-346). Taylor & Francis.
Rajput, S., Singh, S.P., 2021. Industry 4.0 model for integrated circular economy-reverse logistics network. Int. J. Logist. Res. Appl. 1–41.
Rakyta, M., et al., 2016. Proactive approach to smart maintenance and logistics as a auxiliary and service processes in a company. J. Appl. Eng. Sci. 14 (4), 433–442.
Ranjan, J., Foropon, C., 2021. Big data analytics in building the competitive intelligence of organizations. Int. J. Inf. Manage. 56, 102231.
Ratna, V.V., 2020. Conceptualizing Internet of Things (IoT) model for improving customer experience in the retail industry. Int. J. Manage. 11 (5).
Reddy, G.R.K., Singh, H., Hariharan, S., 2016. Supply chain wide transformation of traditional industry to industry 4.0. ARPN J. Eng. Appl. Sci. 11 (18), 11089–11097.
Reed, J., 2018. The Industry 4.0 revolution. DAIRY INDUSTRIES international, (May), pp.40–42.

Reitze, A., et al., 2018. Roadmap for a Smart Factory: A Modular, Intelligent Concept for the Production of Specialty Chemicals. Angewandte Chemie - International Edition 57 (16), 4242–4247.

Rejeb, A., Keogh, J.G., Wamba, S.F., Treiblmaier, H., 2020. The potentials of augmented reality in supply chain management: a state-of-the-art review. Manage. Rev. Quart. 1–38.

Rejeb, A., Keogh, J.G., Wamba, S.F., Treiblmaier, H., 2021. The potentials of augmented reality in supply chain management: A state-of-the-art review. Manage. Rev. Quart. 71 (4), 819–856.

Reyes, M., Meier, R., Pereira, S., Silva, C.A., Dahlweid, F.M., Tengg-Kobligk, H.V., Summers, R.M., Wiest, R., 2020. On the interpretability of artificial intelligence in radiology: challenges and opportunities. Radiol.: Artificial Intell. 2 (3), e190043.

Rodič, B., 2017. Industry 4.0 and the New Simulation Modelling Paradigm. Organizacija 50 (3), 193–207.

Rødseth, H., Schjølberg, P. & Marhaug, A., 2017. Deep digital maintenance. Adv. Manuf. 5(4), pp.299–310. Available at: https://doi.org/10.1007/s40436-017-0202-9.

Romero-Silva, R., De Leeuw, S., 2021. Learning from the past to shape the future: A comprehensive text mining analysis of OR/MS reviews. Omega 100, 102388.

Ruppert, T., Abonyi, J., 2018. Software Sensor for Activity-Time Monitoring and Fault Detection in Production Lines. Available at: Sensors 18 (7), 2346 http://www.mdpi.com/1424-8220/18/7/2346.

Sachdeva, N., Shrivastava, A.K., Chauhan, A., 2021. Modeling supplier selection in the era of Industry 4.0. Benchmarking: Int. J. 28 (5), 1809–1836. https://doi.org/10.1108/BIJ-12-2018-0441.

Sanders, N.R., Boone, T., Ganeshan, R., Wood, J.D., 2019. Sustainable supply chains in the age of AI and digitization: research challenges and opportunities. J. Bus. Logist. 40 (3), 229–240.

Sartal, A., Bellas, R., Mejías, A.M. and García-Collado, A., 2020. The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. Adv. Mech. Eng. 12(5), p.1687814020925232.

Saunders, M., Lewis, P. & Thornhill, A., 2007. Research Methods for Business Students 5th ed.

Sawangwong, A., Chaopaisarn, P., 2021. The impact of applying knowledge in the technological pillars of Industry 4.0 on supply chain performance. Kybernetes.

Schniederjans, D.G., Curado, C., Khalajhedayati, M., 2020. Supply chain digitisation trends: An integration of knowledge management. Int. J. Prod. Econ. 220, 107439.

Schüter, F., Hetterscheid, E., 2017. Supply Chain Process Oriented Supply Chain Process Oriented Technology-Framwork for Industry 4.0. Proceeding of the Hamburg International Conference of Logistics (HICL).

Schütze, A., Helwig, N., Schneider, T., 2018. Sensors 4.0 - Smart sensors and measurement technology enable Industry 4.0. J. Sens. Sens. Syst. 7 (1), 359–371.

Schwab, K., 2016. The Fourth Industrial Revolution. World Economic Forum.

Serrano-Ruiz, J.C., Mula, J., Poler, R., 2021. Smart Master Production Schedule for the Supply Chain: A Conceptual Framework. Computers 10 (12), 156.

Seuring, S. et al., 2005. Conducting a literature review-The example of sustainability in supply chains. Research Methodologies in Supply Chain Management: In Collaboration with Magnus Westhaus, pp.91–106.

Seyedghorban, Z., Tahernejad, H., Meriton, R., Graham, G., 2020. Supply chain digitalization: past, present and future. Prod. Plann. Control 31 (2–3), 96–114.

Shayganmehr, M., Gupta, S., Laguir, I., Stekelorum, R. and Kumar, A., 2021. Assessing the role of industry 4.0 for enhancing swift trust and coordination in humanitarian supply chain. Ann. Oper. Res. pp.1-33.

Shen, B., Dong, C., Ng, C.T., 2021. Technology-Driven Supply Chain Management with OR Applications in Industrial 4.0 Era. Asia-Pacific J. Operational Res. 2102003.

Shukri, S.E., Al-Sayyed, R., Hudaib, A., Mirjalili, S., 2021. Enhanced multi-verse optimizer for task scheduling in cloud computing environments. Expert Syst. Appl. 168, 114230.

Siafara, L.C., et al., 2018. SAMBA – an architecture for adaptive cognitive control of distributed Cyber-Physical Production Systems based on its self-awareness. Available at: Elektrotechnik und Informationstechnik 135 (3), 270–277 https://www.scopus.com/inward/record.uri?eid=2-s2.0-85048000269&doi=10.1007%2Fs00502-018-0614-7&partnerID=40&md5=f457c9ba346e6dc0dbc11d4d303ac1c2.

Sim, S., Cho, M., 2021. Convergence model of AI and IoT for virus disease control system. Pers. Ubiquit. Comput. 1–11.

Simchi-Levi, D., Wu, M.X., 2018. Powering retailers' digitization through analytics and automation. Int. J. Prod. Res. 56 (1–2), 809–816.

Spieske, A. and Birkel, H., 2021. Improving supply chain resilience through industry 4.0: a systematic literature review under the impressions of the COVID-19 pandemic. Comput. Ind. Eng. 158, p.107452.

Srai, J.S. et al., 2016. Distributed manufacturing: scope, challenges and opportunities. Int. J. Prod. Res. 54(23), pp.6917–6935. Available at: http://dx.doi.org/10.1080/00207543.2016.1192302.

Stanisławski, R., Szymonik, A., 2021. Impact of Selected Intelligent Systems in Logistics on the Creation of a Sustainable Market Position of Manufacturing Companies in Poland in the Context of Industry 4.0. Sustainability 13 (7), 3996.

Staudt, F.H. et al., 2015. Warehouse performance measurement: A literature review. Int. J. Prod. Res. 53(18), pp.5524–5544. Available at: http://dx.doi.org/10.1080/00207543.2015.1030466.

Steinhaeusser, T., Reinhart, G., 2017. Ensuring Time-saving and Effective Production Planning by Prioritizing Activities based on Company-specific Validation Success Rates. Procedia CIRP, 61, pp.505–510. Available at: http://dx.doi.org/10.1016/j.procir.2016.11.198.

Stock, R.J., Boyer, L.S., 2009. Developing a consensus definition of supply chain management: a qualitative study. Int. J. Phys. Distrib. Logist. Manage. 39 (8), 690–711.

Strandhagen, J.O., et al., 2017. Logistics 4.0 and emerging sustainable business models. Adv. Manuf.cturing 5 (4), 359–369.

Strandhagen, J.W. et al., 2017. The fit of Industry 4.0 applications in manufacturing logistics: a multiple case study. Adv. Manuf. 5(4), pp.344–358. Available at: https://doi.org/10.1007/s40436-017-0200-y.

Strozzi, F. et al., 2017. Literature review on the 'smart factory' concept using bibliometric tools. Int. J. Prod. Res. 55(22), pp.1–20. Available at: https://doi.org/10.1080/00207543.2017.1326643.

Subramanian, N., Abdulrahman, M.D., Zhou, X., 2014. Integration of logistics and cloud computing service providers: Cost and green benefits in the Chinese context. Transport. Res. Part E: Logist. Transport. Rev. 70 (1), 86–98.

Sun, L., Wang, Y., Hua, G., Cheng, T.C.E., Dong, J., 2020. Virgin or recycled? Optimal pricing of 3D printing platform and material suppliers in a closed-loop competitive circular supply chain. Resour. Conserv. Recycl. 162, 105035.

Sundarakani, B., Kamran, R., Maheshwari, P., Jain, V., 2019. Designing a hybrid cloud for a supply chain network of Industry 4.0: a theoretical framework. Benchmarking: Int. J.

Tang, H., et al., 2017. CASOA: An Architecture for Agent-Based Manufacturing System in the Context of Industry 4.0. IEEE Access 6, 12746–12754.

Tang, D., et al., 2018. Using autonomous intelligence to build a smart shop floor. Int. J. Adv. Manuf. Technol. 94 (5–8), 1597–1606.

Tang, C.S., Veelenturf, L.P., 2019. The strategic role of logistics in the industry 4.0 era. Transport. Res. Part E: Logist. Transport. Rev. 129, 1–11.

Thiebes, S., Lins, S., Sunyaev, A., 2021. Trustworthy artificial intelligence. Electronic Markets 31 (2), 447–464.

Thoben, K.-D., et al., 2017. Industrie 4.0 and Smart Manufacturing - A review of research issues and application examples. Article in Int. J. Automation Technol. https://www.researchgate.net/profile/Thorsten_Wuest/publication/312069858_Industrie_40_and_Smart_Manufacturing_-_A_Review_of_Research_Issues_and_Application_Examples/links/586e0bb108aebf17d3a73562.pdf.

Tibazarwa, A., 2021. Strategic Integration for Hardware and Software Convergence Complexity. IEEE Eng. Manage. Rev. 49 (3), 92–102.

Tjahjono, B., Espluges, C., et al., 2017. What doesIndustry 4.0 mean to Supply Chain? Procedia Manuf., 13, pp.1183–1190. Available at: https://doi.org/10.1016/j.promfg.2017.09.193.

Tjahjono, B., Esplugues, C., et al., 2017. What does Industry 4.0 mean to Supply Chain? Procedia Manuf., 13, pp.1175–1182. Available at: https://doi.org/10.1016/j.promfg.2017.09.191.

Toka, A., 2013. Cloud Computing in Supply Chain Management: An Overview. E-Logistics and E-Supply Chain Management, (January), pp.218–231.

Tran-Dang, H., Kim, D.S., 2021. The Physical Internet in the Era of Digital Transformation: Perspectives and Open Issues. IEEE Access 9, 164613–164631.
Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Available at: Br. J. Manag. 14 (3), 207–222 http://doi.wiley.com/10.1111/1467-8551.00375.
Trappey, A.J.C., Trappey, C. V., Hareesh Govindarajan, U., et al., 2017. A review of essential standards and patent landscapes for the Internet of Things: A key enabler for Industry 4.0. Adv. Eng. Inform. 33, 208–229. Available at: http://dx.doi.org/10.1016/j.aei.2016.11.007.
Trappey, A.J.C., Trappey, C.V., Fan, C.Y., et al., 2017a. IoT patent roadmap for smart logistic service provision in the context of Industry 4.0. Journal of the Chinese Institute of Engineers. Trans. Chinese Instit. Eng., Series A/Chung-kuo Kung Ch'eng Hsuch K'an 40 (7), 593–602.
Trstenjak, M., Cosic, P., 2017. Process Planning in Industry 4.0 Environment. Procedia Manuf. 11 (June), 1744–1750.
Tsuchiya, A. et al., 2018a. Software defined networking firewall for industry 4.0 manufacturing systems. J. Ind. Eng. Manage. 11(2), p.318. Available at: http://www.jiem.org/index.php/jiem/article/view/2534.
Tsuchiya, A. et al., 2018b. Software defined networking firewall for industry 4.0 manufacturing systems. J. Ind. Eng. Manage. 11(2), p.318.
Tupa, J., Simota, J., Steiner, F., 2017. Aspects of Risk Management Implementation for Industry 4.0. Procedia Manuf. 11 (June), 1223–1230.
Tuptuk, N., Hailes, S., 2018. Security of smart manufacturing systems. J. Manuf. Syst. 47 (February), 93–106.
Tuzkaya, U.R., 2021. A Single Side Priority Based GA Approach for 3D Printing Center Integration to Spare Part Supply Chain in Automotive Industry. Tehnički vjesnik 28 (3), 836–844.
Ud Din, F., Paul, D., Ryan, J., Henskens, F., Wallis, M., 2021. AOSR 2.0: A Novel Approach and Thorough Validation of an Agent-Oriented Storage and Retrieval WMS Planner for SMEs, under Industry 4.0. Future Internet 13 (6), 155.
Ustundag, A., Tanyas, M., 2009. The impacts of Radio Frequency Identification (RFID) technology on supply chain costs. Transport. Res. Part E: Logist. Transport. Rev. 45 (1), 29–38.
Vanderroost, M., Ragaert, P., Verwaeren, J., De Meulenaer, B., et al., 2017. The digitization of a food package's life cycle: Existing and emerging computer systems in the logistics and post-logistics phase. Comput. Ind. 87, pp.15–30. Available at: http://dx.doi.org/10.1016/j.compind.2017.02.002.
Vanderroost, M., Ragaert, P., Verwaeren, J., Meulenaer, B. De, et al., 2017. Computers in Industry The digitization of a food package ' s life cycle: Existing and emerging computer systems in the pre-logistics phase. Comput. Ind., 87, pp.1–14. Available at: http://dx.doi.org/10.1016/j.compind.2017.02.002.
Wagire, A.A., Rathore, A.P.S., Jain, R., 2019. Analysis and synthesis of Industry 4.0 research landscape. J. Manuf. Technol. Manage.
Waibel, M.W. et al., 2017. Investigating the Effects of Smart Production Systems on Sustainability Elements. Procedia Manuf. 8(October 2016), pp.731–737. Available at: http://dx.doi.org/10.1016/j.promfg.2017.02.094.
Wang, S., et al., 2016. Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. Available at: Comput. Netw. 101, 158–168 https://ac.els-cdn.com/S1389128615005046/1-s2.0-S1389128615005046-main.pdf?_tid=3c0e75f6-ce9b-11e7-805c-00000aacb361&acdnat=1511255358_ea06e74d398925ac317a9a5de38adbb7.
Wang, Y. et al., 2017. Industry 4.0: a way from mass customization to mass personalization production. Adv. Manuf. 5(4), 311–320. Available at: https://doi.org/10.1007/s40436-017-0204-7.
Wang, J., Lim, M.K., Zhan, Y., Wang, X., 2020. An intelligent logistics service system for enhancing dispatching operations in an IoT environment. Transport. Res. Part E: Logist. Transport. Rev., 135, art. no. 101886.
Wang, C., Jiang, P., Lu, T., 2017. Production events graphical deduction model enabled real-time production control system for smart job shop. Proc. Instit. Mech. Eng., Part C: J. Mech. Eng. Sci. 232 (28), 2803–2820.
Weyer, S., Schmitt, M., Ohmer, M., Gorecky, D., 2015. Towards industry 4.0 - Standardization as the crucial challenge for highly modular, multi-vendor production systems. IFAC-PapersOnLine, 28(3), pp.579–584. Available at: http://dx.doi.org/10.1016/j.ifacol.2015.06.143.
Weyer, S., Schmitt, M., Ohmer, M., Gorecky, D., et al., 2015. Standardization as as the the crucial crucial challenge challenge Towards Standardization as the crucial challenge for highly production systems for highly modular , multi-vendor production systems for highly modular , multi-vendor production. IFAC-PapersOnLine, 48(3), pp.579–584. Available at: http://dx.doi.org/10.1016/j.ifacol.2015.06.143.
Xue, L., Ray, G., Sambamurthy, V., 2013a. The impact of supply-side electronic integration on customer service performance. J. Oper. Manage. 31 (6), 363–375.
Xue, L., Zhang, C., et al., 2013b. Risk Mitigation in Supply Chain Digitization: System Modularity and Information Technology Governance. Available at: J. Manage. Inform. Syst.ms 30 (1), 325–352 http://www.tandfonline.com/doi/full/10.2753/MIS0742-1222300110.
Yan, J., et al., 2017. Industrial Big Data in an Industry 4.0 Environment: Challenges, Schemes, and Applications for Predictive Maintenance. IEEE Access 5, 23484–23491.
Yavas, V., Ozkan-Ozen, Y.D., 2020. Logistics centers in the new industrial era: A proposed framework for logistics center 4.0. Transport. Res. Part E: Logist. Transport. Rev., 135, art. no. 101864.
Zahedi, A., Salehi-Amiri, A., Smith, N.R., Hajiaghaei-Keshteli, M., 2021. Utilizing IoT to design a relief supply chain network for the SARS-COV-2 pandemic. Appl. Soft Comput. 104, 107210.
Zheng, T., Ardolino, M., Bacchetti, A., Perona, M., Zanardini, M., 2020. The impacts of Industry 4.0: a descriptive survey in the Italian manufacturing sector. J. Manuf. Technol. Manage. 31 (5), 1085–1115. https://doi.org/10.1108/JMTM-08-2018-0269.
Zheng, T., Ardolino, M., Bacchetti, A., Perona, M., 2021. The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review. Int. J. Prod. Res. 59 (6), 1922–1954.
Zheng, M., Wu, K., 2017. Smart spare parts management systems in semiconductor manufacturing. Ind. Manage. Data Syst. 117 (4), 754–763.
Zhong, R.Y., et al., 2017. Intelligent Manufacturing in the Context of Industry 4.0: A Review. Engineering 3, 616–630.
Zhu, Q., Sarkis, J., Lai, K.-H., 2014. Supply chain-based barriers for truck-engine remanufacturing in China. Transport. Res. Part E: Logist. Transport. Rev. 68, 103–117.
Zonta, T., da Costa, C.A., da Rosa Righi, R., de Lima, M.J., da Trindade, E.S., Li, G.P., 2020. Predictive maintenance in the Industry 4.0: A systematic literature review. Comput. Ind. Eng. 150, 106889.