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Exploring the reciprocal influences of Industry 4.0 technologies and Sustainability: A Systematic Literature Review

Julien Marius Wenglorz

Work project carried out under the supervision of:

Prof. Paulo Faroleiro

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Abstract

This research explores the reciprocal influences of Industry 4.0 technologies and sustainability based on a systematic literature review to gain knowledge on how to manage the transition towards a more sustainable industrial value creation efficiently and effectively. Quantitative and qualitative analyses based on 120 investigated papers were performed, showing increasing research activity within the field, with a slight tendency towards empirical research and manufacturing focus. Sustainability issues are main drivers for both scientific investigation and the increasing demand for industrial changes, while Industry 4.0 technologies are considered to be suitable solutions to tackle emerging sustainability challenges on each sustainability dimension.

Keywords: Industry 4.0; Sustainable Industrial Value Creation; Sustainability; Systematic Literature Review

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1 Introduction

With 10 years to achieve the United Nation's Agenda 2030 and its 17 Sustainable Development Goals (SDGs), pressure is rising for political, societal, and corporate actors to implement sustainability (SUS) strategies addressing pressing global environmental, social, and economic challenges. While non-binding, these goals have emerged as a roadmap for a more sustainable future, guiding individual and collective action. In recent years, corporations have been challenged by multinational institutions, regulators, customers, and future employees alike to take on responsibility and leverage their power to drive progress and positive change. They are solicited more than ever to incorporate SUS as a whole (People, Planet, and Profit) into their decision-making processes (Elkington 2002; Camilleri 2017). The negative environmental and social externalities of business activities, particularly industrial ones, need to be minimized or, best case, turned into attractive opportunities to create positive and shared value for all stakeholders (Elkington 2002). Indeed, with 27.81% of global value added and 22.0% contribution to global greenhouse gas emissions (World Bank 2018), the industrial sector represents a key lever in shaping a more sustainable and responsible future.

In parallel to this urgent need to reconsider business' role as a societal actor, the industrial sector is currently undergoing a fourth industrial revolution, commonly known as Industry 4.0 (I4.0) (Lasi et al. 2014). Broadly speaking, I4.0 aims to fully integrate machinery and processes both horizontally and vertically across the whole value creation network, using advanced information and communication technologies (ICT) for enhanced real-time data collection, data exchange, and data analysis. Based on the increased granularity and availability of real-time data, smart algorithms cab predict future behaviours and take optimal countermeasures with none or minor human intervention, enhancing operational performance and resource efficiency among others (Abubakr et al. 2020). Leveraging on both advanced ICT and top-edge manufacturing techniques, emerging technologies show promising potential to boost the

transition to a more sustainable industrial value creation (Nara et al. 2021; de Sousa Jabbour et al. 2018), counteracting negative contributions and generating solutions. However, empirical studies conducted in recent years show that performance measurement within the production landscape remains largely focused on economic indicators, with environmental and social metrics appearing to be used solely for legal compliance (Sartal et al. 2020). Whilst literature hints to the potential contribution of I4.0 technologies (I4.0Ts) to the SDGs (Bai et al. 2020; Ivascu 2020), a significant lack of knowledge of the actual relationship between I4.0Ts and SUS remains, e.g., whether environmental benefits outweigh the increased material demand due to the huge increase of integrated technology (Kamble, Gunasekaran, and Gawankar 2018; Bai et al. 2020). Thus, an integrative and interdisciplinary investigation is needed to derive a holistic understanding of the current research status of research (Müller 2020).

This systematic literature review (SLR) aims to contribute to the field with a comprehensive investigation of I4.0Ts's and SUS's reciprocal influence, providing an integrated overview of the status quo in existing research, elaborating on existing insights, ongoing research directions, and research gaps as future research proposals. To do so, following research questions (RQ) have been set:

> **RQ1:** What is the current status of research investigating the relation between Industry 4.0 and sustainability?
>
> **RQ2:** To what extent do Industry 4.0 technologies and sustainability dimensions influence each other?

Furthermore, according sub-research questions (SRQ) were formulated (shown in Section 3) to guide this systematic review. In doing so, this research provides a systematic and comprehensive overview of the research field's current status, its relevant articles, and existing derived insights both academics and practitioners can benefit from by using the provided findings for future research and scientific-based decision making, respectively.

The rest of the research paper is structured as follows. Section 2 provides a brief discussion on this research's main domains, viz., Sustainability, Industry 4.0, and Sustainable Industrial Value Creation, followed by a description of the methodology employed for achieving this research's goals and the respective results in Section 3. Section 4 shows and discusses these results as respective findings. Section 5 provides the paper's limitations and derives successive future research directions before concluding this research paper.

2 Literature Review

2.1 Sustainability

Sustainable development, as it was coined at the turn of the 20th century, emerged as a paradigm seeking to balance social, economic and environmental considerations to ensure a viable, desirable future for the planet and our society (Brundtland 1987). Whilst often perceived to be a matter of political decision-making and institutional powers, harmony between people, planet and profits (Elkington 2002) cannot be achieved without the buy in and proactive involvement of the private sector (Braccini and Margherita 2018). Indeed, economic activities, whilst undeniably serving to generate value to improve the prosperity of societies (Gajdzik et al. 2020), have followed an unbridled growth trajectory, overextending the use of resources and generating of waste beyond planetary boundaries (Jackson 2017). The unbounded negative externalities on the environment and people's basic rights and well-being are a high price being paid for the expansion of economic capital, especially considering the inequality in the distribution of wealth on one hand, and the discriminatory effects of environmental consequence on the other (Ghobakhloo 2020). In recent years, global frameworks like the SDGs have emerged to structure collective progress for a more sustainable future, and been used as a reference point for the private sector to work towards.

The industrial sector, a historic culprit in the linear, often pollution-intensive use of resources, has also been increasingly researching and implementing solutions to better manage the

unwanted externalities of their activities (Tiwari and Khan 2020). Driven by concerns for eco-efficiency, stakeholder scrutiny or truly seeing the competitive advantage they can offer, corporations across the globe are investing into solutions to monitor and reduce their negative externalities and contribute to the development of solutions (Jabbour et al. 2020; Golini, Longoni, and Cagliano 2014). Emerging technologies coined under the umbrella of I4.0 are beginning to prove their potential in supporting the transition of the entire sector towards more environmentally and socially responsible practices, whilst ensuring sustainable economic growth.

2.2 Industry 4.0

The industrial sector, often referred to as "industry", is the part of the economy producing material goods in a thoroughly planned manner with well described, mostly mechanized and automated processes (Lasi et al. 2014). Incremental and fundamental technological innovations have shaped the industry continuously over the past centuries, with four technological leaps being particularly profound, entailing industrial revolutions: The invention of the steam engine, enabling mechanisation of production (Industry 1.0); the electrification of production, enabling mass production based on assembly lines and the division of labour (Industry 2.0); the widespread introduction of computer and industrial robot technology, enabling high degrees of automatization and digitalization (Industry 3.0) (Xu, Xu, and Li 2018; Lasi et al. 2014). The end-to-end integration of smart objects and systems across the whole value chain into an integrated industrial ecosystem based on highly advanced ICT are the main characteristics of the new paradigm shift, namely *Industry 4.0* (Lasi et al. 2014; Xu, Xu, and Li 2018). Main I4.0Ts are thereby Cyber-Physical-Systems, Internet of Things, Cloud Computing, Big Data Analytics – including Artificial Intelligence – and Smart Objects like Smart Sensors and Advanced Robotics (Nara et al. 2021; Hermann, Pentek, and Otto 2016; Lasi et al. 2014; Xu, Xu, and Li 2018). Based on these enabling technologies, further I4.0Ts can be employed, such

as Additive Manufacturing, Advanced Simulations, and Extended Reality (i.e. Augmented Reality and Virtual Reality) (Nara et al. 2021; Bai et al. 2020). Unlike technology trends driving previous industrial revolutions, those underlying the fourth industrial revolution rely on their complementary characteristics, since none of these systems operates independently (Gilchrist 2016). Instead, the smart systems involved communicate and interact with each other in order to make or propose decisions with little to no human intervention (Ghobakhloo 2020).

Based on the performed literature review, following I4.0Ts and principles are further investigated within this SLR's scope, and further explained in Appendix 1: Cyber-Physical-Systems (CPS); Internet of Things (IoT); Cloud Computing (CC); Big Data Analytics (BD); Automation and Robotics (ROB); Horizontal and Vertical System-Integration (HVI); Extended Reality (XR); Additive Manufacturing (AM); Advanced Simulation (SIM); Cyber Security (CS); Blockchain (BC).

2.3 Sustainable industrial value creation

The potential represented by the interplay of these two increasingly present, "hot" opportunities of I4.0 and SUS has engaged academics and practitioners to study the concept of sustainable industrial value creation, in which emerging technologies are leveraged to generate positive value among the social dimension (SO), economic dimension (EC) and environmental dimension (EN) of SUS (Felsberger and Reiner 2020). Integrated, automated and connected technologies, for example, have a crucial role to play in underpinning more resource-efficient production patterns to support corporations' development of sustainable operations. By supporting the optimization of production systems from order to dispatch, not only energy and waste streams, but also health and safety risks can be reduced, generating better environmental (emissions, by-products and waste) and social (working conditions) footprints (Lee et al. 2018; Braccini and Margherita 2018; Margherita and Braccini 2020; R. Kumar, Singh, and Dwivedi

2020). Furthermore, I4.0Ts facilitate the monitoring and accountable reporting of SUS indicators, such as environmental footprint or human rights (Felsberger and Reiner 2020). Even though social concerns surrounding the digitalization and automation of production facilities arise, Felsberger and Reiner (2020) highlight a growing body of research demonstrating that, whilst I4.0 will replace tasks and robotize processes, it is creating jobs across increasingly relevant functions, re-skilling the workforce of the future.

2.4 Need for research

Even though Bai et al. (2020) provide an overview on how latest I4.0Ts may tackle each SDG, there is still a significant lack of scientific knowledge regarding the relationship between I4.0Ts and SUS (Kamble, Gunasekaran, and Gawankar 2018). Whilst most studies focus on I4.0Ts (Felsberger and Reiner 2020) and the correlated positive impacts, such as Margherita and Braccini (2020), Felsberger et al. (2020), and Strandhagen et al. (2020), only few studies focus on risks associated with the introduction of latest I4.0Ts, i.e. Birkel et al. (2019), or the actual intentions of I4.0 implementation efforts, as Brozzi et al. (2020) do. Furthermore, a sharp rise in articles published containing the terms “Sustainability” and “Industry 4.0” in abstract, title or keywords can be observed, with 258 articles published since 2019 compared to 93 articles published before 2019 on Scopus[1]. In view of this sharp rise in research activities relating to the interplay between I4.0 and SUS, an integrative and interdisciplinary investigation is needed to build a comprehensive understanding of ongoing research directions, existing research gaps and respective future research proposals within this field (Müller 2020).

[1] referring to articles in English language

3 Methodology

3.1 Research Design

In accordance to this research's objectives, namely (1) examining the current status of research investigating the relation between I4.0 and SUS, and (2) examining to what extent I4.0Ts and sustainability dimensions (SDs) influence each other, a systematic bibliometric research method was considered as highly suitable for achieving these objectives. In particular, a systematic literature review (SLR), recognized as a transparent, replicable, and scientific method (Mian et al. 2005), was chosen to scrutinize the vast amount of publications in both fields while minimizing potential biases caused by the researcher. Furthermore, the SLR methodology enables a systematic overview of relevant literature and a subsequent content analysis, highlighting scientific consensus and potential divergence and thus proposes viable future research directions (Krippendorff 2018; Duriau, Reger, and Pfarrer 2007). Two main RQs, eleven SRQs, respective RQ aims, as well as needed data and needed analysis to answer these questions were elaborated in order to guide this SLR, fully shown in Appendix 2. Table 1 and Table 2 provide an overview of the two RQs and the respective SRQ.

Table 1 – RQ1 and according SRQs 1.1 – 1.7

RQ1	**What is the current status of research investigating the relation between industry 4.0 and sustainability?**
SRQ1.1	What is the recent development of published articles per year?
SRQ1.2	Which are the most contributing journals?
SRQ1.3	Which are the most cited publications?
SRQ1.4	Which research approach is used most/least often?
SRQ1.5	Which Industry 4.0 domain has research focused on most/least often?
SRQ1.6	Which Industry 4.0 technologies dominate research in the context of sustainable industrial value creation?
SRQ1.7	Which dimensions of sustainability are being primarily investigated in the context of sustainable industrial value creation?

Table 2 – RQ2 and according SRQs 2.1 – 2.4

RQ2	**To what extent do industry 4.0 technologies and sustainability dimensions influence each other?**
SRQ2.1	How do the appearances of sustainability dimensions and Industry 4.0 technologies and principles correlate?
SRQ2.2	Which are specific interdependences among appearance of Industry 4.0 technologies and principles?
SRQ2.3	Which are specific interdependences among appearance of sustainability dimensions?
SRQ2.4	Which are specific interdependences between appearance of sustainability dimensions and appearances of Industry 4.0 technologies and principles

3.2 Data Collection

In order to maximize neutrality during the data collection and analysis process, the steps to be performed for the SLR were clearly predefined before execution. The widely acknowledged PRISMA method (Moher et al. 2009) provided appropriate planning guidelines to further increase generalizability and to enhance the selection's eligibility for statistical and qualitative data descriptions (Bryman 2006; Curry, Nembhard, and Bradley 2009). With the aim to derive the reciprocal influence of I4.0 and SUS, search results ought contain both "Industry 4.0" AND "Sustainability" or one of their respective synonyms in an industrial context, in either the abstract, title or keywords to obtain a comprehensive set of papers. The respective synonyms are based on the literature review previously performed, and shown in Table 3.

Table 3 – Synonyms used for search string

Major term	**Synonyms**
Industry 4.0	Industrie 4.0; 4th Industrial Revolution; fourth industrial revolution; Smart Manufacturing; Connected Manufacturing; IIOT; Industrial Internet of Things; Smart Industry
Sustainability	Sustainability; Sustainable Manufacturing; Sustainable Value Creation; Sustainable Industrial Value Creation; Industrial Sustainable Value Creation; Green Manufacturing; Triple Bottom Line; TBL; Sustainable Production; Sustainable Operations

Relevant academic papers are also subject to (1) be published online and to (2) be published in scientific journals. In order not to exclude any potentially relevant articles, no date constraint was set. Inclusion criteria (IC) and exclusion criteria (EC), as shown in Table 4, were defined to minimize exposure to subjective opinions, ensuring a consistent assessment of search results.

Table 4 – Overview of applied IC and EC during screening process

IC	Research is fully or mainly dedicated to the direct relation between Industry 4.0 and Sustainability
EC1	Paper is a duplicate
EC2	No full text of paper is accessible in English language
EC3	Paper is not an academic article (i.e. conference reviews or forewords)
EC4	Paper is missing an explicit dedication to investigate the relation between Industry 4.0 (or its synonyms) and Sustainability (or its synonyms) in an industrial context

Once the search terms, the search constraints, and the IC and EC were set, the actual search was conducted on three electronic, scientific databases, namely (1) Scopus, (2) Web of Science, and (3) ScienceDirect, all being considered as valid, appropriate databases for rigorous evidence identification for systematic review purposes (Gusenbauer and Haddaway 2020; Harzing and Alakangas 2016), resulting in 351, 231, and 267 articles, respectively. Screening and full-text eligibility analysis, both times applying the defined IC and EC shown in Table 4, resulted in 120 relevant papers. The respective PRISMA flow chart indicating the different stages and numbers of articles included and excluded per stage, is fully shown in Appendix 3.

After collecting these 120 eligible papers for this research's scope, the actual data collection was performed. Next to the paper's title, author(s), abstract, keywords, year of publication, and publishing journal, different type of data was added to the database by the author, derived from the respective SRQs, as described in following paragraphs.

RQ1.4 aims to explore which research approach is used most/least often, thus the applied research approach of the respective paper was extracted and added to the database. Based on common practice within systematic research, such as Kamble et al. (2018) and Felsberger and

Rainer (2020), two main research approaches were considered for categorization, namely (1) *theoretical research* and (2) *empirical research*, further broken down into (1) *conceptual research* and *SLR*, and (2) *case study, interview, survey,* and *simulation*. In this context, theoretical research focusses on theories, ideas, potential opportunities and challenges, and frameworks among others without raising primary data. Empirical research, however, focuses on measurable activities and processes, raising primary data.

RQ1.5 aims to explore which I4.0 domain is explored most/least often, thus the paper's I4.0 domain focus was extracted and added to the database. In this context, three domains of I4.0 were considered, based on previous literature research: Manufacturing (MF), focusing on the actual production processes within a (smart) factory; Supply Chain (SC), focusing on SC processes across factory boundaries; Circular Economy (CE), focusing on the nexus of both MF and SC with the explicit goal to achieve a CE.

RQ1.6 aims to explore which I4.0Ts are talked about most/least often, thus I4.0Ts investigated in the context of SUS were extracted and added to the database to gain insights about which I4.0Ts are driving the sustainable development. As mentioned in Section 2.2, following I4.0Ts were considered: CPS; IoT; CC; BD; ROB; HVI; XR; AM; SIM; CS; BC; SS

RQ1.7 aims to explore which SDs are talked about most/least often, thus SDs investigated in the context of I4.0 were extracted and added to the database to gain insights about research's SD focus (EN, EC, SO).

Furthermore, qualitative data was added to answer **RQ1** and **RQ2** qualitatively, in particular data about (1) What was done? (2) What are the main findings of the author(s)? (3) What is the relation of I4.0 and SUS? The full database is shown in Appendix 11.

3.3 Data analysis

The obtained data was then analysed both quantitatively and qualitatively. Figure 1 illustrates an excerpt of the underlying data the quantitative analyses are based on.

Figure 1 - Excerpt of underlying data for descriptive statistical analyses

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain focus	CPS	IoT	CC	BD	ROB	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
Scopus	Kamble S.S., Gunasekaran A., Gawankar S.A.	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	2018	Process Safety and Environmental Protection	174	no		x	x	x	x		x	x	x	x			x	x	x	SLR

In order to derive answers for RQ1 and its respective SRQ1.1 – SRQ1.7, statistical analyses for main descriptive statistics were performed, investigating the recent development of published articles per year (SRQ1.1), the most contributing journals (SRQ1.2), and the most cited publications (SRQ1.3). Furthermore, the data was statistically analysed on used research approaches (SRQ1.4), I4.0 domain focus (SRQ1.5), investigated I4.0Ts (SRQ1.6), and investigated SDs (SRQ1.7).

In order to derive answers for RQ2 and its respective sub-research questions SRQ2.1 – SRQ2.4, following statistical analyses were performed: General correlation between appearance of SDs and I4.0Ts (SRQ2.1), specific interdependence among appearance of I4.0Ts (i.e. if talked about CPS, then in 97.4% of the cases it is talked about IoT as well; if talked about IoT, then in 38.8% of the cases it is talked about CPS as well) (SRQ2.2), specific interdependence among appearance of SDs (SRQ2.3), and specific interdependence between appearance of SDs and I4.0Ts (SRQ2.4).

The qualitative analyses are based on the respective author's main implications and findings as well as the reciprocal influence per SD, fully shown in Appendix 12.

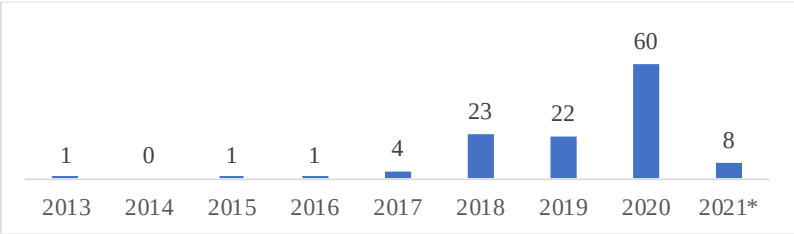
The results for the quantitative and qualitative analyses are shown and discussed in Section 4.

4 Results & discussion

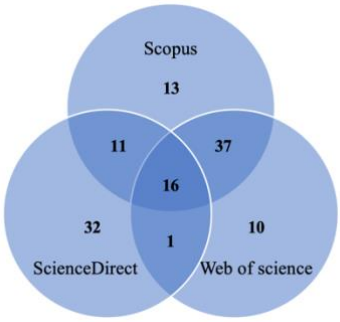
4.1 Descriptive statistics

As described in Section 3.3, the assessed articles were first investigated by main descriptive statistics including their applied research approach and research focus in order to identify respective research developments, research directions, and research gaps.

SRQ1.1: What is the recent development of published articles per year?



*available online already in 2020, to be published in 2021



Research activity within the domain of Sustainability's and I4.0's interplay started in 2013 with the first relevant article published, albeit the relation between I4.0 and SUS gained real attention from scholars starting in 2018 with 23 publications, followed 22 (2019) and 60 (2020) publications in the subsequent years, reflecting the urge of a sustainable development in the industrial context.. More detailed numbers by database can be seen in Appendix 4.

SRQ1.2: Which are the most contributing journals within the respective domain?

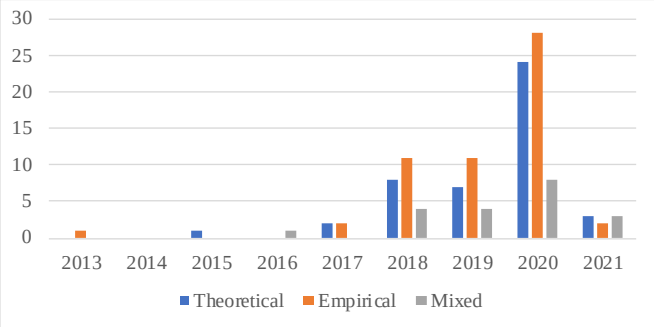
Sustainability (Switzerland), *Journal of Cleaner Production*, and *Procedia Manufacturing* are leading journals with 24 (20.0%), 17 (14.2%), and 10 (8.3%) publications (share), respectively, followed by *Procedia CIRP* (6; 5.0%) and *International Journal of Production Economics* (4; 3.3%). Appendix 5 shows a list of journals contributing with three or more publications.

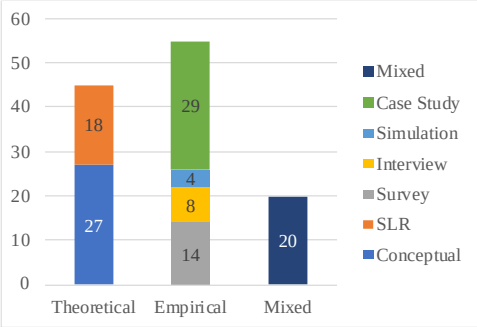
SRQ1.3: Which are the most cited publications within the respective domain?

14 out of the 120 articles (11.7%) are cited more than 100 times, with six articles having a citation-count above 200. The article "Opportunities of Sustainable Manufacturing in Industry

4.0” by Stock and Seliger (2016) attracts high attention as the most cited publication with a citation-count of 1064. A list of all articles cited more than 100 times is shown in Appendix 6.

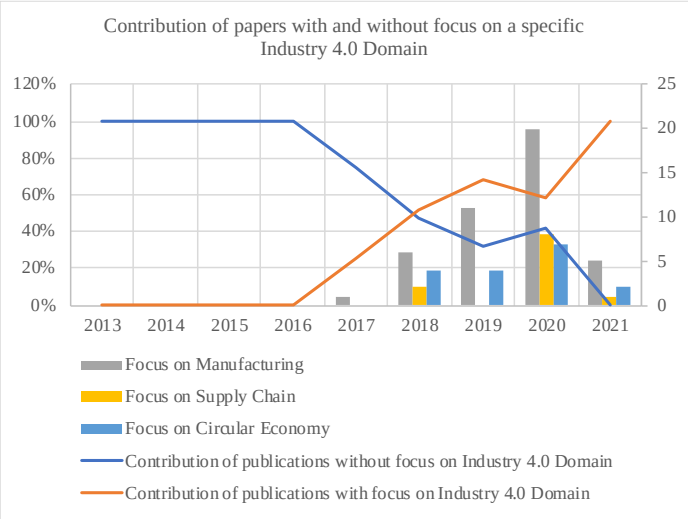
SRQ1.4: Which research approach is used most/least often within the respective domain?

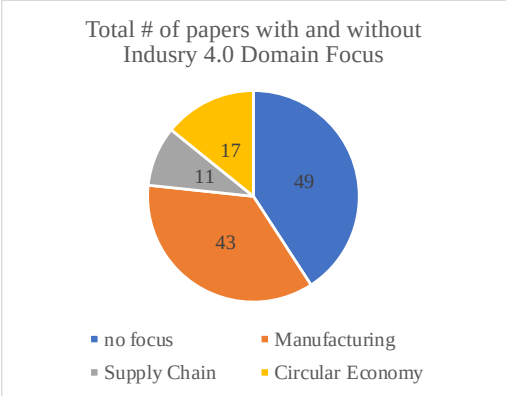




In terms of most/least used research approaches, a consistent dominance of empirical approaches can be spotted from 2018 onwards, with a total of 55 empirical papers, followed by 45 theoretical and 20 mixed approach papers, accounting for 45.8%, 37.5% and 16.7% respectively. This empirical-leaning distribution implies a well-founded and healthy research development, trying to align theory and practice. The share of case studies (24.2%) and conceptual papers (22.5%) are the most used research approaches investigating the relation between I4.0 and SUS, simulations and interviews the least used ones with 3.3% and 6.7%, respectively. Further statistics on used research approaches can be found in Appendix 7.

SRQ1.5: Which I4.0 domain has research focused on most/least within the respective domain?

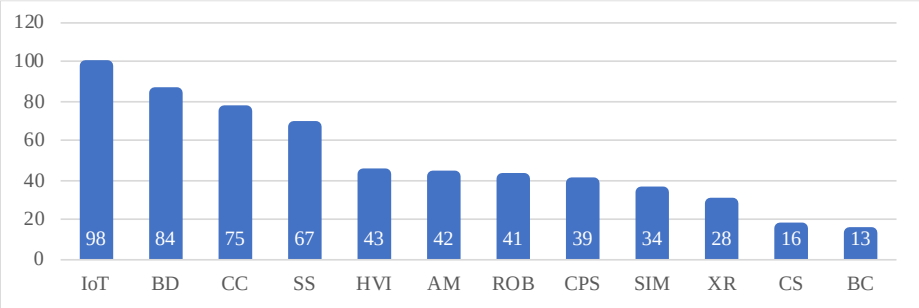




In terms of a I4.0 domain focused on, scholars first investigated the relation between SUS and I4.0 in a general manner, before shifting focus on specific I4.0 domains. While the share of non-focused research was higher than the share of I4.0 domain-focused research until 2017, latter now clearly outweighs the non-focused research. Furthermore, research focused mainly on the relation of SUS and MF (43 publications), followed by CE (17) and SC (11). Further statistics on papers' I4.0 domain focus can be found in Appendix 8.

SRQ1.6: Which I4.0Ts dominate research in the context of sustainable industrial value creation?

Figure 2 – Overview of most dealt with I4.0Ts



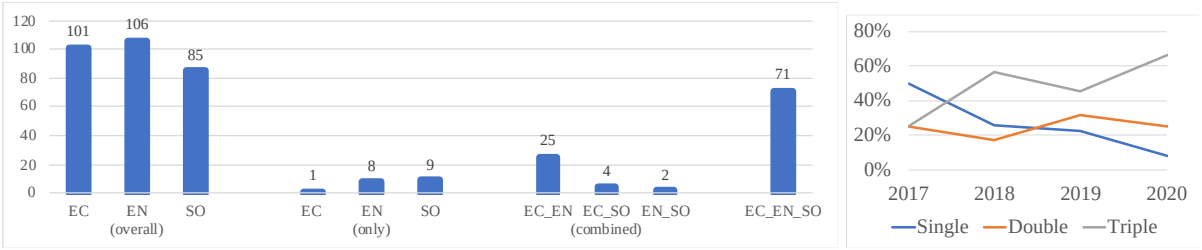
Most dealt with I4.0Ts, when investigating sustainable industrial value creation, are IoT (81.7%), BD (70.0%), and CC (62.5%) followed by SS (55.8%). This reflects the qualitative analysis, considering IoT, CC, and BD as main enabling and SS as main data generating I4.0Ts, without its interplay other I4.0Ts are very limited in their functionalities (Grischa Beier et al. 2020; Braccini and Margherita 2018; Nara et al. 2021). These data processing and data generating technologies are not of big value, however, if there is no HVI (35.8%) of all systems, processes and machines involved for efficient end-to-end communication. Based on this, machines and equipment are enabled to sense, process, send, and receive data across different systems and programming languages, thus operational technologies can be used to their fullest potential, such as AM (35.0%), ROB (34.2%), and full CPS (32.5%). As simulations are most powerful when being able to fully mirror and monitor all physical processes digitally, such as a digital twin, it seems logic that SIM (28.3%) is the next most frequent explored I4.0T,

followed by XR (23.3%), which is, as SIM, also rather from supportive nature. CS (13.3%) is quite surprisingly investigated second least, albeit CS is a crucial element for a sustainable implementation of I4.0, as the entire I4.0 concept and I4.0Ts are logically based on cyber-networking and cyber-communication. Due to I4.0's aim of full connectedness, millions of embedded sensors within a CPS are not uncommon, and thus, malicious software or cyber-attacks can affect whole production systems across multiple companies (Kamble, Gunasekaran, and Gawankar 2018), being a major threat for sustainable operations, urgently demanding future research. BC (10.8%) is investigated last, probably as BC is still in its infancy (Esmaeilian et al. 2020).

Overall, the derived results are almost fully aligned with research's consent about I4.0Ts and their appropriate importance within the whole I4.0 concept. Only CS's level of investigation does not reflect its importance. Further statistics on I4.0Ts are shown in Appendix 9.

SRQ1.7: Which SDs are being primarily investigated in the context of sustainable industrial value creation?

Figure 3 – Overview of SDs primarily investigated and development of investigated SD-combinations



In terms of investigated SDs, research's focuses mainly on EN (88.3%) and EC (84.2%), with SO (70.8%) being least, but still well explored. The combination of EC and EN is the only SD-pair gaining noticeable attention from research (20.8%). Whilst single bottom line approaches dominated in 2017 (50.0%), this share decreased constantly over time, with single bottom line approaches only accounting for 8.3% in 2020; and 0.0% in 2021 so far. On the other hand, the TBL approach increased its share from 25.0% in 2017 up to 66.7% in 2020. This steep increase of a full TBL approach indicates a healthy development within the scientific landscape, as the

core of SUS lies in the interdependency between EC, EN, and SO (Elkington 2002; Felsberger and Reiner 2020). Further statistics on papers' SUS focus can be found in Appendix 10.

4.2 Quantitative analyses

As the sample size of CS and BC is rather low with 16 and 13 appearances, respectively, implications for CS and BC derived from statistical analyses are rather vague, which is why these technologies will not be considered further within following statistical analyses.

SRQ2.1: How do the appearances of SDs and I4.0Ts correlate?

Figure 4 – Correlation Matrix of appearances of SDs and I4.0Ts

		I4.0Ts										SDs		
		CPS	IoT	CC	BD	ROB	HVI	XR	AM	SIM	SS	EC	EN	SO
I4.0Ts	CPS	1												
	IoT	0,283	1											
	CC	0,280	**0,523**	1										
	BD	0,144	**0,442**	**0,470**	1									
	ROB	0,325	0,114	0,231	0,203	1								
	HVI	**0,483**	0,264	0,328	0,224	0,414	1							
	XR	0,080	0,058	0,305	0,146	0,433	0,204	1						
	AM	0,200	0,077	0,316	0,175	0,282	0,290	0,380	1					
	SIM	0,077	0,059	0,220	0,129	0,210	0,379	0,396	0,392	1				
	SS	0,223	0,359	**0,420**	0,223	0,145	0,350	0,173	0,125	0,187	1			
SDs	EC	0,057	0,148	0,183	**0,413**	0,120	0,134	0,131	0,079	0,121	0,074	1		
	EN	0,141	0,163	0,201	**0,272**	**-0,067**	0,109	-0,045	0,158	0,113	0,043	**0,482**	1	
	SO	0,015	-0,020	-0,080	-0,020	0,230	0,174	**0,311**	0,125	0,119	0,020	0,174	**-0,119**	1

Correlation among I4.0Ts: IoT, CC, and BD are highly correlated (>0.4), supporting the implication made for SRQ1.6 and research's consent that these are the main enabling technologies of I4.0, as their interplay serves as a base line for connected industrial processes and equipment. Furthermore, a high correlation between CPS and HVI can be identified, which is supporting the assumption that a CPS's functionality is highly dependent on its level of horizontal and vertical system integration. The fairly high correlation between XR and ROB (0.433) cannot be supported by current qualitative analyses of literature, and thus, can be another further research direction.

Correlation among SDs: A high correlation of EC and EN (0.482) can be identified as well, which supports the consent of various authors within research that environmental benefits.

Increased resource efficiency, for example, comes with both reduced costs and reduced resource consumption, hence, contributing to both SDs. EN and SO seem to be correlated slightly negatively, while being the least explored combination as well. Current research does not provide insights why this is the case, so this poses as possible future research as well.

Correlation between I4.0Ts and SDs: BD seems to have the highest correlation with both EC (0.413) and EN (0.272), whilst SO correlates the most with XR. This is probably due to XR's ability to enhance vocational training, maintenance work, and workplace safety.

SRQ2.2: Which are specific interdependences among appearance of I4.0Ts?

Figure 5 shows the interdependence among the appearance of I4.0Ts, to be understood as follows: If talked about **red technology**, then XX% of times it is talked about **blue technology** as well, i.e. if talked about **CPS**, then 97,4% of the cases it is talked about **IoT** as well; if talked about **IoT**, then 38,8% of the cases it is talked about **CPS** as well).

Figure 5 – Overview of specific interdependence among the appearances of I4.0Ts

	CPS	IoT	CC	BD	ROB	HVI	XR	AM	SIM	SS
CPS		97,4%	82,1%	79,5%	56,4%	69,2%	28,2%	48,7%	33,3%	71,8%
IoT	38,8%		74,5%	79,6%	36,7%	41,8%	24,5%	36,7%	29,6%	64,3%
CC	42,7%	97,3%		86,7%	42,7%	48,0%	33,3%	46,7%	36,0%	72,0%
BD	36,9%	92,9%	77,4%		40,5%	42,9%	27,4%	40,5%	32,1%	63,1%
ROB	53,7%	87,8%	78,0%	82,9%		63,4%	48,8%	53,7%	41,5%	65,9%
HVI	62,8%	95,3%	83,7%	83,7%	60,5%		34,9%	53,5%	51,2%	79,1%
XR	39,3%	85,7%	89,3%	82,1%	71,4%	53,6%		67,9%	60,7%	71,4%
AM	45,2%	85,7%	83,3%	81,0%	52,4%	54,8%	45,2%		52,4%	64,3%
SIM	38,2%	85,3%	79,4%	79,4%	50,0%	64,7%	50,0%	64,7%		70,6%
SS	41,8%	94,0%	80,6%	79,1%	40,3%	50,7%	29,9%	40,3%	35,8%	

Again, it can be clearly seen that IoT, CC and BD are I4.0's main enablers, as it is talked about these technologies most (in average 91.5%, 81.2%, and 82.2%), regardless about which I4.0T is talked about in the first place. AR, on the other hand, seems to be relatively independent when talking about other I4.0Ts, again enforcing the previous implication that AR is rather from supportive nature.

SRQ2.3: Which are specific interdependences among appearances of SDs?

Figure 6 - Overview of specific interdependence among the appearances of SDs

	EC	EN	SO
EC		95,0%	74,3%
EN	90,6%		68,9%
SO	88,2%	85,9%	

Again, it is shown that EC and EN are highly interdependent, while the SO seems to be least interdependent with the EN, supporting previous implications made.

SRQ2.4: Which are specific interdependences between appearances of SDs and appearances of I4.0Ts?

Figure 7 - Overview of specific interdependence when talking about SDs

	CPS	IoT	CC	BD	ROB	HVI	XR	AM	SIM	SS	Average
EC	33,7%	84,2%	66,3%	78,2%	36,6%	38,6%	25,7%	36,6%	30,7%	57,4%	**48,8%**
EN	34,9%	84,0%	66,0%	74,5%	33,0%	37,7%	22,6%	37,7%	30,2%	56,6%	**47,7%**
SO	32,9%	81,2%	60,0%	69,4%	41,2%	41,2%	31,8%	38,8%	31,8%	56,5%	**48,5%**
Average	**33,8%**	**83,1%**	**64,1%**	**74,1%**	**36,9%**	**39,2%**	**26,7%**	**37,7%**	**30,9%**	**56,8%**	

Talking about each SD and its related influence on I4.0Ts, once again IoT (83.1%), BD (74.1%), and CC (64.1%) are to be named, followed by SS (56.8%), further supporting previous implications. Generally speaking, all three SDs seem to demand mentioning IoT, BD and CC the most, and XR (26.7%) as well as SIM (30.9%) the least, again implying that IoT, BD, and CC are needed to achieve SUS, while XR and SIM are rather from optional or supportive nature.

Figure 8 - Overview of specific interdependence when talking about I4.0Ts

	CPS	IoT	CC	BD	ROB	HVI	XR	AM	SIM	SS	Average
EC	87,2%	86,7%	89,3%	94,0%	90,2%	90,7%	92,9%	88,1%	91,2%	86,6%	**89,7%**
EN	94,9%	90,8%	93,3%	94,0%	85,4%	93,0%	85,7%	95,2%	94,1%	89,6%	**91,6%**
SO	71,8%	70,4%	68,0%	70,2%	85,4%	81,4%	96,4%	78,6%	79,4%	71,6%	**77,3%**
Average	**84,6%**	**82,7%**	**83,6%**	**86,1%**	**87,0%**	**88,4%**	**91,7%**	**87,3%**	**88,2%**	**82,6%**	

While SO seems to influence XR only little (31.8%), XR's influence on SO seems to be the highest (96.4%), followed by AM's influence on EN (95.2%). While the former has already been discussed, AM's influence on EN is mostly caused due to its nature of being an additive, not subtractive manufacturing process, maximizing resource efficiency and minimizing waste generation, among others. Generally speaking, EN (91.6%) seems to be most influenced by I4.0Ts, closely followed by EC (89.7%) and SO (77.3%), while XR seems to be the most

influencing I4.0T on average (91.7%), followed by HVI (88.4%), SIM (88.2%) and AM (87.3%), as applying these technologies comes with direct benefits.

4.3 Qualitative analyses

RQ1: What is the current status of research investigating the relation between I4.0 and SUS?

While most papers focus on the positive impacts of I4.0 on an industrial sustainable development, such as Margherita and Braccini (2020), Felsberger et al. (2020), and Strandhagen et al. (2020), only little focus on its negative impacts and corresponding risks, such as Birkel et al. (2019). Furthermore, research does not have a consent yet about the actual main intentions of and main drivers when implementing I4.0, as Brozzi et al. (2020) and Ivascu (2020) imply economic factors to be the main drivers, while Sharma et al. (2020) and Müller, Kiel, and Voigt (2018) highlight environmental and social factors as respective main drivers. Ghobakhloo (2020) thereby considers economic SUS functions as a "more immediate outcome of Industry 4.0, which pays the way for development of more remote socioenvironmental sustainability functions of Industry 4.0". A point research mainly agrees on is the importance of SO for a sustainable industrial development, seeing human-centred I4.0 implementation as a lever to boost not only a factories productivity, but the whole I4.0 implementation process as well (Gregori et al. 2017; Yadav et al. 2020). Accordingly, industrial companies should adopt human-centred I4.0 process designs, while prioritizing vocational training in order to avoid an increasing knowledge and skills gap caused by I4.0's complex technical nature (Müller and Voigt 2018; Ghobakhloo 2020; Felsberger et al. 2020; Bag, Yadav, et al. 2020). Furthermore, I4.0 is considered as a key enabler for the ongoing paradigm shift from a linear economy to a CE (P. Kumar, Singh, and Kumar 2021; Lopes de Sousa Jabbour et al. 2018; Dantas et al. 2021; Nascimento et al. 2019). Research disagrees on I4.0's exact impact on SO though, mainly due to the still not predictable outcome, with threats like job losses on the one hand (Müller and

Voigt 2018; Birkel et al. 2019; Carvalho et al. 2018; G. Beier et al. 2017) and benefits such as job enrichment, increased occupational health and safety, reduced monotonous and bad-posture work task, and enhanced vocational training on the other (T. Stock and Seliger 2016; Tim Stock et al. 2018; Kamble, Gunasekaran, and Gawankar 2018; Müller, Kiel, and Voigt 2018; Kayikci 2018). About 20% of assessed papers propose refined frameworks to capture a more holistic view on enhanced life-cycle-sustainability (Abubakr et al. 2020), on associated risks of sustainable I4.0 implementation (Birkel et al. 2019), and on the interplay of technical and social innovations (Morrar, Arman, and Mousa 2017), among others.

There are still gaps within literature, such as the deeper assessment of BC's potential use cases and related benefits, as well as the role of sustainable SCs and CE in the context of sustainable industrial value creation, contributing only with 8.3% and 14.2%, respectively, albeit recent development indicates a trend towards these I4.0 domains.

RQ2: To what extent I4.0Ts and SDs influence each other?

Talking about the reciprocal influence of SUS and I4.0Ts, following framing can be derived from current literature: SUS and upcoming SUS issues are main drivers for scientific investigation and I4.0 implementation (Sharma et al. 2020; Müller, Kiel, and Voigt 2018; Luthra et al. 2020), while I4.0 and its related technologies and principles are considered to be a suitable solution to tackle these emerging challenges (Bai et al. 2020; Ivascu 2020; Strandhagen et al. 2020). A direct influence of SUS on I4.0Ts, such as I4.0T development, is yet investigated very poorly though, representing the main gap of current research. However, SUS sets boundaries how and which I4.0 technologies are implemented as elaborated by Cochran and Rauch (2020). On the economic level, it is mostly barriers that affect I4.0 implementation, as it demands high initial investments, which need to be overcome for economic long-term SUS and competitiveness (Müller, Kiel, and Voigt 2018; Bag, Yadav, et al. 2020; Kumar, Singh, and Dwivedi 2020). On the environmental level, pressure from

political, societal, and legal side is increasing drastically, demanding industrial companies to take respective countermeasures such as enhancing their environmental performance by implementing I4.0Ts and concepts (Bag, Pretorius, et al. 2020; Harikannan, Vinodh, and Gurumurthy 2020). From a social point of view, I4.0 implementation has to be done human-centred, facilitating and enriching workers' tasks, raising their occupational health and safety, and enhancing their knowledge and skill level, as humans remain the heart of sustainable industrial value creation (Gualtieri et al. 2020; Pinzone et al. 2020).

Overall, the influences of I4.0Ts on SDs tend to be more immediate than vice versa. I4.0Ts enhance data gathering capabilities drastically (Nascimento et al. 2019), and thus, facilitates process improvements during raw material extraction, product design, manufacturing, and distribution (Machado, Winroth, and Ribeiro da Silva 2020). The I4.0 paradigm also facilitates the shift from a linear economy (cradle to grave) to a CE (cradle to cradle), as data granularity and data quality increases, facilitating CE paradigms, such as ReSOLVE (Regenerate; Share; Optimize; Loop; Exchange) and 6R (Recover; Recycle; Remanufacture; Reuse; Reduce; Redesign) (Lopes de Sousa Jabbour et al. 2018; Manavalan and Jayakrishna 2019). Insights derived from data gathered during the use phase can be levered by SIM assessing a decision's future impact during product design already (Yang et al. 2018). During production, operational performance and resource efficiency can be increased (T. Stock and Seliger 2016; Kamble, Gunasekaran, and Gawankar 2018), facilitating sustainable production on demand instead of mass production resulting in high inventory and big amounts of unused products (Waibel et al. 2017). Using XR for enhanced vocational training or advanced maintenance as well as ROB performing monotonous tasks directly impact SO (Blümel 2013; Margherita and Braccini 2020). After all, I4.0Ts enable reliable and valid measurement of SUS indicators, hence, sustainable countermeasures can be carried out in a more systematic manner (Tiwari and Khan 2020; Cochran and Rauch 2020).

5 Limitations, Future Research and Conclusion

5.1 Limitations

Multiple limitations of this research are caused by its nature as a systematic literature review. As this paper builds on existing literature, and data derived from it, implications might build in malicious or misleading previous insights, not validated in practice. The usage of three databases only, and the assessment of papers in English language only, implies another restriction due to limited access to the full academic landscape, potentially leaving out highly relevant articles. The selection of search terms effects the paper's outcome as well. Even though the selection of used search terms was done by the best of the author's knowledge and belief, they are exposed to human bias. Same applies for extracted data by the author, especially when adding qualitative data. Further limitations apply when statistical analyses about interdependencies were performed, as it was not investigated if respective technologies or dimensions are influencing or are being influenced, proposing future research to dig deeper.

5.2 Future Research

Limitations as well as identified research gaps are used for deriving future research proposals. As mentioned earlier, future research could investigate the driving and dependence power of respective I4.0Ts and principles in the context of SUS in more detail, best case in an empirical manner, improving its practicability. Furthermore, systematic empirical investigation on how I4.0 and I4.0Ts effect each other in the context of their impact on the TBL can be of practical benefit, as I4.0 implementation is subject to be planned thoroughly, eliminating as much uncertainties as possible during the respective decision-making. Based on these two future research proposals, research could create an I4.0 implementation roadmap on how to accomplish the sustainable paradigm shift as effective and efficient as possible. In addition, the respective leverage power of I4.0Ts could be investigated, on how to maximise the impact of

I4.0 implementation as a whole, not as a singular technology. The interrelation of EN and SO and the respective underlying reasons are vaguely addressed yet, calling for further investigation. Talking about specific I4.0Ts, the high correlation between XR and ROB (0.433) cannot be explained by current qualitative analyses of literature, and thus, can be another future research direction. In addition, CS and BC in the context of SUS are clearly investigated insufficiently. Especially CS as a crucial part of sustainable industrial development must not be forgotten within future research, as companies across whole value chains are dependent on functioning and secure cyber-systems, definitely demanding further investigation.

5.3 Conclusion

This research paper's objective is twofold, namely (1) examining the current status of research investigating the relation between I4.0 and SUS, and (2) examining to what extent I4.0Ts and SDs influence each other, to gain important knowledge on how to manage the transition towards a more sustainable industrial value creation as efficiently and effectively as possible. To do so, seven and four SRQs were formulated regarding objective (1) and (2), respectively, as shown in Section 3.1 in Table 1 and Table 2, and fully shown in Appendix 2. Considered a highly suitable, bias-reducing methodology for achieving this research's objective, a systematic literature review (SLR) methodology was chosen and performed accordingly. Pre-defined search-strings were performed on three electronic academic databases, extracting a total of 849 papers. By applying pre-defined inclusion and exclusion criteria during the assessment of these papers, the number of relevant articles was reduced to 120 articles, which were finally investigated on criteria derived from the respective sub-research questions. After this being done, quantitative and qualitative analyses were performed to derive answers for each RQ and SRQ. Main findings of these analyses are:

(1) Interest within this field is increasing rapidly, reflected in increasing research activities, with a slight tendency to empirical research, indicating a healthy research development with both theoretical and practical derived insights. In terms of I4.0 domain focus, research started from a general perspective before focusing mainly on certain I4.0 domains, viz., MF, SC, and CE. I4.0Ts investigated most frequently are IoT (81.7% of all papers), BD (70.0%), and CC (62.5%), and CS (13.3%) and BC (10.8%) being least investigated. This frequency-sequence strongly supports the qualitative analysis results, indicating IoT, BD, and CC as main enabling technologies of I4.0, setting the base information and communication technology (ICT) infrastructure. BC, a top-edge technology implying huge potential in the context of sustainable industrial value creation, is yet in its infancy though, requiring a profound implementation process and further investigation.

(2) Insights derived from quantitative and qualitative analyses indicate that the EC and EN are closely linked (0.482 correlation), as most economic benefits come with environmental benefits and vice versa. However, SO is seen as a non-neglectable dimension, as it is still humans that plan, operate, and take decisions to a certain extent, supported by I4.0Ts. Looking at the interrelation between I4.0Ts and SDs, results indicate that all three SDs seem to demand mentioning IoT, BD, and CC the most, and XR as well as SIM the least. Furthermore, EN seems to be most influenced by I4.0Ts, closely followed by EC and SO. XR, however, seems to be the most influencing I4.0T on average, followed by HVI (88.4%), SIM (88.2%), and AM (87.3%). Elaborating on qualitative analyses, I4.0 is seen as a main enabler for CE in particular due to its real-time and prediction capabilities, easing the effective transition to CE by far.

Based on identified research gaps and this paper's limitations, further future research proposals were elaborated to accomplish the sustainable paradigm shift as effectively and efficiently as possible.

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8 Appendices

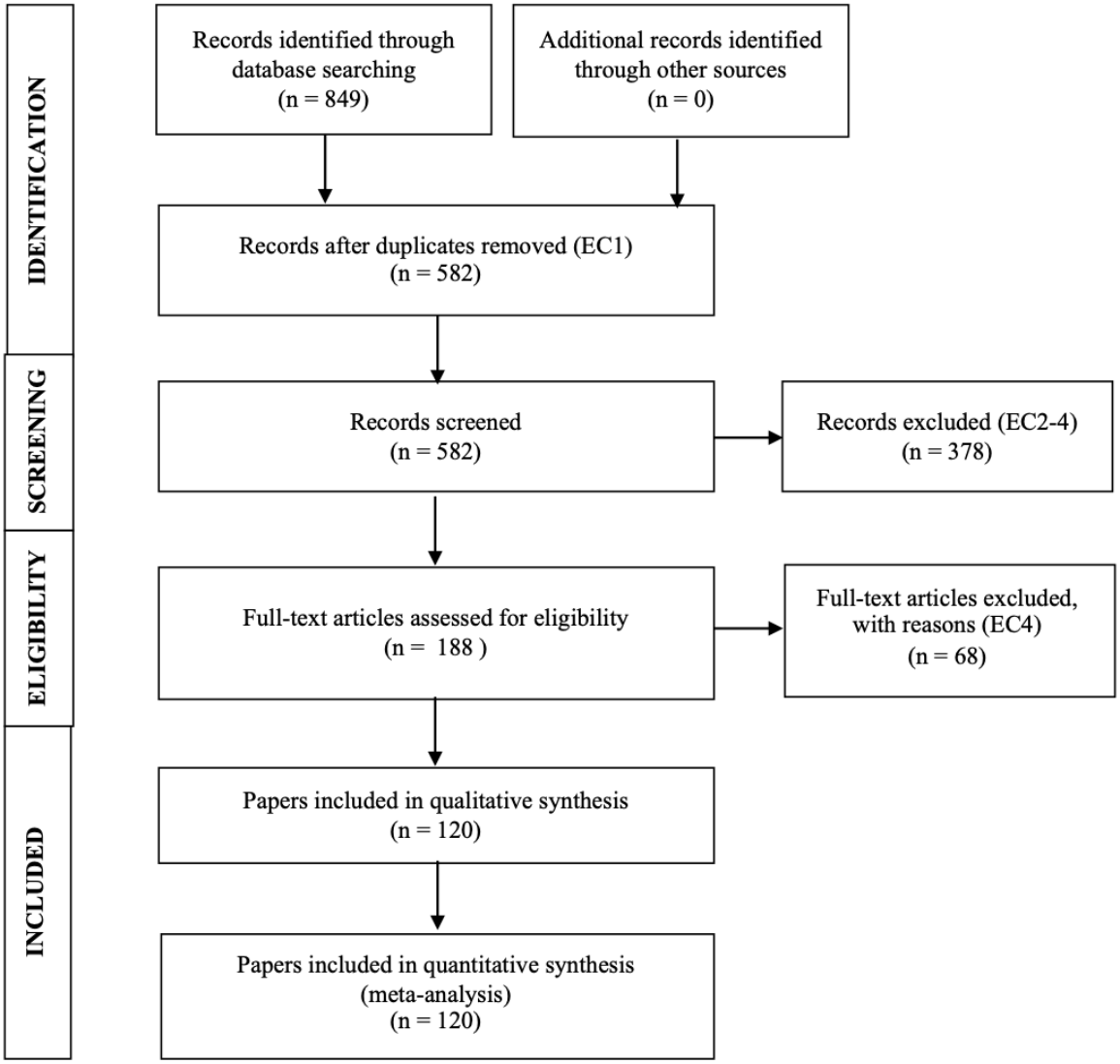
Appendix 1 – Overview of Industry 4.0 Technologies within this paper's scope adapted from Bai, Chunguang, Patrick Dallasega, Guido Orzes, and Joseph Sarkis. 2020. 'Industry 4.0 Technologies Assessment: A Sustainability Perspective'. *International Journal of Production Economics* 229 (November): 107776. https://doi.org/10.1016/j.ijpe.2020.107776

Industry 4.0 Technology	Description
Additive Manufacturing (AM)	is a manufacturing technology that creates three-dimensional (3D) solid objects using a series of additive or layered development frameworks
Advanced Simulation (SIM)	refers to technologies that use computational power for the imitation of a real-world process or system
Automation and Robotics (ROB)	are used to replicate human actions in manufacturing to a very or fully automated manner
Big Data Analytics (BD)	refer to the strategy of analyzing large volumes of data that are used when traditional data mining and handling techniques cannot uncover the insights and meaning of the underlying data
Blockchain (BC)	is a distributed database that maintains a completely, distributed and non-tampering continuously growing list of records using new encryption and authentication technology and network-wide consensus mechanism
Cloud Computing (CC)	refers to any IT services that are provisioned and accessed from a cloud computing provider
Cyber-Physical-System (CPS)	Refers to a system in which the digital and physical levels emerge, enabling self-regulating and self-acting systems with little to no human interaction
Cyber-Security (CS)	refers to preventative methods used to protect information from being stolen, compromised or attacked
Extended Reality (XR)	is a type of interactive, reality-based display environment that takes the capabilities of computer generated display, sound and other effects to enhance the real-world experience
Horizontal & Vertical Integration (HVI)	Refers to a system landscape, in which all relevant systems (physical and software) are integrated, both horizontally (across company-boundaries) and vertically (across whole process landscape within company), enabling full connectivity and communication among integrated systems
Internet of Things (IoT)	analogous to the internet, which basically serves to network computers, the vision of the comprehensive networking of objects of all kinds is referred to as the Internet of Things, supporting enhanced manufacturing and industrial processes
Smart Sensors	is a device that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control)

Appendix 2 - Full overview of research question elaboration

	Research Question	Research Question's Aim	Which data is needed per paper?	Which analysis needs to be run?
1	What is the current status of research investigating the relation between Industry 4.0 and sustainability?	RQ1 aims to provide an comprehensive overview of the status quo of existing research investigating the relation between Industry 4.0 and sustainability, elaborating on existing insights and identifying research gaps as future research proposals		
1.1	What is the recent development of published articles per year?	SRQ1.1 aims to explore the development of the number of articles published in the field to gain insights if it is an emerging or mature field.	publishing year	Number of articles published per year
1.2	Which are the most contributing journals?	SRQ1.2 aims to explore which are the most contributing journals in the field to gain insights about most relevant journals in this field.	publishing journal	Number of articles published per journal
1.3	Which are the most cited publications?	SRQ1.3 aims to explore which are the most cited publications in the field to gain insights about the most relevant articles to build up on.	number cited	
1.4	Which research approach is used most/least?	SRQ1.4 aims to explore which research approach is used most/least often in the field to gain insights about the state of practibility of research's findings	research approach [conceptual; empirical (case study; interview; survey; simulation)]	Number of articles per research approach
1.5	Which Industry 4.0 domain has research focused on most/least?	SRQ1.5 aims to explore which Industry 4.0 domain is explored most/least often in the field to gain insights about potential granularity of scientific insights.	Industry 4.0 domain [no focus (no); manufacturing (MF); supply chain (SC); circular economy (CE)]	Number of articles per P&OM focus
1.6	Which Industry 4.0 technologies dominate research in the context of sustainable industrial value creation?	SRQ1.6 aims to explore which Industry 4.0 technologies are talked about most/least often in the field to gain insights about main Industry 4.0 technologies driving the sustainable development	Industry 4.0 technology talked about [CPS; IoT; CC; BD; ROB; HVI; XR; AM; SIM; CS; BC)	Amount respective Industry 4.0 technology is talked about in the context if sustainability
1.7	Which sustainability dimensions are being primarily investigated in the context of sustainable industrial value creation?	SRQ1.7 aims to explore which sustainability dimensions is talked about most/least often in the field to gain insights about research's sustainability focus	sustainability dimension talked about [Economic; Environmental; Social]	Amount respective sustainability dimension is talked about in the context if Industry 4.0
2	To what extent do Industry 4.0 technologies and sustainability dimensions influence each other?	RQ2 aims to provide comprehensive insights to what extent Industry 4.0 technologies and sustainability dimensions influence each other	qualtative data about author's findings; reciprocal influences per sustainability dimension	qualitative analysis
2.1	How do the appearances of sustainability dimensions and Industry 4.0 technologies correlate?	SRQ2.1 aims to explore the correlation between the appearance of investigated Industry 4.0 technologies and investigated sustainability dimensions to gain insights about potential influences	same as in 1.6 & 1.7	Correlation matrix of investigated Industry 4.0 technologies and investigated sustainability dimensions
2.2	Which are specific interdependences among appearance of Industry 4.0 technologies?	SRQ2.2 aims to explore the interdependence among the appearance of investigated Industry 4.0 technologies to gain insights about potential directional influences	same as in 1.6 & 1.7	Dependence matrix of investigated Industry 4.0 technologies
2.3	Which are specific interdependences among appearance of sustainability dimensions?	SRQ2.3 aims to explore the interdependence among the appearance of investigated sustainability dimensions to gain insights about potential directional influences	same as in 1.6 & 1.7	Dependence matrix of investigated investigated sustainability dimensions
2.4	Which are specific interdependences between appearances of sustainability dimensions and appearances of Industry 4.0 technologies?	SRQ2.4 aims to explore the interdependence between the appearance of investigated Industry 4.0 technologies and investigated sustainability dimensions to gain insights about potential directional influences	same as in 1.6 & 1.7	Dependence matrix of investigated Industry 4.0 technologies and investigated sustainability dimensions

Appendix 3 - PRISMA Flow Chart according to: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097



Appendix 4 – Overview of available publications per database

	Total		2013	2014	2015	2016	2017	2018	2019	2020	2021
Sco	13	10,8%						3	4	6	
WoS	10	8,3%					1		1	8	
ScD	32	26,7%	1		1	1	1	5	6	15	2
Sco; WoS	37	30,8%					1	9	10	17	
Sco; ScD	11	9,2%					1	1	1	3	5
WoS; ScD	1	0,8%								1	
Sco; WoS; ScD	16	13,3%						5		10	1
Total	**120**	**100,0%**	**1**	**0**	**1**	**1**	**4**	**23**	**22**	**60**	**8**

Abbreviations: Scopus (Sco); Web of Science (WoS); ScienceDirect (ScD)

Appendix 5 – List of Publishing Journals with three or more publications included

Publishing Journal	Publications	%
Sustainability (Switzerland)	24	20,0%
Journal of Cleaner Production	17	14,2%
Procedia Manufacturing	10	8,3%
Procedia CIRP	6	5,0%
International Journal of Production Economics	4	3,3%
Process Safety and Environmental Protection	3	2,5%
International Journal of Precision Engineering and Manufacturing - Green Technology	3	2,5%
International Journal of Production Research	3	2,5%
Applied Sciences (Switzerland)	3	2,5%
Resources, Conservation and Recycling	3	2,5%

Appendix 6 – Overview of most cited articles relating to SRQ1.3

Author(s)	Title of Article	Year	Cited by
Kamble S.S., Gunasekaran A., Gawankar S.A.	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	2018	174
Müller J.M., Kiel D., Voigt K.-I.	What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability	2018	172
Lopes de Sousa Jabbour A.B., Jabbour C.J.C., Godinho Filho M., Roubaud D.	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations	2018	150
de Sousa Jabbour A.B.L., Jabbour C.J.C., Foropon C., Filho M.G.	When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors	2018	140
Bonilla S.H., Silva H.R.O., da Silva M.T., Gonçalves R.F., Sacomano J.B.	Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges	2018	91
Ren S., Zhang Y., Liu Y., Sakao T., Huisingh D., Almeida C.M.V.B.	A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions	2019	89
Stock T., Obenaus M., Kunz S., Kohl H.	Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential	2018	81
Birkel H.S., Veile J.W., Müller J.M., Hartmann E., Voigt K.-I.	Development of a risk framework for Industry 4.0 in the context of sustainability for established manufacturers	2019	65
Müller J.M., Voigt K.-I.	Sustainable Industrial Value Creation in SMEs: A Comparison between Industry 4.0 and Made in China 2025	2018	59
Nascimento, DLM; Alencastro, V; Quelhas, OLG; Caiado, RGG; Garza-Reyes, JA; Lona, LR; Tortorella, G	Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context A business model proposal	2019	56

Appendix 7 – Overview of most/least used research approaches per year according to SRQ1.4

		2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
Theore-tical	Conceptual			1		1	5	6	11	3	**27**
	SLR					1	3	1	13		**18**
Empirical	Case Study	1				1	6	8	13		**29**
	Interview						1	1	5	1	**8**
	Survey					1	4	1	8		**14**
	Simulation							1	2	1	**4**
	Mixed				1		4	4	8	3	**20**
	Total	**1**	**0**	**1**	**1**	**4**	**23**	**22**	**60**	**8**	**120**

Appendix 8 - Overview of most/least focused on Industry 4.0 domain per year according to SRQ1.5

	Contribution of publicaitons		Respective I4.0 Domain focus			
	without focus	with focus	MF	SC	CE	No focus
2013	100%	0%				1
2014						
2015	100%	0%				1
2016	100%	0%				1
2017	75%	25%	1			3
2018	48%	52%	6	2	4	11
2019	32%	68%	11	0	4	7
2020	42%	58%	20	8	7	25
2021	0%	100%	5	1	2	
Total			**43**	**11**	**17**	**49**

Appendix 9 - Overview of most/least investigated Industry 4.0 technologies per year according to SRQ1.6

	Total		2013	2014	2015	2016	2017	2018	2019	2020	2021
CPS	39	32,5%			1	1	1	8	5	21	2
IoT	98	81,7%			1	1	3	20	16	49	8
CC	75	62,5%	1		1	1	1	13	12	39	7
BD	84	70,0%			1	1	2	11	16	45	8
ROB	41	34,2%					2	9	5	23	2
HVI	43	35,8%			1	1	1	9	7	22	2
XR	28	23,3%	1			1		3	4	19	
AM	42	35,0%				1		10	4	25	2
SIM	34	28,3%	1					8	7	18	
CS	16	13,3%					1	3	2	8	2
BC	13	10,8%						2	1	8	2
SS	67	55,8%			1	1	2	12	12	36	3
Total Papers	**120**		**1**		**1**	**1**	**4**	**23**	**22**	**60**	**8**

Appendix 10 - Overview of most/least focused on Sustainability Dimension per year according to SRQ1.7

	Total		2013	2014	2015	2016	2017	2018	2019	2020	2021
EC general	101	84,2%	1		1	1	1	16	18	55	8
EN general	106	88,3%	1		1	1	2	21	19	54	7
SO general	85	70,8%	1			1	4	16	12	45	6
EC	1	0,8%							1		
EN	8	6,7%						4	2	2	
SO	9	7,5%					2	2	2	3	
EC_EN	25	20,8%			1			3	7	12	2
EC_SO	4	3,3%								3	1
EN_SO	2	1,7%					1	1			
EC_EN_SO	71	59,2%	1			1	1	13	10	40	5
Total	**120**	**100,0%**	**1**		**1**	**1**	**4**	**23**	**22**	**60**	**8**

Appendix 11 - Full Overview of data base used for quantitative analyses

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
Sco; WoS	**Abubakr M., Abbas A.T., Tomaz I., Soliman M.S., Luqman M., Hegab H.**	Sustainable and smart manufacturing: An integrated approach	2020	Sustainability (Switzerland)	7	no	x	x	x	x		x		x				x	x	x	x	Conceptual
ScD	**Adenuga, Olukorede Tijani; Mpofu, Khumbulani; Boitumelo, Ramatsetse Innocent**	Energy efficiency analysis modelling system for manufacturing in the context of industry 4.0	2019	Procedia CIRP	5	MF		x	x	x								x	x	x		Conceptual; Case Study
Sco; WoS	**Ahmad S., Miskon S., Alabdan R., Tlili I.**	Towards sustainable textile and apparel industry: Exploring the role of business intelligence systems in the era of industry 4.0	2020	Sustainability (Switzerland)	3	no			x	x	x		x	x	x			x	x	x		Interview
ScD	**Ambrogio, Giuseppina; Guido, Rosita; Palaia, Domenico; Filice, Luigino**	Job shop scheduling model for a sustainable manufacturing	2020	Procedia Manufacturing	0	MF		x	x	x									x	x		Case Study
ScD	**Amjad, Muhammad Saad; Rafique, Muhammad Zeeshan; Hussain, Shafqat; Khan, Mohammad Aamir**	A new vision of LARG Manufacturing — A trail towards Industry 4.0	2020	CIRP Journal of Manufacturing Science and Technology	1	MF	x	x	x	x								x	x	x	x	SLR
Sco; WoS; ScD	**Bag S., Yadav G., Wood L.C., Dhamija P., Joshi S.**	Industry 4.0 and the circular economy: Resource melioration in logistics	2020	Resources Policy	2	SC	x	x	x	x	x	x						x	x	x		Survey
ScD	**Bag, Surajit; Gupta, Shivam; Kumar, Sameer**	Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development	2021	International Journal of Production Economics	10	CE		x	x	x									x	x	x	Conceptual; Survey
ScD	**Bag, Surajit; Pretorius, Jan Ham Christiaan; Gupta, Shivam; Dwivedi, Yogesh K.**	Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities	2020	Technological Forecasting and Social Change	0	CE		x	x	x								x	x	x	x	Survey
ScD	**Bag, Surajit; Yadav, Gunjan; Dhamija, Pavitra; Kataria, Krishan Kumar**	Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study	2020	Journal of Cleaner Production	1	CE	x	x	x	x				x					x	x	x	Survey
Sco; WoS; ScD	**Bai C., Dallasega P., Orzes G., Sarkis J.**	Industry 4.0 technologies assessment: A sustainability perspective	2020	International Journal of Production Economics	7	no		x	x	x	x		x	x	x	x	x	x	x	x	x	Conceptual; Case Study
ScD	**Bal, Alperen; Badurdeen, Fazleena**	A Business Model to Implement Closed-loop Material Flow in IoT-enabled Environments	2019	Procedia Manufacturing	1	no		x	x	x								x	x	x		Simulation
Sco; WoS	**Beier G., Niehoff S., Xue B.**	More sustainability in industry through Industrial Internet of Things?	2018	Applied Sciences (Switzerland)	25	no		x												x		Survey
Sco; WoS	**Beier G., Niehoff S., Ziems T., Xue B.**	Sustainability aspects of a digitalized industry – A comparative study from China and Germany	2017	International Journal of Precision Engineering and Manufacturing - Green Technology	86	no														x	x	Survey

Appendix 11 (continued)

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
ScD	**Beier, Grischa; Ullrich, André; Niehoff, Silke; Reißig, Malte; Habich, Matthias**	Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes – A literature review	2020	Journal of Cleaner Production	54	no	x	x	x	x	x	x							x	x	x	SLR
Sco; WoS	**Birkel H.S., Veile J.W., Müller J.M., Hartmann E., Voigt K.-I.**	Development of a risk framework for Industry 4.0 in the context of sustainability for established manufacturers	2019	Sustainability (Switzerland)	102	MF		x	x	x	x	x				x	x	x	x	x	x	Conceptual; Interview
ScD	**Blümel, Eberhard**	Global Challenges and Innovative Technologies Geared Toward New Markets: Prospects for Virtual and Augmented Reality	2013	Procedia Computer Science	14	no			x				x		x				x	x	x	Case Study
Sco; WoS	**Bonilla S.H., Silva H.R.O., da Silva M.T., Gonçalves R.F., Sacomano J.B.**	Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges	2018	Sustainability (Switzerland)	135	no	x	x	x	x	x	x		x	x		x	x		x		SLR
Sco; WoS	**Braccini A.M., Margherita E.G.**	Exploring organizational sustainability of Industry 4.0 under the triple bottom line: The case of a manufacturing company	2018	Sustainability (Switzerland)	26	MF	x	x			x							x	x	x	x	Case Study
ScD	**Bressanelli, Gianmarco; Adrodegari, Federico; Perona, Marco; Saccani, Nicola**	The role of digital technologies to overcome Circular Economy challenges in PSS Business Models: an exploratory case study	2018	Procedia CIRP	43	CE		x		x									x	x	x	Case Study
Sco; WoS	**Brozzi R., Forti D., Rauch E., Matt D.T.**	The advantages of industry 4.0 applications for sustainability: Results from a sample of manufacturing companies	2020	Sustainability (Switzerland)	8	no													x	x	x	Survey
Sco; WoS	**Cagliano R., Canterino F., Longoni A., Bartezzaghi E.**	The interplay between smart manufacturing technologies and work organization: The role of technological complexity	2019	International Journal of Operations and Production Management	7	MF	x	x	x	x	x	x	x	x	x			x			x	Case Study
ScD	**Carvalho, Núbia; Chaim, Omar; Cazarini, Edson; Gerolamo, Mateus**	Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing	2018	Procedia Manufacturing	97	MF	x	x			x	x			x			x	x	x	x	Conceptual
Sco; ScD	**Chiappetta Jabbour C.J., Fiorini P.D.C., Ndubisi N.O., Queiroz M.M., Piato É.L.**	Digitally-enabled sustainable supply chains in the 21st century: A review and a research agenda	2020	Science of the Total Environment	6	SC				x									x	x	x	SLR
ScD	**Cochran, David S.; Rauch, Erwin**	Sustainable Enterprise Design 4.0: Addressing Industry 4.0 Technologies from the Perspective of Sustainability	2020	Procedia Manufacturing	0	no	x	x	x	x	x	x	x	x	x	x		x	x	x	x	Conceptual
ScD	**Dantas, T. E. T.; de-Souza, E. D.; Destro, I. R.; Hammes, G.; Rodriguez, C. M. T.; Soares, S. R.**	How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals	2021	Sustainable Production and Consumption	0	CE	x	x	x	x	x	x				x	x		x	x	x	Conceptual
Sco; WoS; ScD	**de Sousa Jabbour A.B.L., Jabbour C.J.C., Foropon C., Filho M.G.**	When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors	2018	Technological Forecasting and Social Change	222	no	x	x	x					x						x		Conceptual
ScD	**Dev, Navin K.; Shankar, Ravi; Qaiser, Fahham Hasan**	Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance	2020	Resources, Conservation and Recycling	38	CE	x	x	x			x		x	x			x	x	x		Simulation

Appendix 11 (continued)

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
Sco; WoS; ScD	Esmaeilian B., Sarkis J., Lewis K., Behdad S.	Blockchain for the future of sustainable supply chain management in Industry 4.0	2020	Resources, Conservation and Recycling	2	SC		x									x		x	x	x	Conceptual
Sco	Felsberger A., Reiner G.	Sustainable industry 4.0 in production and operations management: A systematic literature review	2020	Sustainability (Switzerland)	1	no	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	SLR
WoS	Felsberger, A; Qaiser, FH; Choudhary, A; Reiner, G	The impact of Industry 4.0 on the reconciliation of dynamic capabilities: evidence from the European manufacturing industries	2020	PRODUCTION PLANNING & CONTROL	1	no	x	x		x		x			x	x		x	x	x	x	Case Study
ScD	Ferrari, Anna Maria; Volpi, Lucrezia; Settembre-Blundo, Davide; García-Muiña, Fernando E.	Dynamic Life Cycle Assessment (LCA) integrating Life Cycle Inventory (LCI) and Enterprise Resource Planning (ERP) in an Industry 4.0 environment	2020	Journal of Cleaner Production	0	MF		x	x									x		x		Case Study
Sco; WoS	Fu B., Shu Z., Liu X.	Blockchain enhanced emission trading framework in fashion apparel manufacturing industry	2018	Sustainability (Switzerland)	59	MF											x			x		Conceptual
WoS	Furstenau, LB; Sott, MK; Kipper, LM; Machado, EL; Lopez-Robles, JR; Dohan, MS; Cobo, MJ; Zahid, A; Abbasi, QH; Imran, MA	Link Between Sustainability and Industry 4.0: Trends, Challenges and New Perspectives	2020	IEEE ACCESS	1	no	x	x		x	x	x		x	x			x	x	x	x	SLR
Sco; WoS	Gajšek B., Stradovnik S., Hace A.	Sustainable move towards flexible, robotic, human-involving workplace	2020	Sustainability (Switzerland)	1	no					x		x						x		x	Case Study
Sco	Garcia-Muiña F.E., González-Sánchez R., Ferrari A.M., Settembre-Blundo D.	The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company	2018	Social Sciences	60	CE		x											x	x	x	Case Study
Sco	Garcia-Muiña F.E., González-Sánchez R., Ferrari A.M., Volpi L., Pini M., Siligardi C., Settembre-Blundo D.	Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design	2019	Social Sciences	12	CE		x											x	x	x	Case Study
Sco; WoS	García-Muiña F.E., Medina-Salgado M.S., Ferrari A.M., Cucchi M.	Sustainability transition in industry 4.0 and smart manufacturing with the triple-layered business model canvas	2020	Sustainability (Switzerland)	8	MF		x											x	x	x	Case Study
Sco; WoS	Garrido-Hidalgo C., Hortelano D., Roda-Sanchez L., Olivares T., Ruiz M.C., Lopez V.	IoT Heterogeneous Mesh Network Deployment for Human-in-the-Loop Challenges Towards a Social and Sustainable Industry 4.0	2018	IEEE Access	47	no		x	x									x			x	Case Study
ScD	Ghobakhloo, Morteza	Industry 4.0, digitization, and opportunities for sustainability	2020	Journal of Cleaner Production	61	no		x	x	x	x	x	x	x	x	x		x	x	x	x	Conceptual
Sco; WoS	Godina R., Ribeiro I., Matos F., Ferreira B.T., Carvalho H., Peças P.	Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context	2020	Sustainability (Switzerland)	1	MF								x					x	x	x	Conceptual

Appendix 11 (continued)

Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	I40TP												SD			Research approach
							CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	
ScD	**Gregori, Fabio; Papetti, Alessandra; Pandolfi, Monica; Peruzzini, Margeherita; Germani, Michele**	Improving a production site from a social point of view: an IoT infrastructure to monitor workers condition	2018	Procedia CIRP	6	MF		x										x			x	Case Study
ScD	**Gregori, Fabio; Papetti, Alessandra; Pandolfi, Monica; Peruzzini, Margherita; Germani, Michele**	Digital Manufacturing Systems: A Framework to Improve Social Sustainability of a Production Site	2017	Procedia CIRP	21	MF		x										x			x	Case Study
Sco; WoS; ScD	**Gružauskas V., Baskutis S., Navickas V.**	Minimizing the trade-off between sustainability and cost effective performance by using autonomous vehicles	2018	Journal of Cleaner Production	13	SC		x	x	x	x								x	x		Simulation; Interview
Sco; WoS	**Gualtieri L., Palomba I., Merati F.A., Rauch E., Vidoni R.**	Design of human-centered collaborative assembly workstations for the improvement of operators' physical ergonomics and production efficiency: A case study	2020	Sustainability (Switzerland)	4	MF					x								x		x	Case Study
Sco; WoS	**Gupta A., Basu B.**	Sustainable Primary Aluminium Production: Technology Status and Future Opportunities	2019	Transactions of the Indian Institute of Metals	5	MF		x	x	x					x				x	x		Conceptual
WoS	**Harikannan, N; Vinodh, S; Gurumurthy, A**	Sustainable industry 4.0-an exploratory study for uncovering the drivers for integration	2020	JOURNAL OF MODELLING IN MANAGEMENT	0	no	x	x	x	x	x	x	x	x					x	x	x	SLR
Sco	**Hoffa-Dabrowska P., Grzybowska K.**	Simulation modeling of the sustainable supply chain	2020	Sustainability (Switzerland)	1	SC									x				x	x	x	Simulation
Sco; WoS	**Horváthová M., Lacko R., Hajduová Z.**	Using industry 4.0 concept – digital twin – to improve the efficiency of leather cutting in automotive industry	2019	Quality Innovation Prosperity	2	MF									x				x			Case Study
Sco	**Iqbal A., Zhao G., Suhaimi H., He N., Hussain G., Zhao W.**	Readiness of subtractive and additive manufacturing and their sustainable amalgamation from the perspective of Industry 4.0: a comprehensive review	2020	International Journal of Advanced Manufacturing Technology	0	MF		x	x	x	x			x				x	x	x		SLR
Sco; WoS	**Ivascu L.**	Measuring the implications of sustainable manufacturing in the context of industry 4.0	2020	Processes	1	no		x	x	x	x							x	x	x	x	Conceptual; Survey
Sco; WoS	**Jasiulewicz-Kaczmarek M., Legutko S., Kluk P.**	Maintenance 4.0 technologies - new opportunities for sustainability driven maintenance	2020	Management and Production Engineering Review	2	MF		x	x	x			x					x	x	x	x	Conceptual
Sco; WoS	**Jena M.C., Mishra S.K., Moharana H.S.**	Application of Industry 4.0 to enhance sustainable manufacturing	2020	Environmental Progress and Sustainable Energy	9	MF		x	x	x		x			x			x	x	x		Conceptual; Case Study
Sco	**Johansson N., Roth E., Reim W.**	Smart and sustainable emaintenance: Capabilities for digitalization of maintenance	2019	Sustainability (Switzerland)	8	MF		x	x	x								x	x	x		Conceptual; Interview
ScD	**Kaczmarek, Małgorzata Jasiulewicz-; Gola, Arkadiusz**	Maintenance 4.0 Technologies for Sustainable Manufacturing - an Overview	2019	IFAC-PapersOnLine	26	MF		x	x	x			x		x			x	x	x	x	Conceptual
Sco	**Kamble S., Gunasekaran A., Dhone N.C.**	Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies	2020	International Journal of Production Research	51	MF		x	x	x	x		x	x				x	x	x	x	survey

Appendix 11 (continued)

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
Sco; ScD	**Kamble S.S., Gunasekaran A., Gawankar S.A.**	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	2018	Process Safety and Environmental Protection	293	no		x	x	x	x		x	x	x	x			x	x	x	SLR
ScD	**Kayikci, Yasanur**	Sustainability impact of digitization in logistics	2018	Procedia Manufacturing	108	SC		x	x	x	x	x	x	x	x			x	x	x	x	Case Study; Interview
Sco; ScD	**Khanzode A.G., Sarma P.R.S., Mangla S.K., Yuan H.**	Modeling the Industry 4.0 adoption for sustainable production in Micro, Small & Medium Enterprises	2021	Journal of Cleaner Production	1	MF		x	x	x						x			x		x	Interview
Sco; WoS	**Kim H., Jung W.-K., Choi I.-G., Ahn S.-H.**	A low-cost vision-based monitoring of computer numerical control (CNC) machine tools for small and medium-sized enterprises (SMES)	2019	Sensors (Switzerland)	4	MF		x	x									x	x	x		Case Study
Sco; ScD	**Kristoffersen E., Blomsma F., Mikalef P., Li J.**	The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies	2020	Journal of Business Research	3	CE		x		x									x	x		Conceptual
Sco; ScD	**Kumar P., Singh R.K., Kumar V.**	Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers	2021	Resources, Conservation and Recycling	1	SC		x	x	x				x					x	x	x	Conceptual; Interview
Sco; WoS; ScD	**Kumar R., Singh R.K., Dwivedi Y.K.**	Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges	2020	Journal of Cleaner Production	2	no	x	x	x	x	x		x	x				x	x	x	x	Survey
Sco; WoS; ScD	**Kumar R., Singh S.P., Lamba K.**	Sustainable robust layout using Big Data approach: A key towards industry 4.0	2018	Journal of Cleaner Production	28	MF				x									x	x	x	Conceptual; Interview
Sco; ScD	**Leng J., Ruan G., Song Y., Liu Q., Fu Y., Ding K., Chen X.**	A loosely-coupled deep reinforcement learning approach for order acceptance decision of mass-individualized printed circuit board manufacturing in industry 4.0	2021	Journal of Cleaner Production	0	MF		x		x									x	x		Simulation
WoS; ScD	**Leng, JW; Ruan, GL; Jiang, PY; Xu, KL; Liu, Q; Zhou, XL; Liu, C**	Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey	2020	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	0	MF											x		x	x	x	Conceptual
Sco; WoS; ScD	**Li Y., Dai J., Cui L.**	The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model	2020	International Journal of Production Economics	9	no		x	x	x									x	x		Survey
Sco; WoS; ScD	**Liboni L.B., Liboni L.H.B., Cezarino L.O.**	Electric utility 4.0: Trends and challenges towards process safety and environmental protection	2018	Process Safety and Environmental Protection	6	no		x	x	x		x						x	x	x	x	Conceptual
Sco; ScD	**Lim C.H., Lim S., How B.S., Ng W.P.Q., Ngan S.L., Leong W.D., Lam H.L.**	A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach	2021	Renewable and Sustainable Energy Reviews	1	MF		x	x	x							x	x	x	x		Conceptual
Sco; WoS	**Lin Y.-C., Yeh C.-C., Chen W.-H., Liu W.-C., Wang J.-J.**	The use of big data for sustainable development in motor production line issues	2020	Sustainability (Switzerland)	0	MF				x								x	x	x		Interview
Sco; WoS	**Lindström J., Kyösti P., Birk W., Lejon E.**	An initial model for zero defect manufacturing	2020	Applied Sciences (Switzerland)	1	MF	x	x	x	x					x			x	x	x		Interview

Appendix 11 (continued)

Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	I40TP												SD			Research approach
							CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	
WoS	Liu, Y; Zhu, QH; Seuring, S	New technologies in operations and supply chains: Implications for sustainability	2020	INTERNATIONAL JOURNAL OF PRODUCTION ECONOMICS	0	no		x	x	x		x		x	x		x	x	x	x	x	SLR
Sco; WoS	Lopes de Sousa Jabbour A.B., Jabbour C.J.C., Godinho Filho M., Roubaud D.	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations	2018	Annals of Operations Research	237	CE	x	x	x	x				x				x	x	x		Conceptual
Sco; WoS	Luthra S., Kumar A., Zavadskas E.K., Mangla S.K., Garza-Reyes J.A.	Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy	2020	International Journal of Production Research	16	SC	x	x	x	x	x								x	x	x	Interview
ScD	Ma, Shuaiyin; Zhang, Yingfeng; Liu, Yang; Yang, Haidong; Lv, Jingxiang; Ren, Shan	Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries	2020	Journal of Cleaner Production	3	MF		x	x	x								x	x	x	x	Case Study
ScD	Ma, Shuaiyin; Zhang, Yingfeng; Lv, Jingxiang; Ge, Yuntian; Yang, Haidong; Li, Lin	Big data driven predictive production planning for energy-intensive manufacturing industries	2020	Energy	1	MF		x		x								x	x	x		Case Study
Sco; WoS	Machado C.G., Winroth M.P., Ribeiro da Silva E.H.D.	Sustainable manufacturing in Industry 4.0: an emerging research agenda	2020	International Journal of Production Research	74	no	x	x	x	x	x	x	x	x	x	x		x	x	x	x	SLR
Sco; WoS; ScD	Majeed A., Zhang Y., Ren S., Lv J., Peng T., Waqar S., Yin E.	A big data-driven framework for sustainable and smart additive manufacturing	2021	Robotics and Computer-Integrated Manufacturing	4	MF		x	x	x				x				x	x	x	x	Conceptual; Case Study
ScD	Manavalan, E.; Jayakrishna, K.	An Analysis on Sustainable Supply Chain for Circular Economy	2019	Procedia Manufacturing	19	CE		x		x									x	x	x	Case Study
WoS	Margherita, EG; Braccini, AM	Industry 4.0 Technologies in Flexible Manufacturing for Sustainable Organizational Value: Reflections from a Multiple Case Study of Italian Manufacturers	2020	INFORMATION SYSTEMS FRONTIERS	0	MF		x		x	x	x						x	x	x	x	Case Study
Sco	Mark B.G., Hofmayer S., Rauch E., Matt D.T.	Inclusion of workers with disabilities in production 4.0: Legal foundations in Europe and potentials through worker assistance systems	2019	Sustainability (Switzerland)	2	no					x		x					x			x	Conceptual
Sco; WoS	Mastos T.D., Nizamis A., Vafeiadis T., Alexopoulos N., Ntinas C., Gkortzis D., Papadopoulos A., Ioannidis D., Tzovaras D.	Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution	2020	Journal of Cleaner Production	3	SC	x	x	x				x					x	x	x	x	Case Study
Sco	Meng Y., Yang Y., Chung H., Lee P.-H., Shao C.	Enhancing sustainability and energy efficiency in smart factories: A review	2018	Sustainability (Switzerland)	16	no		x	x	x		x		x	x			x	x	x	x	SLR
WoS	Morrar, R; Arman, H; Mousa, S	The Fourth Industrial Revolution (Industry 4.0): A Social Innovation Perspective	2017	Technology Innovation Management Review	270	no		x		x	x										x	Conceptual

Appendix 11 (continued)

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
Sco; WoS	**Müller J.M., Kiel D., Voigt K.-I.**	What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability	2018	Sustainability (Switzerland)	278	no	x	x	x	x	x	x		x	x	x			x	x	x	Survey
Sco; WoS	**Müller J.M., Voigt K.-I.**	Sustainable Industrial Value Creation in SMEs: A Comparison between Industry 4.0 and Made in China 2025	2018	International Journal of Precision Engineering and Manufacturing - Green Technology	106	no		x											x	x	x	Survey
Sco	**Murmura F., Bravi L.**	Additive manufacturing in the wood-furniture sector: Sustainability of the technology, benefits and limitations of adoption	2018	Journal of Manufacturing Technology Management	21	MF								x					x	x	x	Survey
ScD	**Naderi, Mahdi; Ares, Enrique; Peláez, Gustavo; Prieto, Daniel; Araújo, Madalena**	Sustainable Operations Management for Industry 4.0 and its Social Return	2019	IFAC-PapersOnLine	3	MF		x		x			x		x				x	x	x	Conceptual
Sco; ScD	**Nara E.O.B., da Costa M.B., Baierle I.C., Schaefer J.L., Benitez G.B., do Santos L.M.A.L., Benitez L.B.**	Expected impact of industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry	2021	Sustainable Production and Consumption	1	MF	x	x	x	x	x	x						x	x	x	x	Conceptual
WoS	**Nascimento, DLM; Alencastro, V; Quelhas, OLG; Caiado, RGG; Garza-Reyes, JA; Lona, LR; Tortorella, G**	Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context A business model proposal	2019	Journal Of Manufacturing Technology Management	119	CE				x				x	x				x	x	x	Conceptual; Interview
Sco; WoS	**Nouiri M., Trentesaux D., Bekrar A.**	Towards energy efficient scheduling of manufacturing systems through collaboration between cyber physical production and energy systems	2019	Energies	2	MF	x													x		Case Study
Sco	**Oláh J., Aburumman N., Popp J., Khan M.A., Haddad H., Kitukutha N.**	Impact of industry 4.0 on environmental sustainability	2020	Sustainability (Switzerland)	7	no	x	x	x	x	x	x	x	x			x		x	x	x	Conceptual
Sco; WoS	**Ordieres-Meré J., Remón T.P., Rubio J.**	Digitalization: An opportunity for contributing to sustainability from knowledge creation	2020	Sustainability (Switzerland)	8	MF		x	x	x								x	x	x	x	Case Study
WoS	**Papetti, A; Gregori, F; Pandolfi, M; Peruzzini, M; Germani, M**	A method to improve workers' well-being toward human-centered connected factories	2020	JOURNAL OF COMPUTATIONAL DESIGN AND ENGINEERING	0	MF		x										x			x	Case Study
Sco; WoS	**Park K.T., Kang Y.T., Yang S.G., Zhao W.B., Kang Y.-S., Im S.J., Kim D.H., Choi S.Y., Do Noh S.**	Cyber Physical Energy System for Saving Energy of the Dyeing Process with Industrial Internet of Things and Manufacturing Big Data	2020	International Journal of Precision Engineering and Manufacturing - Green Technology	7	MF	x	x		x									x	x		Case Study
ScD	**Patsavellas, John; Salonitis, Konstantinos**	The Carbon Footprint of Manufacturing Digitalization: critical literature review and future research agenda	2019	Procedia CIRP	1	no		x	x	x										x		Conceptual

Appendix 11 (continued)

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
Sco; WoS	**Pham T.T., Kuo T.-C., Tseng M.-L., Tan R.R., Tan K., Ika D.S., Lin C.J.**	Industry 4.0 to accelerate the circular economy: A case study of electric scooter sharing	2019	Sustainability (Switzerland)	8	CE	x	x	x	x		x						x	x	x	x	Case Study
Sco; WoS; ScD	**Pinzone M., Albè F., Orlandelli D., Barletta I., Berlin C., Johansson B., Taisch M.**	A framework for operative and social sustainability functionalities in Human-Centric Cyber-Physical Production Systems	2020	Computers and Industrial Engineering	20	no	x	x	x	x	x	x	x					x	x		x	Conceptual; Case Study
ScD	**Piscitelli, Giuseppina; Ferazzoli, Angela; Petrillo, Antonella; Cioffi, Raffaele; Parmentola, Adele; Travaglioni, Marta**	CIRCULAR ECONOMY MODELS IN THE INDUSTRY 4.0 ERA: A REVIEW OF THE LAST DECADE	2020	Procedia Manufacturing	4	CE		x	x	x				x				x	x	x	x	SLR
Sco; WoS; ScD	**Ramirez-Peña M., Sánchez Sotano A.J., Pérez-Fernandez V., Abad F.J., Batista M.**	Achieving a sustainable shipbuilding supply chain under I4.0 perspective	2020	Journal of Cleaner Production	11	SC		x	x	x	x	x	x	x	x	x	x		x	x	x	Conceptual
Sco; ScD	**Ren S., Zhang Y., Liu Y., Sakao T., Huisingh D., Almeida C.M.V.B.**	A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions	2019	Journal of Cleaner Production	114	no	x	x	x	x		x						x	x	x		Conceptual
ScD	**Saetta, Stefano; Caldarelli, Valentina**	How to increase the sustainability of the agri-food supply chain through innovations in 4.0 perspective: a first case study analysis	2020	Procedia Manufacturing	3	no		x		x								x	x	x	x	Survey
Sco	**Sartal A., Bellas R., Mejías A.M., García-Collado A.**	The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review	2020	Advances in Mechanical Engineering	4	no		x	x		x	x	x	x	x				x	x	x	SLR
Sco; WoS	**Scharl S., Praktiknjo A.**	The Role of a Digital Industry 4.0 in a Renewable Energy System	2019	International Journal of Energy Research	6	no		x		x		x				x			x	x		Interview
ScD	**Sharma, Mahak; Kamble, Sachin; Mani, Venkatesh; Sehrawat, Rajat; Belhadi, Amine; Sharma, Vardaan**	Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies	2020	Journal of Cleaner Production	0	no		x	x	x			x	x	x	x		x	x	x	x	Conceptual; Survey
ScD	**Shayganmehr, Masoud; Kumar, Anil; Garza-Reyes, Jose Arturo; Moktadir, Md Abdul**	Industry 4.0 enablers for a cleaner production and circular economy within the context of business ethics: A study in a developing country	2020	Journal of Cleaner Production	0	CE		x	x	x				x			x					Conceptual
Sco; ScD	**Sony M., Naik S.**	Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model	2020	Technology in Society	9	no						x									x	SLR
Sco; WoS; ScD	**Stock T., Obenaus M., Kunz S., Kohl H.**	Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential	2018	Process Safety and Environmental Protection	141	no	x	x	x			x			x			x		x	x	Interview
ScD	**Stock, T.; Seliger, G.**	Opportunities of Sustainable Manufacturing in Industry 4.0	2016	Procedia CIRP	1064	no	x	x	x	x		x	x	x				x	x	x	x	Conceptual; Case Study

Appendix 11 (continued)

							I40TP												SD			
Data-base	Author(s)	Title of Article	Year	Publishing Journal	Cited by	I40 domain	CPS	IoT	CC	BD	RO	HVI	XR	AM	SIM	CS	BC	SS	EC	EN	SO	Research approach
WoS	**Strandhagen, JW; Buer, SV; Semini, M; Alfnes, E; Strandhagen, JO**	Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain	2020	PRODUCTION PLANNING & CONTROL	0	no		x	x	x		x	x	x	x			x	x	x	x	Conceptual; Case Study
WoS	**Tavares, TM; Godinho, M; Ganga, GD; Callefi, MH**	THE RELATIONSHIP BETWEEN ADDITIVE MANUFACTURING AND CIRCULAR ECONOMY: A SISTEMATIC REVIEW	2020	INDEPENDENT JOURNAL OF MANAGEMENT & PRODUCTION	0	CE								x						X		SLR
Sco; WoS	**Tirabeni L., De Bernardi P., Forliano C., Franco M.**	How can organisations and business models lead to a more sustainable society? A framework from a systematic review of the industry 4.0	2019	Sustainability (Switzerland)	10	no	x	x	x	x	x	x		x	x			x	x	x	x	SLR
Sco; WoS; ScD	**Tiwari K., Khan M.S.**	Sustainability accounting and reporting in the industry 4.0	2020	Journal of Cleaner Production	11	no	x	x	x	x	x	x	x					x	x	x	x	Interview
Sco	**Turner C., Moreno M., Mondini L., Salonitis K., Charnley F., Tiwari A., Hutabarat W.**	Sustainable production in a circular economy: A business model for re-distributed manufacturing	2019	Sustainability (Switzerland)	9	MF						x		x				x	x	x	x	Case Study
Sco; WoS	**Varela L., Araújo A., Ávila P., Castro H., Putnik G.**	Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability	2019	Sustainability (Switzerland)	19	no				x	x								x	x	x	Survey
Sco; ScD	**Waibel M.W., Steenkamp L.P., Moloko N., Oosthuizen G.A.**	Investigating the Effects of Smart Production Systems on Sustainability Elements	2017	Procedia Manufacturing	81	no	x	x	x	x	x	x				x		x	x	x	x	SLR
ScD	**Waibel, M. W.; Oosthuizen, G. A.; Toit, D. W. du**	Investigating current smart production innovations in the machine building industry on sustainability aspects	2018	Procedia Manufacturing	8	no		x	x	x	x	x	x	x	x			x	x	x	x	Conceptual; Survey
Sco; WoS; ScD	**Yadav G., Kumar A., Luthra S., Garza-Reyes J.A., Kumar V., Batista L.**	A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers	2020	Computers in Industry	2	MF	x	x		x				x					x	x	x	Conceptual; Survey; Case Study
Sco; WoS; ScD	**Yadav G., Luthra S., Jakhar S.K., Mangla S.K., Rai D.P.**	A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case	2020	Journal of Cleaner Production	28	SC		x	x	x		x			x			x	x	x	x	Conceptual; Survey; Case Study
Sco; WoS	**Yang S., Raghavendra M.R.A., Kaminski J., Pepin H.**	Opportunities for industry 4.0 to support remanufacturing	2018	Applied Sciences (Switzerland)	51	CE	x	x	x		x	x		x		x		x	x	x		Case Study
ScD	**Yue, Xuejun; Cai, Hu; Yan, Hehua; Zou, Caifeng; Zhou, Keliang**	Cloud-assisted industrial cyber-physical systems: An insight	2015	Microprocessors and Microsystems	134	no	x	x	x	x		x						x	x	x		Conceptual

Appendix 12 – Full Overview of data base used for qualitative analyses

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Abubakr M., Abbas A.T., Tomaz I., Soliman M.S., Luqman M., Hegab H.	Sustainable and smart manufacturing: An integrated approach	2020	- integrated sustainable smart manufacturing performance by incorporating sustainable manufacturing measures - the conventional life cycle analysis (LCA) is upgraded with the TBL principle --> the Life-Cycle-Sustainability-Assessment (LCSA) - discussion of current and future challenges	- implementing a factory will indeed improve the overall process and product performance, quality, and flexibility, although at the same time, it will require a considerable capital investment compared to the conventional one	**Economic**: - reduced the number of manufacturing steps - increased process flexibility, process efficiency, data granularity, data quality, and automation enable improved process performance **Environmental**: - reduction in waste and energy consumption - improved sustainable use of resources **Social**: - lowering job opportunities and increasing unemployment
Adenuga, Olukorede Tijani; Mpofu, Khumbulani; Boitumelo, Ramatsetse Innocent	Energy efficiency analysis modelling system for manufacturing in the context of industry 4.0	2019	- The paper proposes an "Energy Efficiency Analysis Modelling System" (EEAMS) as a tool to provide an estimation of energy costs in a manufacturing plant - Therefore, a bottom- up approach is adopted, which uses information on energy cost as a baseline for a web-based interacting platform - an energy efficiency software framework (EESF) is proposed to determine the economic impacts of energy measurements - the authors proposed an Energy Efficiency Sustainable Software through IoT architecture and big data analytics model and allow centralization of data for cloud hosting, through a web-based interacting platform, using EESF to determine the economic impacts of energy measurement, and verification on energy consumption and environment	- The article provides a platform for the digitalization of the use of energy, which is beginning to have a significant impact on the energy sector and energy efficiency is emerging as a key arena for innovation - The efficient use of electricity at its end by a production equipment is a useful output on the demand-side energy efficiency policies - The adherence to the determination of energy usage baselines in accordance with SANS 5001 and determination of energy efficiency saving potentials through the use of the Energy Efficiency Sustainability Framework (EESF) as the means of energy performance indicators for monitoring energy performance, helps in the preparation of reports on the implementation of the energy management plans, and achieved energy savings	**Economic:** - reduced energy costs - facilitated report creation **Environmental:** - reduced energy consumption
Ahmad S., Miskon S., Alabdan R., Tlili I.	Towards sustainable textile and apparel industry: Exploring the role of business intelligence systems in the era of industry 4.0	2020	- investigating the determinants of business intelligence system (BIS) adoption with an eye towards understanding how BIS can resolve sustainability issues in T&A companies with Industry 4.0 technologies - 14 semi-structured in-depth interviews, The snowball and purposeful sampling strategy is used to select the participants. - qualitative content analysis technique is used to analyze the interview data	- sustainability issues in T&A companies improved value creation processes with leading business inteligence solutions (BIS), and perceived difficulties in the adoption of BIS - Major improvements are perceived in the apparel retail business because apparel companies are more prone to adopt the Industry 4.0 technologies with advanced BIS - A major improvement was observed in retail business with fast insights and well-informed decision-making - high-end apparel companies from advanced countries are more prone to adopt the Industry 4.0 technologies	**Economic**: - improved supply chain management, inventory management, marketing, fast merchandising, quick shipments, retailing, and distribution processes - optimization of a company's business, customer satisfaction and cost saving **Environmental**: - improved the resource utilization in terms of business processes, energy consumption, and material usage
Ambrogio, Giuseppina; Guido, Rosita; Palaia, Domenico; Filice, Luigino	Job shop scheduling model for a sustainable manufacturing	2020	- this study aims at introducing a smart tool, based on the application of a mathematical model, already proposed in literature, for the job scheduling from an energy saving perspective into a real company IT system - After a preliminary introduction on the concepts of sustainability and industry 4.0, and how they are connected to each other, and a second part that will deal with Smart Factory, smart factories oriented to customization and flexibility, the mathematical model of activity scheduling will be discussed and than applied to a specific IT system	- This model, in fact, properly implemented into a Manufacturing Execution System (MES) will represent a powerful tool oriented to the efficient use of energy resources	**Economic:** - reduced energy costs **Environmental:** - reduced energy consumption

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Amjad, Muhammad Saad; Rafique, Muhammad Zeeshan; Hussain, Shafqat; Khan, Mohammad Aamir	A new vision of LARG Manufacturing — A trail towards Industry 4.0	2020	- The objective of this study is to explore the possibility of collaboration between constituents of LARG (Lean, Agile, Resilient and Green) Manufacturing with the facets of Industry-4.0 - In this context, a thorough systematic literature review has been conducted to validate the research gap regarding integration of LARG Manufacturing with Industry 4.0	- LARG constituent practices can be amalgamated with various facets of Industry-4.0 to provide operational, economic and environmental benefits - Once the manufacturing processes are ridden of wastes, the adoption of Industry 4.0 concepts becomes easier - The increased process visibility, elimination of wastes, fast processes, high level of responsiveness to disruptions and eco-friendly manufacturing are the salient features of the LARG Manufacturing & Industry-4.0 synergy, fuelled by automation and BigData	**Economic:** - increased process visibilit - fast processes / reduced delivery times - high level of responsiveness to disruptions - enhanced risk mitigation - informed decision making **Environmental:** - elimination of wastes - eco-friendly manufacturing - reduced carbon foot print **Social:** - replacement of labour with machines
Bag S., Yadav G., Wood L.C., Dhamija P., Joshi S.	Industry 4.0 and the circular economy: Resource melioration in logistics	2020	- This study investigates how Industry 4.0 resources impact smart logistics and further influence dynamic remanufacturing and green manufacturing capability and, the final effect on business logistics sustainability. - Survey data were collected from 150 respondents using an online survey of South African executives in firms operating mines, quarries, and processing plants. - Partial Least Squares based structural equation modelling (PLS-SEM) was used to test the hypotheses	- Industry 4.0 resources have a strong effect on intelligent logistics compared to its impact on interconnected logistics and instrumented logistics - The impact of intelligent logistics is found to be very high compared to that of interconnected logistics and instrumented logistics on dynamic remanufacturing and green manufacturing capability - dynamic remanufacturing and green manufacturing capability are found to have a positive influence business logistics sustainability	**Economic**: - operational and cost efficiencies based on improved decisions - redued supply and demand uncertainties in the forward and reverse logistics network **Environmental**: - lowering of wastages in the supply chain network - cleaner and closed-loop economy with increased longevity of resources - reduced solid waste generation - lower environmental pollution levels
Bag, Surajit; Gupta, Shivam; Kumar, Sameer	Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development	2021	- the current study aspires to examine how great an effect Industry 4.0 adoption has on 10R (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) advanced manufacturing capabilities and its outcome on sustainable development under the moderating effect of an Industry 4.0 delivery system - Practice-based view and Dynamic capability view theories are used to conceptualise the theoretical model - The research team statistically validated the theoretical model considering 124 data points that were collected using an online survey with a structured questionnaire - The study concludes with key take away points for managers	- firms with a high degree of I4.0 implementation lead to a positive development of 10 R advanced manufacturing capabilities - 10 R advanced manufacturing capabilities are found to have a positive influence on sustainable development outcomes - I4.0 delivery system is found to have a moderating effect on the relationship degree of I4.0 adoption and 10 R advanced manufacturing capabilities - This suggests that firms should focus on the degree of I4.0 adoption and 10 R advanced manufacturing capabilities to enhance sustainable development outcomes and achieve their goals - However, serious focus on the development of infrastructure for I4.0 delivery systems is essential	**Economic:** - increase economic prosperity **Environmental:** - reduced use of natural resources - increased reuse of still functional products/components - increased repairing and maintanance of defective products - enhanced restoring of old products - enhanced recycling capabilities **Social:** - increased need for collaborative skills development - increased social equity
Bag, Surajit; Pretorius, Jan Ham Christiaan; Gupta, Shivam; Dwivedi, Yogesh K.	Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities	2020	- this study employs institutional theory and resource-based view theory to elucidate the way in which automotive firms configure tangible resources and workforce skills to drive technological enablement and improve sustainable manufacturing practices and furthermore develop circular economy capabilities - tested the research hypothesis using primary data collected from 219 automotive and allied manufacturing companies operating in South Africa	- coercive pressures and mimetic pressures are positively associated with tangible resources - coercive pressures and normative pressures indicate a positive association with workforce skills - Tangible resources and workforce skills indicate a positive association with Big Data Analytic powered by Artificial Intelligence (BDA-AI) adoption - BDA-AI adoption was found to have a positive association with SMP and Circular Economy (CE) capabilities -SMP were found to have a positive association with CE capabilities - the enabling effect of BDA-AI and CE capabilities is positively moderated by organizational flexibility and industry dynamism	**Economic:** - increase information granularity for better decision making - increased operational performance **Environmental:** - I40 implementation accelerated by environmental pressure - reduced resource damage - reduced environmental pollution **Social:** - I40 implementation accelerated by social pressure - increased support of local economy and network

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Bag, Surajit; Yadav, Gunjan; Dhamija, Pavitra; Kataria, Krishan Kumar	Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study	2020	- This study aspires to develop a theoretical model linking key resources for Industry 4.0 adoption that are essential to drive technological progress; and its effect on sustainable production and circular economy capabilities - The review of literature led to the identification of thirty-five resources that are essential for the adoption of Industry 4.0 - exploratory factor analysis was used to group the variables under relevant factors and thereafter research team developed a theoretical model that was further tested using PLS-SEM technique	- production systems, human resources, project management, management leadership, green logistics, green design, information technology, big data analytics and collaborative relationships are key resources for Industry 4.0 adoption - Industry 4.0 adoption have a positive relationship with sustainable production - sustainable production has a positive relationship with circular economy capabilities - CE related awareness creation among stakeholders can be helpful to eradicate unethical practices	**Economic:** - enhanced elimination of the resource scarcity problems - high initial investment - enabled production in masses and meet customer demands without manufacturing excess - restriction of uncontrolled use of resources **Environmental:** - Green logistics & green design have a positive relationship with I4.0 adoption - cleaner ways of manufacturing without producing wastages **Social:** - Human resources have a positive relationship with I4.0 adoption - increased skill development
Bai C., Dallasega P., Orzes G., Sarkis J.	Industry 4.0 technologies assessment: A sustainability perspective	2020	- we further examine Industry 4.0 technologies in terms of application and sustainability implications - We introduce a measures framework for sustainability based on the United Nations Sustainable Development Goals; incorporating various economic, environmental and social attributes. - We also develop a hybrid multi-situation decision method integrating hesitant fuzzy set, cumulative prospect theory and VIKOR	- Take advantage of Industry 4.0 technology adoption to improve sustainability impact but each technology needs to be carefully evaluated as specific technology will variably influence industry and sustainability dimensions - Investment in such technologies should consider appropriate priority investment and championing - Industry 4.0 can tackle each of the 17 SDGs	**Economic**: - reduced set-up and lead times - reduced labor and material costs - increased production flexibility - higher productivity and enhanced customization **Environmental**: - reduced energy and resource consumption - reduction in waste and CO2-emissions - Products can be disassembled into their component elements for reuse, recycling, or remanufacturing **Social**: - support of employee health and safety - higher employee satisfaction and motivation - reduced employment - information security issues
Bal, Alperen; Badurdeen, Fazleena	A Business Model to Implement Closed-loop Material Flow in IoT-enabled Environments	2019	- In this research we propose a 'Lease-First, Then-Sell' (LFTS) business model adopting the multiple lifecycle approach to design, manufacture and use products - Simulation is used to study the logistics network configuration when implementing this model for different scenarios to identify TBL benefits as well as opportunities and challenges to implement the IoT-enabled LFTS model - A case study for Turkish refrigerator market is presented to observe the expected results over 12 years (2024-2035)	- LFTS provide the opportunity to companies to expand and diversify their markets - companies could experiment the business model which could possibly make them to reach more environmentally friendly and more profitable supply chain - Results indicate when LFTS is implemented, total supply chain profit has a tendency to increase	**Economic:** - increased total supply chain profit - reduced total manufacturing cost **Environmental:** - reduced total lifecycle energy consumption - reduced use phase emission level
Beier G., Niehoff S., Xue B.	More sustainability in industry through Industrial Internet of Things?	2018	- This paper discusses how the environmental dimension of a sustainable development can potentially benefit from the IIoT—focusing especially on three topics: resource efficiency, sustainable energy and transparency. - It presents a state of the art literature analysis of IIoT-enabled approaches addressing the three environmental topics. This analysis is compared with the findings of a survey among Chinese industrial companies, investigating the sustainability-related expectations of participants coming along with the implementation of IIoT solutions - the survey was conducted with the means of a questionnaire	- barriers and concerns regarding the digital inclusion of suppliers have to be addressed - Expectations relating to improved resource efficiency are high (88.1% expect very high or high material saving potentials, 83.5% foresee very high or high energy savings), but further research has to focus on assessing real potentials taking possible rebound effects into account	**Environmental**: - improved environmental management of companies

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Beier G., Niehoff S., Ziems T., Xue B.	Sustainability aspects of a digitalized industry – A comparative study from China and Germany	2017	- This paper discusses the changes that digitalization is expected to bring about in the industrial sector by comparing a highly industrialized (Germany) with a major emerging industrial economy (China) - empirical investigation of how the digitalization of industry is likely to affect sustainability aspects of manufacturing companies in two countries with very different industrial structures (Germany & China) - this transformation will not only impact the ecological dimension (resource efficiency, renewable energy), but that the technical transformation is likely to be accompanied by social transformations.	- this transformation should receive more attention from a sustainability point of view and be embedded in national and international sustainability policies to ensure the proper exploitation of opportunities and the identification of potential risks and respective countermeasures from the very beginning	**Environmental**: - improvements in resource efficiency - increased employment of renewable energy sources **Social**: - major job losses due to the increased automatization of production
Beier, Grischa; Ullrich, André; Niehoff, Silke; Reißig, Malte; Habich, Matthias	Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes – A literature review	2020	- This paper provides a de-facto definition of the concept "Industry 4.0" from a sociotechnical perspective based on systematically deriving and describing the constituting key features of the concept Industry 4.0 through a qualitative literature review - a thorough review of how far the concept of sustainability is incorporated in it	- Industry 4.0 does not seem to be a sharply defined, homogeneous development rather a collective term of different developments, inculding huge overlaps of key features between all categories, underlining that Industry 4.0 is a sociotechnical development that can and should not be reduced to technical aspects - it is not clear to what extent Industry 4.0 will contribute to a sustainable development - Many text fragments claim improved resource efficiency as a consequence of Industry 4.0; It is not made clear though under which circumstances those efficiency gains are to be expected - In total only 17 out of 684 text fragments describing the concept Industry 4.0 provide evidence or a reference to such evidence that postulate effects of key features on sustainability aspects - only very few of the articles establish a scientific link between Industry 4.0 and sustainability aspects although often authors' presentations are suggesting otherwise - A contribution to a sustainable development of industry can only be expected when the transformation includes clear in- tentions from the very beginning - The leading question should not be how much positive influence Industry 4.0 will have on sustainable development but how sustainable digitalization of industry could look like	**Economic:** - potential accelerated growth in productivity **Environmental:** - effect on reosurce & energy efficiency **Social:** - effects on future work conditions - potential for more diverese and flexible career paths - imporved work conditions
Birkel H.S., Veile J.W., Müller J.M., Hartmann E., Voigt K.-I.	Development of a risk framework for Industry 4.0 in the context of sustainability for established manufacturers	2019	- proposes a framework of risks in the context of Industry 4.0 that is related to the Triple Bottom Line of sustainability - framework is developed from a literature review, as well as from 14 in-depth expert interviews	- creates an initial and holistic understanding of the risks expected by Industry 4.0	**Economic**: - risks that are associated with high or false investments - threatened business models and increased competition from new market entrants **Ecological**: - increased waste and energy consumption - possible ecological risks related to the concept "lot size one" **Social**: - risk of job losses - risks associated with organizational transformation - risks of employee requalification - internal resistance

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Blümel, Eberhard	Global Challenges and Innovative Technologies Geared Toward New Markets: Prospects for Virtual and Augmented Reality	2013	- This paper examines means by which digital engineering and virtual and augmented reality technologies can support the creation of sustainable smart manufacturing and smart logistics processes as well as on-the-job training and qualification and knowledge transfer	- It is imperative that the design and simulation tools implemented in the process chain have coordinated interfaces and the data is thus consistently integrated - Real work systems for on-the-job qualification and training will increasingly be supplemented or supplanted by VR work systems - Since digital engineering already allows the virtually seamless integration of real working systems in virtual environments and vice versa, both the basic technological and economic conditions will make the widespread use of interactive VR technologies in basic and advanced vocational training of technical specialists possible in the near future	**Economic:** - enhanced factory planning - improved productivity - time savings **Environmental:** - enhanced maintenance execution - enhanced process planning for improved resource & energy efficiency **Social:** - enhanced vocational training - increased job safety
Bonilla S.H., Silva H.R.O., da Silva M.T., Gonçalves R.F., Sacomano J.B.	Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges	2018	- conduct a literature-based analysis to discuss the sustainability impact and challenges of Industry 4.0 from four different scenarios: deployment, operation and technologies, integration and compliance with the sustainable development goals, and long-run scenarios. -analysis of the impact on sustainability, based on a scenario approach - the effects of Industry 4.0 on the deployment and operation scenarios are explored, and the positive and negative impacts on sustainability are identified	- we identified both positive and negative expected impacts, with some predominance of positives that can be considered positive secondary effects derived from Industry 4.0 activities - only through integrating Industry 4.0 with the sustainable development goals in an eco-innovation platform, can it really ensure environmental performance - The convergence of Industry 4.0 technologies towards the SDGs platform is possible but requires supportive innovation and policies	**Ecological**: - negative environmenal impact at the deployment stage, - positive environmental impact during operation stage/period.
Braccini A.M., Margherita E.G.	Exploring organizational sustainability of Industry 4.0 under the triple bottom line: The case of a manufacturing company	2018	- Our investigation considered the adoption of I40 in a manufacturing company which we analyzed as a single case study - We describe the level of I40 adoption and the process through which the unit has adopted them.	- Our case confirms that I40 applications support the triple bottom line through the improvement of productivity and product quality (economic), continuous energy consumption monitoring (environmental), and safer work environment and less intense work-load and job enrichment (social) - In the trajectories found, the three dimensions of sustainability influence and reinforce each other	**Economic:** - Increased production by 30% - more efficient and flexible processes - improved quality of product **Environmental:** - reuse of resources (i.e. water & heat) - continuous energy consumption monitoring **Social**: - safer work-environment and for a less intense work-load - opportunities for enriching the jobs of the workforce, making the job more gratifying and less alienating. - new workforce skills
Bressanelli, Gianmarco; Adrodegari, Federico; Perona, Marco; Saccani, Nicola	The role of digital technologies to overcome Circular Economy challenges in PSS Business Models: an exploratory case study	2018	- this paper explores how new digital technologies can overcome in practice the main Circular Economy challenges through a case study of a company who leverages Internet of Things, Big Data and Analytics in the provision of its Product-Service Systems Business Model	- the case indicates that, following the adoption of IoT, Big Data and Analytics, a company is able to offer a set of functionalities that, in turn, helps to overcome Dircular Economy challenges	**Economic:** - enhanced preventive and predictive mainenance - reduced operational risks related to Circular Economy **Environmental:** - increased recycling, reuse and refurbish opportunities - enhanced engineering opportunities to design products extending a products usage phase **Social:** - increased customer value (i.e. facilitated product upgrades)

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Brozzi R., Forti D., Rauch E., Matt D.T.	The advantages of industry 4.0 applications for sustainability: Results from a sample of manufacturing companies	2020	- conduct a study to investigate the benefits of Industry 4.0 applications for sustainability - use the results from a sample of manufacturing companies, which were asked by means of a questionnaire. - investigate to what extent manufacturing companies see Industry 4.0 as an advantage for economic, environmental and social sustainability	- overall the perception of economic opportunities prevail, while the association of a beneficial impact of Industry 4.0 on environmental sustainability is rather low across companies, regardless of their size, turnover and digital level - the results suggest a strong association of the size and the digital level to specific Industry 4.0 related advantages, referring to the social and economic dimension of sustainability, respectively - The social opportunity relating to flexible organisation of work emerges as a driver in large companies, more so than SMEs	**Economic:** - Increased quality - improved logistic performance - time savings - reduction of cost **Environmental:** - lower environmental impact **Social**: - lower physical stress
Cagliano R., Canterino F., Longoni A., Bartezzaghi E.	The interplay between smart manufacturing technologies and work organization: The role of technological complexity	2019	- providing evidence on how Smart Manufacturing (SM) affects work organization on both micro & macro level - reports on a multiple-case study of 19 companies implementing SM.	- a higher level of technological complexity is associated to decentralization of decision making and a reduction in the number of hierarchical levels - low levels of technological complexity in the SM context are associated with an organizational scenario in which operators perform a limited number of tasks, with limited job autonomy, cognitive demand, and vise versa - the study offers valuable practical insights related to the importance of including work organization considerations when defining the technological strategy within companies - the interplay between technology and work organization cannot be considered in a deterministic way	**Social**: - more effective human-centric and socially sustainable manufacturing and organizational paradigms - increased number of tasks, job autonomy and cognitive demand for operators
Carvalho, Núbia; Chaim, Omar; Cazarini, Edson; Gerolamo, Mateus	Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing	2018	- This paper seeks to describe the main forms of collaboration of Industry 4.0 in relation to sustainability	- industry 4.0 has a considerable area of significant aspects for sustainable industrial development - To achieve its environmental potential, this technological development must be tied to sustainable awareness - Regarding its interconnection to Ecotreneurship, this new revolution has an unparalleled potential for fast and significant change - While some sustainability improvement can be inferred from the increased efficiency and adaptation to demand curves, a deepen impact on sustainability can only be achieved by incorporating environmental and social issues into the very concept of manufacturing companies' success	**Economic:** - increased dynamization of factory time - lower production costs **Environmental:** - enhanced waste minimization - enhanced sensible use of natural resources and raw materials - increased energy efficiency **Social:** - enhanced efficiency of employee training - increased worker motivation - potential job losses

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Chiappetta Jabbour C.J., Fiorini P.D.C., Ndubisi N.O., Queiroz M.M., Piato É.L.	Digitally-enabled sustainable supply chains in the 21st century: A review and a research agenda	2020	- this study aims to systematise published studies which address the implications of big data for sustainable supply chain management through a systematic literature review - A systematisation of the knowledge in this field is presented with a focus on big data. - A research agenda containing pressing research gaps is presented.	- overview of extant literature on this topic in recent years - proposition of seven gaps in the literature in order to foster future investigations on big data-driven sustainable supply chains; - four lessons for business practitioners aiming to use big data for sustainable supply chain practices (i) developing big data analytics capability has to become a business priority in order to effectively build competitive sustainable supply chains (ii) big data has benefits for each of the dimensions of the triple-bottom-line in supply chains (iii) development of complementary organizational capabilities is needed to overcome challenges and facilitate the benefits of big data technology for sustainable supply chain management	**Economic:** - prediction of financial impact of supply chain-related decisions - improvement of inventory management and demand forecasting - Cost savings - Enhancement of productivity levels - optimization of distribution and logistics - faster response to market demands **Environmental:** - knowledge of environmental impact of partners - monitoring of environmental indicators such as gases emissions and air pollutants - resource and energy savings - accurate environmental impact assessment **Social**: - monitoring and tracking of social issues in multi-tier global supply chains - assessment of compliance history of suppliers - prediction of social problems accross the supply chain
Cochran, David S.; Rauch, Erwin	Sustainable Enterprise Design 4.0: Addressing Industry 4.0 Technologies from the Perspective of Sustainability	2020	- This paper aims to present an approach to better address sustainability as well as Industry 4.0 in terms of long-term strategic, enterprise design that is sustainable - the authors are looking from the perspective of the Triple Bottom Line concept to investigate the Why, What and How for economic, environmental and social sustainability based on physical solutions derived from Industry 4.0 - as a result, a list of needs, functional requirements as well as possible Industry 4.0 physical solutions is proposed to achieve a long-term sustainable enterprise design -a framework for integrating Industry 4.0, sustainability and long- term sustainable enterprise design is presented	- From an economic perspective, the main aim of Industry 4.0 is digitization to connect products with machines, workers and the enterprise environment outside the smart factory, enhancing automated manufacturing processes to be able to produce small lot sizes in a highly efficient way - Industry 4.0 also raises the awareness of environmental sustainability by making the degree of sustainability measurable through enabling technologies like IoT, smart sensors and real-time connectivity - on the social dimension, the requirement is to provide the appropriate qualification and use of new technologies that provide new opportunities for Associates to collaborate and interact with machines, robots and computers, and with each other	**Economic:** - enhanced ability for Associates to co-create products and services - efficient business & operational processes - increased quality standards **Environmental:** - less environmental harm - awareness of current energy consumption - more precise usage of resources and materials - reduced waste **Social:** - need for human integration into manufacturing system - enhanced safety at work - enhanced vocational training
Dantas, T. E. T.; de-Souza, E. D.; Destro, I. R.; Hammes, G.; Rodriguez, C. M. T.; Soares, S. R.	How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals	2021	- This research performes a systematic literature review to identify how the combination of Circular Economy practices and Industry 4.0 technologies, could contribute to achieving the Sustainable Development Goals (SDG) - A total of 50 peer-review articles that addressed the simultaneous or individual link between CE and I4.0 to sustainability are assessed - The articles were first screened with regard to the I4.0 technologies and CE practices applied, and further analyzed in order to understand the stronger links to the SDG - The specific targets addressed by the com- bined implementation of CE practices and I4.0 technologies are disclosed and discussed	- Findings show that the CE-I4.0 nexus directly benefits SDG 7, SDG 8, SDG 9, SDG 11, SDG 12, and SDG 13 - the CE-I4.0 nexus is pivotal in the endeavors to reach the SDG, as it connects innovative technologies with novel circular production and business models, which ultimately brings the opportunity to tackle the SDG targets intensified in this study	**Economic:** - new circular business models - higher and optimized productivity - promoting inclusive, reliable and sustainable production **Environmental:** - optimization in energy & resource use - promotion of renewable energy - reduction of fossil fuel use - safe and smart waste management to minimize and reinsert waste **Social:** - job creation and reallocation - promoting local economy and communities

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
de Sousa Jabbour A.B.L., Jabbour C.J.C., Foropon C., Filho M.G.	When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors	2018	- Literature review - elaboration of Critical success factors (CFS) and how I40T can support them - setting up framework of I40 - green manufacturing - CSF	- Industry 4.0 technologies can unlock the full potential of environmentally-sustainable manufacturing practices	**Environmental:** - enhanced environmentally-sustainable manufacturing practices
Dev, Navin K.; Shankar, Ravi; Qaiser, Fahham Hasan	Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance	2020	- The present research proposes a roadmap to the excellence of operations for sustainable reverse supply chain/ logistics by the joint implementation of principles of Industry 4.0 (I4.0) and ReSOLVE model of circular economy (CE) approaches - The connection between I4.0 and CE is unveiled by addressing the case-based model affecting the economic and environmental performances - The effectiveness of the virtual world in I4.0 environment is explored using simulation of reverse logistics model	- Based on the trade-off analysis between environmental and economic performances, appropriate combinations of information-sharing and family- based dispatching rules are suggested - the implementation of technology characteristics of operational excellence in terms of I4.0, reverse logistics, and lean approach provides valuable guidance to practice for the sustainable performances of a circular SC	**Economic:** - improcved economic performance - decresed procurement costs - increased process efficiency **Environmental:** - improved environmental performance - increased rate of reuse and recycling - reduced emissions
Esmaeilian B., Sarkis J., Lewis K., Behdad S.	Blockchain for the future of sustainable supply chain management in Industry 4.0	2020	- provide an overview of Blockchain technology and Industry 4.0 for advancing supply chains towards sustainability - we evaluate the capabilities of Industry 4.0 for sustainability extracted from the existing literature - unfolding the capabilities that Blockchain offers for increasing sustainability - Blockchain technology capabilities for contributing to social and environmental sustain- ability, research gaps, adversary effects of Blockchain, and future research directions are discussed.	- Blockchain as an enabler for the successful implementation of sustainability and circular economy concepts by: - (1) promoting green behavior through designing specialized tokens - (2) enhancing the visibility of product lifecycle - (3) increasing systems efficiency and decreasing development and operational costs, - (4) enhancing corporate performance reporting and sustainability monitoring capabilities	**Economic:** - increasing systems efficiency - decreasing development and operational costs - increasing systems efficiency and decreasing development and operational costs **Environmental:** - promoting green behavior through designing specialized tokens - enhancing visibility of produc lifecycle **Social:** - increased transparency
Felsberger A., Reiner G.	Sustainable industry 4.0 in production and operations management: A systematic literature review	2020	- systematic literature review approach in order to identify the literature that is related to sustainability in I4.0 and its impact in the area of production and operations management (P&OM) - executed via bibliometric and text mapping tools - focus group discussion with experts to derive practical insights - based on this analysis, a conceptual model for a new TBL approach is introduced that considers the technological development along with the social, economic and environmental dimensions of sustainability	- there is room for researchers and practitioners to realize the need of simultaneously covering EcEvS aspects of sustainability in order to create sustainable manufacturing environments - several economic, environmental, and social impacts already exist and are expected to increase within the next year - Technological progress influences each of the three dimensions of sustainability and has direct and indirect influences on sustainability across the whole value chain	**Economic**: - decrease in production time through automated decision-making - faster and more reliable production systems - rapid learning cycles - increase in automation and communication **Environmental**: - increased energy efficiency - less fuel consumption - reduction of waste, CO2 emissions, and hazardous accidents **Social**: - new processes will change work behavior - new job systems and company networks, - new challenges for society, - reduction of specific job functions

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Felsberger, A; Qaiser, FH; Choudhary, A; Reiner, G	The impact of Industry 4.0 on the reconciliation of dynamic capabilities: evidence from the European manufacturing industries	2020	- multiple case study analysis, how I40 impacts sustainability KPIs in all three dimensions	- I40 has big potential in improving all dimensions of sustainability - the results of this study contribute to theory development regarding how to evaluate value chain process improvement after innovative technical adaptations - The results pave the way for integration of the digital transformation and digital process improvements to increase the competitiveness of manufacturing companies in Europe	**Economic:** - positive influence on flexibility, speed, cost and quality of operations and production processes in supply chains **Environmental:** - positive influence on energy efficiency (energy consumption) and material resource efficiency (waste reduction) of manufacturing processes **Social:** - enhanced innovation as well as problem-solving skills and knowledge among employees - shift of skill set and up-skilling of employees
Ferrari, Anna Maria; Volpi, Lucrezia; Settembre-Blundo, Davide; García-Muiña, Fernando E.	Dynamic Life Cycle Assessment (LCA) integrating Life Cycle Inventory (LCI) and Enterprise Resource Planning (ERP) in an Industry 4.0 environment	2020	- This paper aims to explore the potential of IoT technologies and the Industry 4.0 paradigm to automate, by digitizing, the inventory analysis phase underlying Life Cycle Assessment (LCA) - some research questions were proposed and then empirically verified both from a conceptual and operational point of view	- Industry 4.0 paradigm and IoT technologies are indeed enabling technologies for environmental sustainability - it was verified that IoT technologies in the Industry 4.0 paradigm, which capture, process and store a large amount of data from sensors distributed within the production plant, can be used effectively to automatically perform inventory analysis (LCI) for environmental assessment (LCA) purposes - business intelligence combined with an ERP system and LCA analysis tool makes it easy to process data from the factory and provide real-time environmental impact KPIs	**Environmental:** - possible to capture the data useful for environmental assessment - enhanced LCA and LCI anaylsis, lowering the environmental impact
Fu B., Shu Z., Liu X.	Blockchain enhanced emission trading framework in fashion apparel manufacturing industry	2018	- an innovative environmentally sustainable solution is proposed for the fashion apparel manufacturing industry (FAMI) - the blockchain supported ETS framework, the carbon emissions of clothing manufacturing life cycle, and the emission link powered procedures are introduced in detail - A theoretical case study is provided to demonstrate the carbon emission evaluation procedure - a multi-criteria evaluation is performed to demonstrate the benefits and drawbacks of the proposed system	- Supported by blockchain and the smart measurement devices, the carbon emission could be easily measured and recorded with less human labor as a reliable approach to reduce carbon emissions for FAMI - BCELF offers significant improvements compared with the conventional ETS in FAMI, especially in terms of the environmental performance and the political acceptability	**Environmental:** - blockchain supported emission tracking systems - improved overall environmental performence
Furstenau, LB; Sott, MK; Kipper, LM; Machado, EL; Lopez-Robles, JR; Dohan, MS; Cobo, MJ; Zahid, A; Abbasi, QH; Imran, MA	Link Between Sustainability and Industry 4.0: Trends, Challenges and New Perspectives	2020	- bibliometric performance and network analysis (BPNA), describing the existing relationship between industry 4.0 and sustainability, the strategic themes from 2010 to March 2019, as well as the research gaps for proposing future work	- I4.0 impacts manufacturing in several ways, and can be used as a potential strategy for the development of sustainable production, capable of social, economic and ecological changes - scientific efforts are focused to enhance economic and environmental aspects and highlights a lack of effort relating the social sphere - Although the number of studies in the area is increasing, it is still difficult to achieve a qualitative and quantitative combination of TBL dimensions, as these impact both the internal and external environment of the organization - Environmental benefits are strongly related to the economic development of the organization as they enhance the company's image and attract investors, while social efforts bring financial advantages when made public - our finding shows the energy issue is considered as one of the main factors to promote sustainable development	**Economic:** - react more quickly to change - reduction of resource costs (energy, raw materials, water) - increased productivity through supply-chain integration **Environmental:** - reduce overproduction and waste - enhanced incorporation of smart grids for efficient energy management - improved resource efficiency (energy, raw materials, water) **Social:** - increased process safety & well-being of employees
Gajšek B., Stradovnik S., Hace A.	Sustainable move towards flexible, robotic, human-involving workplace	2020	- With the help of literature review and testing in the production environment, we approach the design of a procedure for planning a sustainable technological upgrade of craft production	- The introduction of new technologies certainly increases sustainability, as technologically equipped workplaces produce less waste, save time, and maintain health	**Economic:** - increased quality **Social:** - reliefed human operator in terms of inappropriate posture, repetitive movements, and increased workplace safety

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Garcia-Muiña F.E., González-Sánchez R., Ferrari A.M., Settembre-Blundo D.	The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company	2018	- This paper explores the phases of the transition from a linear to a circular economy and proposes a procedure for introducing the principles of sustainability (environmental, economic and social) in a manufacturing environment, through the design of a new Circular Business Model (CBM) - tested and validated in an Italian company producing ceramic tiles, using the digitalization of the production processes of the Industry 4.0 environment, to implement the impact assessment tools	- Strategies aimed at integrating sustainability into business, as well as improving environmental conditions and social cohesion, become a competitive advantage for the companies that implement it - The business transformation introduced with Industry 4.0 favors convergence between business and technology in new production models, promoting a sustainable evolution of human existence in its social, environmental and economic dimensions - The Industry 4.0 paradigm and the technologies of the Internet of Things are able to stimulate the transition from a linear to a circular business model - circular economy is a possible economic model that goes beyond the mere business perimeters	**Economic:** - increased operational performance **Environmental:** - enhanced transition from a linear to a circular business model **Social:** - empowered local economy
Garcia-Muiña F.E., González-Sánchez R., Ferrari A.M., Volpi L., Pini M., Siligardi C., Settembre-Blundo D.	Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design	2019	- test eco-design as a tool to define the equilibrium point between sustainability and circular economy in the manufacturing environment of ceramic tile production, and to demonstrate how new business opportunities can be created through evolution from a linear to a circular business model, thanks to IoT and Industry 4.0 technologies used as enabling factors. - demonstration of the effectiveness of the Industry 4.0 paradigm as an enabling factor for sustainability	- The circular economy can become a paradigm of sustainability through the use of eco-design to find the equilibrium of the system between regeneration capacity and minimization of environmental and socio-economic effects - A circular business model can reduce operating costs by strengthening relations with stakeholders (suppliers, employees, customers, institutions, territory) and stimulating competitiveness	**Economic:** - capability to intervene on processes to mitigate them - reduced operating costs **Environmental:** - capability to intervene on processes to mitigate them - enhanced eco-design - minimizing negative environmental effects **Social:** - minimizing negatie socio-economic effects
García-Muiña F.E., Medina-Salgado M.S., Ferrari A.M., Cucchi M.	Sustainability transition in industry 4.0 and smart manufacturing with the triple-layered business model canvas	2020	- The paper explores the still limited literature on the application of sustainable business models in operational scenarios. - analyze the introduction of sustainability in the corporate value proposition, through the evolution from a traditional to a sustainable business model - The business model innovation will be investigated in the case of a ceramic tile producer in the district of Sassuolo, Italy. - results illustrate the new company's sustainable value proposition, considering all three pillars of sustainability: environment, economy, and society	- In manufacturing, industry 4.0 leads to greater efficiency and control of production processes and provides new opportunities in terms of sustainability introduction and impact assessment	**Economic:** - greater efficiency and control of production processes **Environmental:** - enhanced sustainability introduction and impact assessment of processes **Social:** - enhanced sustainability introduction and impact assessment of processes
Garrido-Hidalgo C., Hortelano D., Roda-Sanchez L., Olivares T., Ruiz M.C., Lopez V.	IoT Heterogeneous Mesh Network Deployment for Human-in-the-Loop Challenges Towards a Social and Sustainable Industry 4.0	2018	- green I3A smart factory (GreenISF) scenario is presented, where the deployment of a collaborative mesh network based on Bluetooth low energy (BLE) and long range wide-area network (LoRaWAN) technologies promotes human–machine collaboration towards socially sustainable factories - smart wristband prototype OperaBLE is introduced in this paper as key enabler for human-in-the-loop systems	- encourage sustainable techniques and algorithms to avoid social disruption caused by the incoming industrial paradigm	**Social:** - safer workplaces and operator prevention from harmful environments
Ghobakhloo, Morteza	Industry 4.0, digitization, and opportunities for sustainability	2020	- the study first reviews the fundamental design principles and technology trends of Industry 4.0 and introduces the architectural design of Industry 4.0 - the study further draws on the interpretive structural modelling technique to model the contextual relationships among the Industry 4.0 sustainability functions	- economic sustainability functions tend to be the more immediate outcome of Industry 4.0, which pays the way for development of more remote socioenvironmental sustainability functions of Industry 4.0	**Economic:** - increased production efficiency - enhanced business model innovation **Environmental:** - increased energy sustainability - harmful emission reduction **Social:** - social welfare improvement - shrinking low skill job opportunities , increasingly demanding technical skills - improved effectiveness of on-the-job training

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Godina R., Ribeiro I., Matos F., Ferreira B.T., Carvalho H., Peças P.	Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context	2020	- through the lenses of Industry 4.0 and its technological concepts, this paper aims to contribute to the knowledge about the impacts of additive manufacturing technology on sustainable business models. This aim is accomplished through a proposed framework, as well as the models and scales that can be used to determine these impacts. - effects are assessed by taking into account the social, environmental and economic impacts of additive manufacturing on business models and for all these three dimensions a balanced scorecard structure is proposed.	- additive manufacturing has the potential to favorably impact the manufacturing sector by reducing costs in production, logistics, inventories, and in the development and industrialization of a new product	**Economic:** - increased efficiency of an improved lean supply chain - possibility of producing locally at a reduced cost - transport routes can be greatly reduced - parts with defects can be completely recycled - The organization is able to meet the market with better efficiency, higher quality, lower cost and lower delivery time resulting in increased Market share **Environmental:** - transport routes can be greatly reduced - By switching to additive manufacturing, the waste is practically eliminated - parts with defects can be completely recycled - 0 hazardous waste produced, 0 kg of landfill waste, 0 kg of water usage per component - energy efficiency improvements **Social:** - indirect benefits such as knowledge creation and lower environmental impacts
Gregori, Fabio; Papetti, Alessandra; Pandolfi, Monica; Peruzzini, Margeherita; Germani, Michele	Improving a production site from a social point of view: an IoT infrastructure to monitor workers condition	2018	- this paper focuses on integration of workers in the digitalized factory - it proposes a method to design an IoT infrastructure and acquire human-related data from a production site in order to improve workers wellbeing and overall productivity - A case study was developed in collaboration with an Italian sole - producer to validate the method and the related data acquisition system	- IoT infrastructures enable methods permitting to identify bottlenecks and criticalities from a social point of view, focusing on the human performance, and define corrective actions at different levels (operations, plant layout or shift management)	**Social:** - enhanced worker monitoring to identify criticalitites from a social point of view - enhanced workplace improvement and operational safety - prevention of occupational diseases and disturbs - avoiding absenteeism, turnover
Gregori, Fabio; Papetti, Alessandra; Pandolfi, Monica; Peruzzini, Margherita; Germani, Michele	Digital Manufacturing Systems: A Framework to Improve Social Sustainability of a Production Site	2017	- this paper proposes a method to acquire social related data in a production plant - After a discussion on production plants facilities and features, the parameters that need to be considered to guarantee socially sustainable manufacturing processes are identified	- a smart architecture within the concept of IoT factory permits to monitor the parameters that could influence social sustainability in a production site - Guaranteeing social sustainability could boost the factory productivity - main novelty of the proposed method is a tool (Social Decision Matrix) that lets the designers consider the workers' conditions and performances during the design and development process of a new production system	**Social:** - improved production system from a social point of view - enhanced noise and dust reduction at workplace - increased vision on workplace - optimized worker tasks from the design phase
Gružauskas V., Baskutis S., Navickas V.	Minimizing the trade-off between sustainability and cost effective performance by using autonomous vehicles	2018	- discussing the limited possibilities to achieve cost effective performance and sustainability	- conducted literature analysis indicates that there is a lack of industry 4.0 practices for supply chain management - more sustainable supply chain is using consolidation warehouses, which indicated 19% lower transportation costs and 55% lower CO2 emission level than just-in-time distribution strategy	**Economic:** - decreased costs of the whole logistic network - using the autonomous vehicle distribution strategy the transportation costs have been reduced by 5% if compared to the traditional distribution system - more flexibility, redundancy and adaptive abilities to achieve long-term competitiveness advantage **Environmental:** -by implementing the autonomous vehicles strategy along with the consolidation warehouses CO2 emission level can be decreased by 22% - using the autonomous vehicle distribution strategy CO2 emission level have been reduced by 22% if compared to the traditional distribution system - less food wastage

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Gualtieri L., Palomba I., Merati F.A., Rauch E., Vidoni R.	Design of human-centered collaborative assembly workstations for the improvement of operators' physical ergonomics and production efficiency: A case study	2020	- a manual workstation for wire harness assembly was transformed into a collaborative one as follows - Analysis of the current situation in terms of physical ergonomics; - Evaluation of the potentials for collaborative robotics; - Workstation re-design for physical ergonomics and production efficiency enhancement. - the transformation of a manual workstation for wire harness assembly into a collaborative and human-centered one is presented	- factory of the future should focus on the implementation of adaptable, reconfigurable, and sustainable production systems, which consider the human as their core and valuable part - Strengthening actual assembly workstations by integrating smart automation solutions for the enhancement of operators' occupational health and safety will be one of the main goals of the near future	**Economic:** - increased level of productivity (reduction of the cycle time of 12.3% has been achieved, potential annual reduction of 1460 working hours) **Social:** - reduction of work-related biomechanical overload, especially in manual assembly activities (by 12.0% for the right part and by 28% for the left part in terms of manual handling, and by 50% for the left part and by 57% for the right part in terms of working postures) - improvement of operators' occupational work conditions
Gupta A., Basu B.	Sustainable Primary Aluminium Production: Technology Status and Future Opportunities	2019	this article will discuss Digital Twin technology for aluminium production and will show how this can assist aluminium industries in addressing energy and emission challenges.	- With fast pace development in Industry 4.0 technology platforms (like internet of things, cloud technology, machine learning, artificial intelligence, etc.), digital twin will be a new disruptive technology intervention in aluminium smelting that will enable industries to achieve the highest level of operational and performance benchmark in energy and emission	**Economic:** - reduction in energy consumption **Environmental:** - reduction in energy consumption
Harikannan, N; Vinodh, S; Gurumurthy, A	Sustainable industry 4.0-an exploratory study for uncovering the drivers for integration	2020	- Interpretive structural modeling (ISM) is used to derive the structural model for analyzing the causal association between drivers. - Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) analysis is being performed to group the drivers. - 20 drivers identified from literature review for simultaneous deployment of I4.0 and sustainable manufacturing are presented	- ISM shows that the drivers for deploying sustainable I4.0 are highly inter-related - the dominant drivers derived are societal pressure and public awareness, government policies on support I4.0, top management involvement and support and government promotions and regulations	**Economic:** - higher operative efficiency & productivity - earlier time to market - reduced cost **Environmental:** - reduced disposal, wastage of materials, scrap, etc. - reduced material consumption - reduced travel and utilization of other resources (such as physical training, physical equipment, etc.) **Social:** - reduced monotony & fatigue - enhanced training opportunities
Hoffa-Dabrowska P., Grzybowska K.	Simulation modeling of the sustainable supply chain	2020	- building simulation models showing the supply chain and the sustainable supply chain - The benefits of sustainable supply chain in economic and environmental aspects will be presented using a computer simulation tool	- modeling supply chains in their virtuality and analysis, many resources can be saved in reality	**Economic:** - cost reduction **Environmental:** - emission reduction **Social:** - amount of trucks on the road will decrease, which will also have a positive impact on social aspects, such as less traffic and potentially fewer accidents
Horváthová M., Lacko R., Hajduová Z.	Using industry 4.0 concept – digital twin – to improve the efficiency of leather cutting in automotive industry	2019	- In this case study, an automotive company processing a natural leather material that enters the process of a large-scale production was explored - ways of improving the efficiency of the material processing were proposed and tested in a digital environment	- By the use of Digital twin and other Industry 4.0 principles and solutions in the process of material selection and processing in the company selected, the increased efficiency and cost savings were achieved	**Economic:** - advanced simulation allows finding more efficient ways of conducting processes without blocking the real production capacities - increased productivity

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Iqbal A., Zhao G., Suhaimi H., He N., Hussain G., Zhao W.	Readiness of subtractive and additive manufacturing and their sustainable amalgamation from the perspective of Industry 4.0: a comprehensive review	2020	- article provides a comprehensive review of the published literature to establish the states of readiness of the two most important manufacturing technologies: subtractive and additive and their sustainable merger from the perspective of Industry 4.0. - subtractive-additive amalgamation is scrutinized	- The review establishes that the subtractive manufacturing (SM) domain is nearly compatible regarding speed and agility but needs improvements in respect of sustainability and customer centricity - Additive manufacturing (AM), on the other hand, appears strong on agility and customer-centricity fronts but needs amelioration regarding production speed and sustainability - both SM & AM seem to be compatible regarding automation, whereas significant improvements are required in connectivity and data sensing and collection - The amalgamation of SM & AM, especially in a done-in-one configuration, has, succeeded to retain the favorable traits of the two manufacturing technologies, thus, bringing the merger much closer to the Industry 4.0 requirements - Proper process planning and optimal work distribution between the subtractive and additive modes are critical for operating an amalgamated system at high levels of the key characteristics	**Economic:** - reduced production cost and lead time - improved product quality **Environmental:** - High capability of remanufacturing end-of-life components lowers environmental impact **Social:**
Ivascu L.	Measuring the implications of sustainable manufacturing in the context of industry 4.0	2020	- This research proposes a hierarchical framework for sustainability assessment of manufacturing industry in Romania - market research by means of a questionnaire applied to 100 manufacturing industry experts - the Delphi method involving one facilitator and 40 experts - All the phases of the research are progressively completed, and finally, the proposed framework is pre-tested and validated.	- waste management and the interests of the stakeholders are major implications that must be measured and properly motivated	**Economic:** - Cost reduction (75%), Competitiveness (63%), Need for higher control for top management (51%), demand from partners (83%), challenges of the era (53%), financial benefits (73%), Times of delivery (65%), increased customer satisfaction (53%), efficiency improvement (65%), flexibility (73%), reliable operation (81%), and production interruptions (78%) **Environmental:** - efficiency improvement (65%) **Social:** - efficiency improvement (65%), reliable operation (81%)
Jasiulewicz-Kaczmarek M., Legutko S., Kluk P.	Maintenance 4.0 technologies - new opportunities for sustainability driven maintenance	2020	- describe the latest trends within the area of maintenance management from the perspective of the challenges of the fourth industrial revolution and the economic, environmental and social challenges of sustainable development	- development in the area of intelligent technologies and models for analysing large data sets has created new opportunities not only in the scope of increasing the reliability, availability and efficiency of using technical objects, but also in the scope of challenges of environmental and social implementation of sustainable development	**Economic:** - Improved economic efficiency - reduced maintanance time - Improved machine performance - Decreased spare parts inventories (spare part delivery on predicted demand, not on stock) **Environmental:** - Decreased spare parts and lubricant utilization - Improved environmental safety - Minimized end of life waste - Optimized energy consumption **Social:** - XR for maintanance Implements new educational model - improved workers safety - improved working conditions - improved workers satisfaction

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Jena M.C., Mishra S.K., Moharana H.S.	Application of Industry 4.0 to enhance sustainable manufacturing	2020	- a smart factory framework is presented by vertical integration of various components that incorporates industrial network, cloud, and supervisory control terminals with different functions for optimizing resource utilization and eliminating all type wastages to enhance sustainable manufacturing - To evaluate the outcome of this model implementation, a case study has been conducted on a cement plant	- Although through this automation some part of human being at work will be replaced by machines with high degree of automation and intelligent manufacturing, still it is expected that the whole world is going to adopt the Industry 4.0 to cope up the pace of production and service of one with other sooner or later	**Economic:** - total production has been increased by 13.24% - OEE improved by 12.94% - total downtime reduced by 30.58% - MTBF increased by 24.68% - MTTR reduced by 25.58% - customer complaint reduced by 30% **Environmental:** - increased processed waste by 12.79% - specific energy consumption came down by 9.33% - specific carbon foot print came down by 9.33% - specific water consumption came down by 3.12%
Johansson N., Roth E., Reim W.	Smart and sustainable emaintenance: Capabilities for digitalization of maintenance	2019	- develop a framework that presents the required capabilities and their connection when an organization wants to implement eMaintenance, as well as to identify the outcomes of the transition to eMaintenance - based on 26 interviews with a digital railway maintenance development company and its main customer, the traffic agency - The framework also analyzes the outcomes of implementing digital maintenance, which demonstrate a variety of economic, environmental, and social benefits	- five main capabilities for implementing eMaintenance are: digital technology development, organizational development, change of work routines, compliance with regulations, and assuring information security - management of information security and regulations and monitoring are a primary challenge when implementing eMaintenance - increased sustainability was identified as a main driver for eMaintenance	**Economic:** - improved information on condition for advanced decision-making - increased capacity - more efficient maintenance - optimized costs - increased lifetime of mashinery **Environmental:** - improved resource utilization - increased lifetime of mashinery - less waste
Kaczmarek, Małgorzata Jasiulewicz-; Gola, Arkadiusz	Maintenance 4.0 Technologies for Sustainable Manufacturing - an Overview	2019	- maintenance processes and their evaluation during the last frew decades are described - maintenance contribution to business competitiveness and sustainable manufacturing operations are presented - new IT technologies in machines and devices that can support maintenance function are described	- Maintenance 4.0 can break the trade-offs of the older strategies by enabling companies to maximize the useful life of their production equipment while avoiding unplanned downtime, minimizing planned downtime, increasing process and people safety, minimizing energy and resources consumption and saving costs - From a sustainable production perspective, the Maintenance 4.0 contribution can be applied to Life Cycle Thinking, services and aftersales, resources and processes, inventories, asset utilization, and labor - the role of Maintenance 4.0 for sustainable manufacturing is still in its infancy and it has big potentiality that need to be investigated	**Economic:** - maximize the useful life of their production equipment - avoiding unplanned downtime, minimizing planned downtime - reduced costs **Environmental:** - minimizing energy and resources consumption - lowered environmental impact **Social:** - increased process and people safety - enhanced working conditions
Kamble S., Gunasekaran A., Dhone N.C.	Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies	2020	- this research study investigates the indirect effects of Industry 4.0 technologies (I4 T) on sustainable organizational performance (SOP) with lean manufacturing practices (LMP) as the mediating variable - furthermore, it aims to confirm or not the direct effects of I4 T on LMP and SOP - The study is based on data collected from 205 managers, working in 115 manufacturing firms	- The findings reveal that Industry 4.0 technologies have a positive and direct influence on LMP and SOP - Industry 4.0 technologies' sustainability effects are amplified by Lean Manufacturing processes - The study also identified LMP as a significant mediating variable - companies should clearly outline their sustainable objectives and prioritise the different Industry 4.0 technologies based on the contributions they can make in creating smart products and processes	**Economic:** - reduced costs in terms of: production, product development, energy, inventory, raw material purchasing, waste treatment & rejection and rework - improved profits **Environmental:** - reduction of waste (solid, liquid, energy) and gas emissions - decrease of consumption of hazardous/harmful/toxic materials - improvement of firm's environmental situation **Social:** - Improved working conditions, workplace safety & employee health - Improved labour relations & morale

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Kamble S.S., Gunasekaran A., Gawankar S.A.	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	2018	- Selected 85 papers were classified in five research categories namely conceptual papers on Industry 4.0, human-machine interactions, machine-equipment interactions, technologies of Industry 4.0 and sustainability - The review primarily attempted to seek answers to the following two questions: (1) What are different research approaches used to study Industry 4.0? and (2) What is the current status of research in the domains of Industry 4.0? - We propose a sustainable Industry 4.0 framework based on the findings of the review with three critical components viz., Industry 4.0 technologies, process integration and sustainable outcomes	- The study identifies that the proposed relationship between the modern technologies and the process integration results in benefits such as virtualization, real-time capability, interoperability, service orientation, and decentralization - This implies that practitioners can have a better industrial control on the processes, increasing the flexibility and agility of the organizations - The practitioners can make decisions in real time, offer highly customized products in shorter lead times by efficiently using the available resources and low energy consumption	**Economic:** - reduced costs of manufacturing & product development - improved economic performance of manufacturing processes and process stability - cost optimized global production networks - improved predictive maintenance - improved purchasing decisions - offering highly customized on-demand manufacturing **Environmental:** - efficient resource allocation, incl. water, energy, raw material and other products **Social:** - improved working conditions - safe manufacturing environment
Kayikci, Yasanur	Sustainability impact of digitization in logistics	2018	- this study highlights the benefits of the digitization of logistics process and examines the sustainability impact of digitization in logistics - this study is persued as a single case study within the FMCG companies and their transport service providers in Turkey and it is based on a qualitative method and on connected semi-structured interviews	'- the sustainability impact of digitization with respect of economic implication was more important than the other dimensions - In terms of logistics cost, delivery time, delay, inventory, reliability and flexibility issues, a great potential of digitization in logistics can be seen - the social implications of digitization (improved health outcomes, lover accident rates) have generally poor impact	**Economic:** - reduced logistics costs, Delivery time and Transport delay - Inventory reduction - increased forecast accuracy and flexibility **Environmental:** - reducing waste, pollution and emission of greenhouse gases - increased energy and resource consumption **Social:** - improved health outcomes, lover accident rates - low acceptence
Khanzode A.G., Sarma P.R.S., Mangla S.K., Yuan H.	Modeling the Industry 4.0 adoption for sustainable production in Micro, Small & Medium Enterprises	2021	- This study assesses the barriers involved in implementing Industry 4.0 for sustainable production, and it attempts to find causality among the barriers using the 'Decision Making Trial and Evaluation Laboratory' method - The study considers eight barriers to implement Industry 4.0 for sustainable production. These barriers are interrelated and have causal relationships among them. This causality is represented graphically. It also illustrates the strength of the influence of one barrier over the other through numerical values	- 'Technological upgradation', 'lack of policy frameworks' are the top two barriers involved in implementing Industry 4.0 for sustainable production in the MSME sector	**Economic:** - increasing costs of cyber security **Social:** - Social security of employees (Fear of Job Loss) barrier for implementation of industry 4.0 driven sustainable production
Kim H., Jung W.-K., Choi I.-G., Ahn S.-H.	A low-cost vision-based monitoring of computer numerical control (CNC) machine tools for small and medium-sized enterprises (SMES)	2019	- A monitoring system of machine tools on the shop floor using a low-cost webcam and open-source software, such as Python for the application development, Google Tesseract for the OCR process, OpenCV for image processing was proposed	- using open-source platforms which are lightweight, cost-effective, and flexible to configure can boost the speed of software development in few weeks and reduce the barrier to entry to the digital transformation for SMEs	**Economic:** - reduced time in operation - reduced energy consumption **Environmental:** - reduced energy consumption, and thus, reduced environmental impact for the sustainable production
Kristoffersen E., Blomsma F., Mikalef P., Li J.	The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies	2020	- Develop a framework that supports the systematic identification of BA requirements needed to advance different smart circular strategies. - Consolidate and further advance the framework through the development of a knowledge base that can be used for BA gap analysis and the creation of roadmaps for the application of smart circular strategies within organizations	- The smart use of resources in the Circular Economy can be supported by the creation, extraction, processing, and sharing of data from Digital Technologies - Effectively using this digital transformation will be pivotal for organizations in transitioning to, and leveraging, the Circular Economy at scale - Industry 4.0 technologies are enablers / amplifiers for a Circular Economy adoption, and thus, influences sustainability	**Economic:** - increased systemic resource efficiency and productivity - improved quality, productivity, and flexibility **Environmental:** - enhanced sustainable resource consumption

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Kumar P., Singh R.K., Kumar V.	Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers	2021	- This study identifies the major criteria for sustainable operations and barriers that need to be overcome to achieve the objectives of sustainability through literature review and experts' opinions - An integrated approach comprising Analytic Hierarchy Process (AHP) and Elimination and Choice Expressing Reality (ELECTRE) is used to analyze these barriers and ensure the sustainable supply chain operations	- To ensure sustainability of operations, digitization of processes requires linkage of Industry 4.0 technologies with CE dimensions - Resource circularity, increasing profits from green products, and designing processes for resource and energy efficiency are major sustainability criteria - Barriers to the implementation of Industry 4.0 include, but are not limited to, a lack of a skilled workforce that understands Industry 4.0, ineffective legislation and controls, ineffective performance framework, and short-term corporate goals - ineffective strategies for the integration of industry 4.0 with sustainability measures, combined with a lack of funds for industry 4.0 initiatives, are just two of the major barriers	**Economic:** - increased systemic resource efficiency and productivity - improved quality, productivity, and flexibility - risk of misinvestment - Insufficient market demand **Environmental:** - enhanced sustainable resource consumption **Social:** - lack of skilled workforce - risk of misinvestment - Insufficient market demand
Kumar R., Singh R.K., Dwivedi Y.K.	Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges	2020	- we have identified fifteen challenges, impacting the application of Industry 4.0 technologies in SMEs - A questionnaire was designed for collecting the response from industry and academic experts - On the collected data, the DEMATEL approach has been applied to check the degree of influence and interrelationship among challenges, categorizing these factors as cause and effect - Sensitivity analysis is also performed to validate the results obtained from the DEMATEL approach	- lack of motivation from partners and customers on the application of I4.0 technologies is the leading challenge - Fear of failure of I4.0 technologies is the main effect group challenge	**Economic**: - improved energy, equipment, and human resource utilization - Lack of funds for investment in I4.0 technologies - Lack of dedicated resources for research & development on I4.0 technologies **Environmental**: - saving energy - reduction of scrap - reducing carbon footprints **Social**: - enhanced ethical and sustainable working conditions - Lack of trained workforce for sustainable operations & I4.0 technologies - Lack of trained workforce for sustainable operations & I4.0
Kumar R., Singh S.P., Lamba K.	Sustainable robust layout using Big Data approach: A key towards industry 4.0	2018	- this work proposes an embedded simulated annealing based meta-heuristic and principal component analysis (PCA) approach using large scale data to solve sustainable robust stochastic cellular facility layout problem (sustainable-RSCFLP) - data for the problem is collected considering basic 3Vs of Big Data i.e. Volume, Variety, and Velocity - Fourteen different criteria are identified and evaluated by 100 experts to group them	- The integration of Big Data approach can greatly assist layout managers to incorporate various qualitative factors in the design ensuring all the relevant factors are being utilized, hence, making the layout more suited to the changing market dynamics - Additionally, the same is also supplemented by robustness of the layouts ensured by considering the expected values and the variances	**Economic**: - improved maintanance - improved material handling - reduced energy consumption - increased space utilization **Environmental**: - reduced energy consumption - improved material handling - improved environmental protection **Social**: - improved working conditions
Leng J., Ruan G., Song Y., Liu Q., Fu Y., Ding K., Chen X.	A loosely-coupled deep reinforcement learning approach for order acceptance decision of mass-individualized printed circuit board manufacturing in industry 4.0	2021	- An order acceptance decision model is established based on a loosely-coupled integration of deep learning and reinforcement learning techniques - deep learning algorithm is presented for accurately predicting the production cost, makespan, and carbon consumption of incoming PCB orders in the large-scale manufacturing system	- Promoting new industrial artificial intelligence infrastructures is a crucial driver of economic growth and sustainable development in the manufacturing sector - Under a long-term accumulation of artificial intelligence, the higher acceptance rate of PCB with lower manufacturer's carbon consumption per unit profit will drive the optimizing of PCB design toward a more sustainable development way	**Economic**: - increased profit - increased order acceptance rate - increased production capacity - improved material consumption **Environmental**: - reduced energy consumption - improved material consumption - lower environmental pollution

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Leng, JW; Ruan, GL; Jiang, PY; Xu, KL; Liu, Q; Zhou, XL; Liu, C	Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey	2020	- This paper surveys how blockchain can over- come potential barriers to achieving sustainability from two perspectives, namely, the manufacturing system perspective and the product lifecycle management perspective - The paper first examines literature on these two perspectives, following which the state of research in blockchain-empowered sustainable manufacturing is presented, which sheds new light on urgent issues as part of the UN's Sustainable Development Goals - discussion of challenges regarding techniques, social barriers, standards, and regulations with respect to blockchain-empowered manufacturing applications - discussion of challenges and social barriers that blockchain technology must overcome to demonstrate its sustainability in industrial and business spheres	- blockchain-empowered transformation of a sustainable manufacturing paradigm is still in an early stage of the hype phase, proceeding toward full adoption - From the manufacturing system perspective, blockchain could be designed as an enabler to drive existing manufacturing information systems, such as ERP and MES, which already exist in manufacturers' workshops - From the product management perspective, blockchain could provide a tool for the product lifecycle management community (including designers, manufacturers, assemblers, and manufacturing service providers) to establish a unified database to share product information and make deals, enabling untrusted manufacturers to exchange capabilities and requirements freely	**Economic:** - high initial impementation costs - increased cyber security - auditable and transparent transactions to eliminate the security vulnerabilities of traditional IIoT - enhanced negotiation technologies (i.e. smart contracts) **Environmental:** - enhanced capture of carbon footprint **Social:** - lack of knowledge and awareness - increased data-security & privacy
Li Y., Dai J., Cui L.	The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model	2020	- Based on information processing theory, this study intends to explore how digital technologies influence economic and environmental performance in the new era of Industry 4.0 - The mediating effect of digital supply chain platforms and the moderating effect of environmental dynamism are proposed and evaluated using a survey of Chinese manufacturing firms.	- digital supply chain platforms mediate the effects of digital technologies on both economic and environmental performance - the effectiveness of digital technologies should be realized through the establishment of digital supply chain platforms - manufacturing firms should not only rely on internal information processing capabilities by use of digital technologies but also need to make the utmost digital supply chain platforms access more sufficient information externally, thereby realizing higher economic and environmental performance	**Economic**: - Growth in return on sale, return on sale, profit, sales & market share **Environmental**: - Reduction of air emission, waste water, & solid waste - Improvement of the firm's environmental situation
Liboni L.B., Liboni L.H.B., Cezarino L.O.	Electric utility 4.0: Trends and challenges towards process safety and environmental protection	2018	- qualitative research based on a systemic approach, using the Soft System Methodology (SSM) to address the challenges brought by the industry 4.0 paradigm in the electric system industry in Brazil, focusing on the topic of environmental protection and process safety - point out important capabilities needed by these companies to keep up with the new industrial revolution - indicating the three main dynamic capabilities that have emerged: new policies to enable innovation, bureaucracy reduction, and investments in education	- The main short- term challenges are to overcome existing practices and beliefs such as organizational culture and more investments in educating the final users of the importance of a smart utility to enable companies to adapt and innovate - Long-term challenges comprise training data science-driven employees, designing better IT systems, asset management systems, personal hazard systems, assessing regulatory constraints on asset management and environmental policies, and feeding back information transparently to regulators	**Economic**: - increase in the electricity quality - reduction of the electricity cost - better maintenance service **Environmental**: - more significant environmental awareness in the management of distributed electricity generation **Social**: - safer environments for employees and users
Lim C.H., Lim S., How B.S., Ng W.P.Q., Ngan S.L., Leong W.D., Lam H.L.	A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach	2021	- conduct a detailed review of the current state of the palm oil industry development toward Industry 4.0 - novel Hazard and Operability Analysis (HAZOP) approach is adopted i) to ensure a detailed evaluation of the existing problems, and ii) to identify potential implementation of Industry 4.0 technologies in the palm oil industry - investigation of the possible adaptation of Industry 4.0 technologies to improve the palm oil industry - Existing Industry 4.0 technologies and features were evaluated to identify feasible adaptation in the industry	- 23 recommendations to improve the palm oil industry with Industry 4.0 technologies to achieve a higher standard in sustainable production	**Economic**: - improved logistics - smart Crude Palm Oil production forecast - dynamic process optimisation - equipment defect detection **Environmental**: - improved logistics - smart farming & irrigation using less resources - improved harvest routes and harvest planning for less waste and less resource consumption **Social**: - smart contracts for fair pricing and fair salaries
Lin Y.-C., Yeh C.-C., Chen W.-H., Liu W.-C., Wang J.-J.	The use of big data for sustainable development in motor production line issues	2020	- This study explores big data gathered from motor production lines to gain a better understanding of production line issues - 3606 datapoints from the company's testing equipment were statistically analyzed - focused on secondary data and expert interview results to further define the relevant statistical dimensions - a theoretical model for the monitoring of the motor production line was proposed	- in the future of Industry 4.0, big data will become the key to the sustainable development of enterprises	**Economic**: - improved production line efficiency - increased competitiveness - reduced number of meetings, documents, and handwritten records associated with the production process **Environmental**: - reduced waste

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Lindström J., Kyösti P., Birk W., Lejon E.	An initial model for zero defect manufacturing	2020	- This paper investigates an initial model for Zero Defect Manufacturing (ZDM) using a cost function where the operation and condition of a production process are reflected, and the quality of the output/product and the production process (as well as safety aspects) can be considered - The outset of the study is based on empirical data collected from five manufacturing companies, and proposes an initial model for ZDM with an Industry 4.0 perspective	- the development of the Industry 4.0 concept enables the ZDM concept to be more easily implemented, due to the availability of the necessary amounts of data (Big Data) required for techniques such as ML to work; however, a much better integration and coordination of the capacity of each technique or method used is still required	**Economic**: - reduced costs - increased Overall Equipment Efficiency (OEE) - more predictable product quality **Environmental**: - reduced energy and resource consumption - reduced waste
Liu, Y; Zhu, QH; Seuring, S	New technologies in operations and supply chains: Implications for sustainability	2020	- introducing the theme and objectives of special issue on new technologies in operations and supply chains as well as their implications for sustainability - The papers comprising the special issue are then summarized, and major findings are briefly presented	- most existing research focuses on one or two technologies, and on certain stages of a supply chain - collaboration among manufacturing enterprises and information technology providers/platforms demands further in-depth studies - it seems that we have mainly focused on the pros of new technologies on sustainability in operations and supply chain but so far rarely addressed the cons of new technologies that they may bring along, especially from the social perspective	**Economic:** - enhanced tracking and transparency of supply chain for better decision-making and enhanced preventive actions **Environmental:** - enhanced opportunities for circular economies, resulting in increasing recycling, refurbishment, and re-use of components **Social:** - lower employment in developing countries
Lopes de Sousa Jabbour A.B., Jabbour C.J.C., Godinho Filho M., Roubaud D.	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations	2018	- This work makes a case for the integration of the increasingly popular and largely separate topics of Industry 4.0 and the circular economy (CE) by proposing a pioneering roadmap to enhance the application of CE principles in organisations by unveiling how different Industry 4.0 technologies could underpin CE strategies	- Industry 4.0 and the CE is a mutually beneficial relationship	**Economic**: - enhanced circulation of energy and materials - increased productivity (i.e. based on improved predictive maintanance) **Environmental**: - improved repair, reuse, remanufacture, and recycling capabilities - extension of product life - reduced waste in production systems across supply chains
Luthra S., Kumar A., Zavadskas E.K., Mangla S.K., Garza-Reyes J.A.	Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy	2020	- this study aims to examine the drivers of I4.0 to diffuse sustainability in Supply Chains (SCs) - this research identifies the most relevant drivers through the literature and discusses them with area experts - Afterwards, an empirical analysis is conducted to validate the key drivers - Finally, the Grey based DEMATEL method is employed to examine the influential strength of the identified drivers and to build an interrelationship diagram	- Key drivers to Industry 4.0 to diffuse sustainable supply chains are: Collaboration and transparency among supply chain members; Management support and effective governance; Development of infrastructure and information technology (IT) based facilities; Competitiveness; Improved information sharing system and resource development; Reduction in waste and improved cost efficiency; Workforce knowledge and expertise in managing resources; Government supportive policies; Adoption of innovative business models	**Economic**: - improved economic efficiency **Environmental**: - improved ecological efficiency - saving resources **Social**: - improved people welfare - improved skills and expertise of workers and staff
Ma, Shuaiyin; Zhang, Yingfeng; Liu, Yang; Yang, Haidong; Lv, Jingxiang; Ren, Shan	Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries	2020	- This paper presented a framework of data-driven sustainable intelligent/smart manufacturing based on demand response for energy-intensive industries - multi-level demand response models were developed based on machine, shop-floor and factory to save energy cost	- the sustainability in energy management system must be assessed to meet the requirements of energy with an enhanced economic, ecological and social performance from a national context - In the background of Industry 4.0, the integration of Cleaner Production and intelligent manufacturing forms a new discipline regarded as sustainable intelligent manufacturing, which provides numerous opportunities for managers to develop and implement CE strategies	**Economic:** - cost savings - improved competitiveness **Environmental:** - increased energy efficiency in manufacturing industries - reduction of pollutants **Social:** - exposure to less pollutants
Ma, Shuaiyin; Zhang, Yingfeng; Lv, Jingxiang; Ge, Yuntian; Yang, Haidong; Li, Lin	Big data driven predictive production planning for energy-intensive manufacturing industries	2020	- in this paper, the big data driven predictive production planning is proposed to improve energy and resource efficiency for energy- intensive manufacturing industries - An industrial case study is presented to process energy big data and predict energy consumption parameters and production status	- the proposed long short-term memory models outperform back propagation neural network, autore- gressive moving average and support vector regression	**Economic:** - increased production complexity - improved competitive advantage **Environmental:** - reduced waste and emissions - reduced energy and resource consumption

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Machado C.G., Winroth M.P., Ribeiro da Silva E.H.D.	Sustainable manufacturing in Industry 4.0: an emerging research agenda	2020	- This systematic review intends to identify how sustainable manufacturing research is contributing to the development of the Industry 4.0 agenda and for a broader understanding about the links between the Industry 4.0 and Sustainable Manufacturing by mapping and summarising existing research efforts, identifying research agendas, as well as gaps and opportunities for research development.	- the concepts of sustainable manufacturing and the use of the new technologies can enable Industry 4.0 to have positive impacts on all the sustainability dimensions in an integrated way, and also supporting the implementation of the Industry 4.0 agenda in the following aspects: developing sustainable business models; sustainable and circular production systems; sustainable supply chains; sustainable product design; and policy development to ensure the achievement of the sustainable goals in the Industry 4.0 agenda	**Economic**: - improved product-life-cycle management - improved predictive maintenance **Environmental**: - improved resource and energy management - cleaner production **Social**: - improve human-machine interaction and learning
Majeed A., Zhang Y., Ren S., Lv J., Peng T., Waqar S., Yin E.	A big data-driven framework for sustainable and smart additive manufacturing	2021	- the significant techniques of smart manufacturing, sustainable manufacturing, and additive manufacturing are combined to make a unified term of sustainable and smart additive manufacturing (SSAM) - developing a framework by combining big data analytics (BDA), additive manufacturing (AM), and sustainable smart manufacturing (SSM) technologies which is beneficial to the additive manufacturing enterprises - an application scenario of the additive manufacturing industry was presented to demonstrate the proposed framewor	- The marketing department is responsible for classifying the unspoken needs of the forecast customers' and promising customers - The R & D department inputs for AM will be increased in the future, which may be due to the development and usage of innovative technologies for the manufacturing of cleaner production - In the production department, BDA and SSAM framework should be applied to manage the production of AM systems, improve the energy efficiency of AM systems, and monitor the quality of AM product - In the services department, the customers' satisfaction is increased by the state-of-the-art service strategies, such as, real-time monitoring service of product quality and predictive maintenance service which should be attained by continuous monitoring of product's status	**Economic**: - improved market demands perception and prediction - improved product design for lower production costs - product quality improvement - intelligent predictive maintenance **Environmental**: - improved product design for lower material consumption and higher durability - energy consumption control and reduction
Manavalan, E.; Jayakrishna, K.	An Analysis on Sustainable Supply Chain for Circular Economy	2019	- The research paper has analyzed a case example in a supply chain organization to meet industry 4.0 requirements and enable circular economy - analysis on supply chain industry has been conducted with the focus on 6Rs such as Recover, Reuse, Remanufacture, Recycle, Redesign, Reduce - The article highlights the opportunities available in the transformation from linear economy to circular economy	- combining the concept of circular economy with sustainable supply chain can deliver strong benefits from an environmental perspective - Investment in technology helps organizations to improve operational efficiency, resulting in more proficient implementation of circular supply chain - the investment is in technology a major challenge in various industries at early stages, but in the long term, it allows the organization to become more sustainable	**Economic:** - enhanced decision making - more efficient and remote resource mangement - improved operational efficiency **Environmental:** - increased adoption of environmentally friendly products - increased use of renewable raw materials - recover generated energy and reduce production wastes **Social:** - increased workers moral and safety
Margherita, EG; Braccini, AM	Industry 4.0 Technologies in Flexible Manufacturing for Sustainable Organizational Value: Reflections from a Multiple Case Study of Italian Manufacturers	2020	- analysis of the value creation of Industry 4.0 (I40) technologies in flexible manufacturing (FM) under a sustainability perspective - performs a multiple case study analysis of four Italian manufacturing organizations that have successfully implemented I40 technologies in FM without eliminating jobs - describtion how the adoption of I40 technology in FM leads to sustainable organizational value and positive economic, environmental and social sustainability outcomes - employment of the TBL of sustainability in the IT value discourse to analyse the sustainable organizational value of I40 adoption in FM	- I40 technologies support sustainable organizational value when they are deployed with a worker-centric approach - I40 technologies can be adopted in FM to support all the dimensions of sustainability and thus can deliver sustainable organizational value and contribute to building a sustainable society - data plays a crucial role in supporting the organizational sustainability of manufacturing companies and thus in the development of a sustainable society - Vocational training plays a crucial role and should be provided for each worker employed in the FM production process	**Economical**: - more efficient production process (increased output, reduced defect rate, improved product quality, reduced lead time) - better circulation of information **Environmental**: - Reduction of energy usage and natural resources - Reduction of waste and faulty products **Social**: - improved competencies, work conditions, and worker competencies through tailor-made vocational training - facilitating workers' tasks - increased task autonomy and responsibilities for workers leading to empowerment

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Mark B.G., Hofmayer S., Rauch E., Matt D.T.	Inclusion of workers with disabilities in production 4.0: Legal foundations in Europe and potentials through worker assistance systems	2019	- This article examines to what extent the trend towards Industry 4.0 offers potential for the inclusion of people with disabilities in Production 4.0 - based on a literature review, it is examined which technological aids in the form of worker assistance systems derived from Industry 4.0 can make jobs in the manufacturing sector accessible for people with disabilities	- Three types of assistance systems are eligable for inclusion of workers with disabilities: sensorial aid systems, physical aid systems, and cognitive aid systems	**Social**: - inclusion of workers with disabilities in production 4.0
Mastos T.D., Nizamis A., Vafeiadis T., Alexopoulos N., Ntinas C., Gkortzis D., Papadopoulos A., Ioannidis D., Tzovaras D.	Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution	2020	- The purpose of this paper is to provide evidence of the impact of an IoT solution on the sustainable supply chain management (SSCM) performance - A case study from a scrap metal producer that operates in the lift industry and a waste management company is presented, in order to illustrate how the deployment of a state-of-the-art industry 4.0 solution has the potential to improve sustainability both in the firm level and in the supply chain level.	- five key management areas that should receive careful attention in order to improve SSCM with the deployment of industry 4.0 solutions: (1) Business based smart operations, (2) technology based smart products, (3) sustainable development, (4) collaboration, (5) management strategy and organization are the key strategic priorities that should be integrated in order to create more sustainable supply chains	**Economic**: - automation of monitoring and negotiation procedures for the produced scrap metal - improved resources availability & financial stability - response time optimization **Environmental**: - Reduced non-renewable energy resource **Social**: - CO2 emissions' reduction on streets - improved quality of work and safety of employes
Meng Y., Yang Y., Chung H., Lee P.-H., Shao C.	Enhancing sustainability and energy efficiency in smart factories: A review	2018	- In this paper, the state-of-the-art of sustainable and smart manufacturing is first reviewed based on the PRISMA framework, with a focus on how they interact and benefit each other - Key problems in both fields are then identified and discussed; Specially, different technologies emerging in the 4th industrial revolution and their dedications on sustainability are discussed - In addition, the impacts of smart manufacturing technologies on sustainable energy industry are analyzed - Finally, opportunities and challenges in the intersection of the two are identified for future investigation	- when developing smart manufacturing techniques, the consideration of energy efficiency and sustainability will yield multi-objective, multi-constraint problems, which can be so complicated that conventional methods are incapable - the enhancement of product quality using inline sensing and monitoring, real-time control, and sampling inspection methodology shows great potential in increasing the sustainability of additive manufacturing - additive manufacturing will play a vital role in the transition towards a more sustainable industrial system since the applications of additive manufacturing technologies creates opportunities for more sustainable production and consumption - The exploitation of such opportunities will lead to changes in the distribution of manufacturing, reconfiguration of values chains, and simplification of supply chains	**Economic**: - improved production efficiency & product quality - costly computation and maintenance - make the production process more efficient, sustainable, cost-effective, and customized **Environmental**: - improved sustainability of some renewable energies - energy savings - make the production process more efficient, sustainable, cost-effective, and customized **Social**: - support of local economy leading to increased social welfare
Morrar, R; Arman, H; Mousa, S	The Fourth Industrial Revolution (Industry 4.0): A Social Innovation Perspective	2017	- proposes a framework that can facilitate the interaction between technological and social innovation to continuously come up with proactive, and hence timely, sustainable strategies	- The social perspective demonstrates that technical innovations are likely to positively affect the diffusion of social innovation, and vice versa - The technological revolution that accompanies the Industry 4.0 achieve its true potential in combination with social innovation - Hence, businesses that succeed in Industry 4.0 will be those that offer both social progress and economic benefits - The discussion of social innovation in the context of Industry 4.0 is important to happen at early stages to address the growing concern of any possible negative externalities on individuals and society at large - Using sustainability as a filter provides guidance to scrutinize technology developments coming out of Industry 4.0 - The digitized nature of Industry 4.0 innovative products is likely to lead to both economic outcome as well as social benefits, if managed under the umbrella of sustainable development	**Social**: - increased employee involvement & motivation

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Müller J.M., Kiel D., Voigt K.-I.	What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability	2018	- this study examines the relevance of Industry 4.0-related opportunities and challenges as drivers for Industry 4.0 implementation in the context of sustainability, taking a differentiated perspective on varying company sizes, industry sectors, and the company's role as an Industry 4.0 provider or user - A research model comprising relevant Industry 4.0-related opportunities and challenges as antecedents for its implementation is hypothesized - In order to test the model, partial least square structural equation modeling is applied for a sample of 746 German manufacturing companies from five industry sectors	- strategic, operational, as well as environmental and social opportunities are positive drivers of Industry 4.0 implementation, whereas challenges with regard to competitiveness and future viability as well as organizational and production fit impede its progress - the perception of Industry 4.0-related opportunities and challenges as antecedents to Industry 4.0 implementation depends on different company characteristics	**Economic**: - New business models through Industry 4.0 - New value offers for enhanced competitiveness - Increased efficiency, quality, speed % flexibility - Decreasing costs - Load balancing & stock reduction - High implementation efforts regarding, e.g., costs and standardization **Environmental**: - Reduction of environmental impact - lower scrap rate - physical transport and logistics processes are reduced **Social**: - Reduction of monotonous work - Age-appropriate workplaces - more adaptable working time models - preserved employees' health - Employee fear and concerns - Lack of expertise
Müller J.M., Voigt K.-I.	Sustainable Industrial Value Creation in SMEs: A Comparison between Industry 4.0 and Made in China 2025	2018	- This study aims provide a research context about the Industrial Internet of Things (IIoT) benefits and challenges that encompasses all three dimensions of sustainability - data is obtained from 329 SMEs, 222 in Germany and 107 in China using 5 point Likert scales - comparison of the concepts "Industrie 4.0" and "Made in China 2025" in the context of SMEs	- Chinese SMEs expect a larger impact through "Made in China 2025" than German SMEs through "Industrie 4.0" - German SMEs perceive that "Industrie 4.0" might be designed more towards the requirements of larger enterprises - Chinese SMEs foremost see social benefits - Challenges whilst introducing "Industrie 4.0" by German SMEs as well as several frame conditions are perceived more relevant than for "Made in China 2025", as seen by Chinese SMEs	**Economic**: - increased competitiveness due to ability to respond more individually to customer demands - generating larger revenues by shortening processes - higher efficiency and novel business models - losing the own competitive position **Environmental**: - higher resource efficiency - increased energy efficiency **Social**: - benefits through employee assistance systems - more socially acceptable workplaces - skills shortages - job losses
Murmura F., Bravi L.	Additive manufacturing in the wood-furniture sector: Sustainability of the technology, benefits and limitations of adoption	2018	- investigate the potential sustainable benefits and limitations to the implementation of 3D printing in the wood-furniture sector in Italy, considering the companies that have already implemented this technology - Data were collected using a structured questionnaire survey performed on a sample of 234 Italian companies in this sector	- companies using 3D-printing are companies aimed at innovating through the search for new products and product features, they pay high attention to the image they convey to the market and are highly oriented to the final customer, and to the satisfaction of their needs - Italian businesses have a great tradition in this sector and also a strong ability to innovate, from an environmental and technological point of view	**Economic**: - Reduction in time to market of products - freedom of design - improved prototyping - reduced production costs **Environmental**: - reduced use of material - reduced transportation - energy saving **Social**: - Ability to co-design with the customer

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Naderi, Mahdi; Ares, Enrique; Peláez, Gustavo; Prieto, Daniel; Araújo, Madalena	Sustainable Operations Management for Industry 4.0 and its Social Return	2019	- this paper develops a methodology and procedures that allow predicting the systems performance as a whole	- The development of tools and procedures to facilitate multi- criteria decision processes and pro-active attitudes, in order to identify the associated risks and mitigate the negative impacts on economic, environmental and social development from the Analysis of Manufacturing Processes, allows greater efficiency on the improvement of the corporate sustainability	**Economic:** - improved economic and functional efficiency of manufacturing processes **Environmental:** - lowered environmental impact **Social:** - imporved working conditions and Social Return
Nara E.O.B., da Costa M.B., Baierle I.C., Schaefer J.L., Benitez G.B., do Santos L.M.A.L., Benitez L.B.	Expected impact of industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry	2021	-This study investigates the impact of Industry 4.0 technologies on sustainability using the Triple Bottom Line perspective for sustainable development - A sustainability-oriented model for evaluating the influence of Industry 4.0 technologies on sustainable metrics is proposed, analyizing the impact of Industry 4.0 technologies on several key performance indicators related to sustainable development - The model was tested in the plastics industry - a fuzzy TOPSIS multi-criteria method was used to classify Industry 4.0 technologies, identifying those with the strongest and weakest impacts on sustainable development	- the internet of things, cyber-physical systems, sensors, and big data implementation are drivers for sustainable development - these technologies are associated with substantial positive impacts on economic metrics - however, there was a much smaller positive influence on environmental and social metrics, suggesting an imbalance on the Triple Bottom Line perspective for the plastics industry - negative impacts from robots on job creation and low influence from cloud computing and system integration technologies for sustainable development	**Economic:** - increased revenues, return on investment, Profitability - reduced cost of manufacturing & cost of materials - Increase of customers & Market share **Environmental:** - improved energy efficiency - reduced water, energy & raw material consumption - sustainable or eco-friendly products - use of renewable or recycling resources - reduced use of chemicals and hazardous materials - reduced Waste generation and disposal **Social:** - improved work conditions - reduced work injuries - increased occupational health and safety and employee satisfaction - loss of jobs
Nascimento, DLM; Alencastro, V; Quelhas, OLG; Caiado, RGG; Garza-Reyes, JA; Lona, LR; Tortorella, G	Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context A business model proposal	2019	- stage 1: literature review of the concepts, successful factors and barriers related to the transition to a CE - stage 2: providing a conceptual framework for integrating and evaluating the synergistic potential of each of the concepts revealed in stage 1 - stage 3: validation of the proposed model by collecting rich qualitative data based on a focus group and semi-structured interviews with managers, researchers and professors in the field of operations management.	- recommendation of a circular model to reuse scrap electronic devices, integrating web technologies, reverse logistics and additive manufacturing to support CE practices - results suggest a positive influence from improving business sustainability by reinserting waste into the supply chain to manufacture products on demand - reuse of wasted material enables the development of local business networks that generate jobs and improve economic performance	**Economical**: - increased data gathering and analytics for better decison-making - reduced operational costs **Environmental**: - reduced environmental impact **Social**: - support of local business network development - job creation
Nouiri M., Trentesaux D., Bekrar A.	Towards energy efficient scheduling of manufacturing systems through collaboration between cyber physical production and energy systems	2019	- In this paper, a multi-agent architecture aimed at elaborating predictive and reactive energy-efficient scheduling through collaboration between cyber physical production and energy systems is proposed - smart, sustainable decision tools for cyber physical production systems (CPPS) and cyber physical energy systems (CPES) are proposed - Dynamic mechanisms in CPPS and CPES are proposed to adjust the energy consumption of production systems based on the availability of the renewable energy - The proposed approach was validated on a physically distributed architecture - A series of instances inspired from the literature were tested to assess the performance of the proposed method	- smart, sustainable decision tools for cyber physical production systems (CPPS) and cyber physical energy systems (CPES) enable the connected factories to adjust especially their consumption in terms of an energy threshold communicated in real-time by CPES	**Environmental:** - improved energy efficiency and consumption

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Oláh J., Aburumman N., Popp J., Khan M.A., Haddad H., Kitukutha N.	Impact of industry 4.0 on environmental sustainability	2020	- this research debates the effects on environmental sustainability and the challenges facing Industry 4.0 - analysis of a literature review of manuscripts discussing topics related to Industry 4.0 and environmental sustainability published between 2000 and 2020 - Four scenarios are discussed: a deployment scenario, an operation scenario, integration and compliance with sustainable development goals, and a long-run scenario	- there is a negative relationship related to the flow of the production process from the inputs to the final product, including raw materials, energy requirements, information, and waste disposal, and their impacts on the environment - However, the integration of Industry 4.0 and the sustainable development goals enhance environmental sustainability to create ecological support that guarantees high environmental performance with a more positive impact than before - Companies investing in research and development bring more awareness of sustainable ways of enabling technology to be better reused, reduced, recycled, and replaced, so that effective use of raw materials, information, and energy is encouraged, as is responsible consumption, according to the SDGs	**Economic:** - reduced energy consumption - more efficiency in energy use - produce only what is needed - quality improvement **Environmental:** - reduction in pollution - more efficiency in energy use - produce only what is needed - waste can be turned to energy use **Social:** - better working conditions - employees can work from their homes
Ordieres-Meré J., Remón T.P., Rubio J.	Digitalization: An opportunity for contributing to sustainability from knowledge creation	2020	- The paper looks to show how I4.0 can help to increase the organizational knowledge, in particular in rather complex environments - discuss the effects of digitalization by focusing on its drivers, like the implementation of Industry 4.0, mainly oriented not only on production but also on the health of workers and environmental working conditions - two case studies are performed	- improvements impacting sustainability need to be adopted as explicit knowledge by the company to be permanent - knowledge increases when framed in a convincing strategy that can support direct and indirect improvements, including the sustainability dimension - To consider workers' behavior inside the cloud manufacturing schema can bring additional perspective about process variability, which can contribute to further improvement of the whole system	**Economic:** - reduced truck loading duration **Environmental:** - increased environmental performance **Social:** - increased worker motivation - increased awareness of the relationship between their own (employees') parameters and the activities
Papetti, A; Gregori, F; Pandolfi, M; Peruzzini, M; Germani, M	A method to improve workers' well-being toward human-centered connected factories	2020	- the paper provides a novel transdisciplinary engineering method to measure and promote social sustainability on production sites - it exploits Internet of Things technology to support the (re)design of manufacturing processes and plants toward human-centered connected factories - the method has been implemented in a real industrial case study within the footwear industry - the sole finishing process has been analyzed from different perspectives to solve ergonomics-related problems and implement effective improvement strategies	- Results confirmed that the improvement of the manufacturing system from the social point of view has to be a win-win strategy with positive relapses on both operators' health and company productivity	**Social**: - improved condition monitoring of physical, cognitive, and environmental perspective - enhanced worker's well-being improvement measures
Park K.T., Kang Y.T., Yang S.G., Zhao W.B., Kang Y.-S., Im S.J., Kim D.H., Choi S.Y., Do Noh S.	Cyber Physical Energy System for Saving Energy of the Dyeing Process with Industrial Internet of Things and Manufacturing Big Data	2020	- In this study, a cyber physical energy system that improves the energy efficiency of the dyeing process by collecting and analyzing manufacturing big data was developed - the implemented system was applied to actual dyeing and finishing shops, and its effects were verified	- The energy consumption of the dyeing process can be reduced by utilizing the CPES instead of pur- chasing expensive machines	**Economic:** - improve the energy efficiency of the dyeing process **Environmental:** - improve the energy efficiency of the dyeing process
Patsavellas, John; Salonitis, Konstantinos	The Carbon Footprint of Manufacturing Digitalization: critical literature review and future research agenda	2019	- this paper ascertains the absence of any structured assessment framework of CO2 emissions of the various components of industrial digitalization, as an evaluation tool of the accelerating digital transformation of manufacturing within a sustainable growth context	- There is notable absence of peer-reviewed published work in relation to the possible emissions from the impending 4th industrial revolution - The evidence of the existing studies on the growth of data generating sources and the potential merit that such data can have when turned into intelligent insights that can be acted upon automatically in manufacturing, calls for action in transparency of its carbon impact	**Environmental:** - increased energy consumption due to excessive data generating, transmitting, consuming, storing, analyzing, retrieving and retransmitting

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Pham T.T., Kuo T.-C., Tseng M.-L., Tan R.R., Tan K., Ika D.S., Lin C.J.	Industry 4.0 to accelerate the circular economy: A case study of electric scooter sharing	2019	- This paper discusses the fundamental concepts of Industry 4.0 and explores the influential factors of Industry 4.0 that accelerate the sharing economy in the CE context via a case of electric scooters in Taiwan	- technologies of Industry 4.0 (IoT, CPS, CC, and data-driven analysis) provide a powerful set of tools to overcome barriers to Circular Economy implementation - Industry 4.0 Technologies are facilitators for Circular Economy practices, and thus, increase the sustainability affects of Circular Economy	**Economic:** - improved maintenance - greater automation & improved process resilience - enhanced waste reduction, re-use, and recovery - increased energy efficiency **Environmental:** - enhanced waste reduction, re-use, and recovery - reduced carbon foot print - increased energy efficiency **Social:** - reduced personal carbon footprint - increased transparency
Pinzone M., Albè F., Orlandelli D., Barletta I., Berlin C., Johansson B., Taisch M.	A framework for operative and social sustainability functionalities in Human-Centric Cyber-Physical Production Systems	2020	- This paper synthesizes the diverse literature regarding CPS and social sustainability in production systems - it conceptualizes a holistic framework, the CyFL Matrix, and outlines a guideline to analyze how the functionalities of a CPPS relate to operational and social sustainability-related performance impacts at different levels of analysis - Finally, it presents an industrial use case, which the CyFL Matrix and the related guidelines are applied to	- Identifying and measuring social aspects in manufacturing, and determining their interaction with production and operative dimensions is crucial to progress towards the Industry 4.0 paradigm in a socially sustainable way and to shape the competitive and human-centric workplaces of the future - Without clear frameworks, methods and tools to integrate human and social sustainability aspects in the design and deployment of future CPPS, there is the risk these aspects will be overlooked or considered as an add-on to core value-creation processes	**Economic:** - reduced rate of human errors - increased potential for preventive actions - increased flexibility (process, volume, expansion, market), time and cost efficiency **Environmental:** **Social:** - operator's learning curve will improve for increased knowledge, skills and competencies - increased well-being - enhanced employee satisfaction, flexibility and work-life-balance
Piscitelli, Giuseppina; Ferazzoli, Angela; Petrillo, Antonella; Cioffi, Raffaele; Parmentola, Adele; Travaglioni, Marta	CIRCULAR ECONOMY MODELS IN THE INDUSTRY 4.0 ERA: A REVIEW OF THE LAST DECADE	2020	- This paper analyzes and reviews the scientific literature to examine current state-of-the-art of Circular Economy (CE) with I4.0 perspective and highlight its benefits from the point of view of sustainability within the industry - different types of studies have been collected, dividing theoretical studies from technical-application case studies	- CE shows great application potential in many industrial operations, the choice to implement CE model ultimately, depends on the application field of the I4.0 system - we cannot have a circular economy without the 4th Industrial Revolution, and we cannot have a socially useful and sustainable 4th Industrial Revolution without advancing the circular economy	**Economic:** - minimized production and labor costs - enhanced operation process insights for enhanced decision making **Environmental:** - reduced waste generation (energy, chemical material, raw material, CO2 emissions) **Social:** - enhanced skill development
Ramirez-Peña M., Sánchez Sotano A.J., Pérez-Fernandez V., Abad F.J., Batista M.	Achieving a sustainable shipbuilding supply chain under I4.0 perspective	2020	- this article aims to connect each of the key enabling I4.0 technologies with the most significant supply chain paradigms: Lean, Agile, Resilience and Green to define what the Shipbuilding Supply Chain should be	- The results obtained imply the implementation of enabling technologies in two phases - A first phase would achieve a sustainable shipbuilding supply chain that improve economic, energy and environmental aspects through the implementation of the following technologies: Autonomous Robots, Additive Manufacturing, Cloud Computing, Autonomous Robots, Cybersecurity and Augmented Reality - A second phase where converge the Functional and Social aspects through the implementation of Horizontal & Vertical Integration, Big Data, Blockchain, Simulation, Internet of Things and Artificial Intelligence, reinforcing the Resilient and Agile paradigms - in this way, it is achieved total visibility and connectivity required on the Shipbuilding Supply Chain 4.0	**Economic:** - improved agility & resilience - improved lean operations **Environmental:** - improved environmental aspects - improved lean & green operations **Social:** - improved social aspects - improved resilience

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Ren S., Zhang Y., Liu Y., Sakao T., Huisingh D., Almeida C.M.V.B.	A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions	2019	- A comprehensive overview of big data in smart manufacturing was conducted, and a conceptual framework was proposed from the perspective of product lifecycle - through combining the key technologies of smart manufacturing and the idea of ubiquitous servitization in the whole lifecycle, the term of sustainable smart manufacturing was coined	- The goals of SSM for using the emerging information technol- ogies and advanced analytics are: (a) to reduce resource waste; (b) to decrease environmental impacts; (c) to increase digitization level; (d) to achieve global intellectualization in manufacturing and service	**Economic:** - Perceiving and predicting market demands - Improved product & service design, product quality and yield - Optimized shop-floor logistics - Controlling and reducing energy consumption - predictive maintenance service and intelligent spare part prediction **Environmental:** - Improved product & service design - Controlling and reducing energy consumption - Providing predictive maintenance service and intelligent spare part prediction services - Optimizing recovery decisions and reducing environment impacts - Reduced waste of raw materials **Social:**
Saetta, Stefano; Caldarelli, Valentina	How to increase the sustainability of the agri-food supply chain through innovations in 4.0 perspective: a first case study analysis	2020	- Through the administration of surveys to different companies the agri-food sector, a preliminary assessment of possible solutions is made, identifying logistic improvements and technological innovations for the increase of the sustainability	- The introduction of a hub, a facility shared by several companies, allows to have a single shared point of departure and arrival - Load consolidation, vehicles loaded in a more effective and efficient way, together with route optimization, lead to a reduction in the kilometers traveled, increasing not only economic but also environmental sustainability	**Economic:** - enhanced load consolidation - increased market opportunities for small-scale producers **Environmental:** - reduction in kilometers traveled - reduce greenhouse gas emissions **Social:** - support of local economies and communities - improving local air pollution
Sartal A., Bellas R., Mejías A.M., García-Collado A.	The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review	2020	- this article first presents an overview of the main concepts related to sustainable manufacturing, and metrics to evaluate organizations' sustainability performance, and then an outlook of current trends - Our work highlights the consistencies and inconsistencies in the research community related to the interpretations of sustainable manufacturing and Industry 4.0, as well as the lack of consensus about the true social impact of Industry 4.0	- the positive ecological and economic impacts of sustainable manufacturing are fairly widespread - lack of consensus about the true impact of Industry 4.0 regarding the social dimension - In this way, sustainable manufacturing practices are to be reinforced by initiatives within the fourth stage of industrialization – the so-called Industry 4.0 – which offers great opportunities for sustainable manufacturing, thanks to digital transformation - The empirical studies show that the indicators most used by productive companies can be summarized in about 20 and are mostly focused on the economic dimension, while the social and environmental dimensions often seem to be addressed with the sole goal of complying with legal aspects	**Economic:** - preventing unnecessary manufacturing steps, waste and superfluous inventory - saved cost and reduced rejection levels **Environmental:** - increased visibility and awareness of energy consumption - reduced manufacturng waste and energy consumption - reduced production of unneeded goods **Social:** - improve equipment and operator safety through real-time hazard warnings - improving standard operating conditions - reducing workload and possible musculoskeletal disorders - enhanced training of workers at a low cost
Scharl S., Praktiknjo A.	The Role of a Digital Industry 4.0 in a Renewable Energy System	2019	- this paper explores the expert discourse on the role of industry 4.0 in a renewable energy system - for this purpose, 21 qualitative semistructured interviews are conducted - it describes what new capacities industry 4.0 will develop and industry's willingness to interact in the energy transition, as seen by these experts	- By reducing uncertainties in the forecasting of industrial energy consumption and generation as well as in the identification of technical failures, security of energy supply can increase significantly although power generation is increasingly dependent on the weather conditions - security of energy supply can increase significantly - the discourse on the transformation of the industry into a supporting role for the energy transition could fail due to a communication barrier between the different disciplines - Policy has to address the missing incentives to participate in the energy system and provide a transparent legal framework for asset-less businesses to foster knowledge spillovers between industry and the energy system - industry requires strong legislation on data security and transparency together with robust technical means of enforcing this	**Economic:** - additional flexibility for renewable energy systems - accurate predictions of industrial energy consumption and generation - more effective identification of failures within the energy system **Environmental:** - enhance energy efficiency and decrease energy consumption

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Sharma, Mahak; Kamble, Sachin; Mani, Venkatesh; Sehrawat, Rajat; Belhadi, Amine; Sharma, Vardaan	Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies	2020	- evaluation of drivers and barriers for implementation of Industry 4.0 in multi-tier manufacturing supply chains - Based on practitioner's opinion, a total of 37 drivers and 21 barriers were identified under five dimensions viz., technological, organizational, economic, environmental, and social, and their inter-relationships were also established in a multi-tier supply chain - The study highlights drivers and barriers to industry 4.0 adoption with the sustainability context in multi-tier manufacturing supply chain	- the sustainable aspects, that includes the environmental and social factors, were the highest-ranked drivers and identified as the causal variables - At the same time, organizational and environmental dimensions were identified as the highly ranked barriers and causal factors - need for developing global standards, data sharing protocols, and ethical code and standards between the stakeholders in multi-tier manufacturing supply chain	**Economic:** - economic barrier for Industry 4.0 implementation - improved productivity and decisiom-making - cost reductin (labour, logistics, inventory) **Environmental:** - environmental factor is high driver and high barrier for Industry 4.0 development - reduced production waste, emission, and energy consumption **Social:** - social factor is high driver for Industry 4.0 development - improved collaboration and safety
Shayganmehr, Masoud; Kumar, Anil; Garza-Reyes, Jose Arturo; Moktadir, Md Abdul	Industry 4.0 enablers for a cleaner production and circular economy within the context of business ethics: A study in a developing country	2020	- In this paper, a novel framework was proposed to illustrate the important role of Industry 4.0 enablers in the implementation of CP and CE within business ethics - Firstly, the most important enablers were defined and validated through the Fuzzy Delphi method - The importance of the validated enablers was established through the IVFS AHP method	- The most important enablers were "Technical capability", Security and safety", "Policy and Regulation", "System flexibility", "Education and participation" and "Support and maintenance" - technical capability is the most important enabler for the successful adoption of CP and sustainable development, including Industry 4.0 technologies such as Big Data and IoT for accelerating the CP implementation and development	**Economic:** - enhanced supply chains performance and efficiency - better process monitoring and product or service design **Environmental:** - improved resource efficiency and environmental management - accelerated CE implementation, reducing environmental impact **Social:** - increasing need for skill development and privacy regulations - improved workers' health and safety
Sony M., Naik S.	Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model	2020	- Building on the previous literatures on Socio-Technical Systems Theory and Industry 4.0, the article proposes bringing the two approaches together and presents a framework for integration mechanism - This study suggests a design mechanism for three types of integration mechanism in Industry 4.0 by considering the socio-technical systems impact on people, infrastructure, technology, processes, culture and goals - Further, the integration is also sug- gested for analysis on the impact of stakeholders, economic situation and regulatory frameworks around which the operating organizations are operating	- there is a need for Industry 4.0 systems to bring in the inclusivity of all types of workers in the smart factories especially in terms of being proficient in assisting the ageing, disabled and other disadvantaged workers - Industry 4.0 can be socially sustainable if organizations will accompany its technological transformations with training and development programs for their workforce - there is a need for human elements working in tandem with the technical systems for the success of Industry 4.0 - while designing the socio-technical architecture of vertical integration, social principles such as the impact on people, infrastructure, technology, processes, culture and organization goal must be considered	**Social:** - increased possibility to promote inclusion - increased possibility to adapt workplaces on employee's needs
Stock T., Obenaus M., Kunz S., Kohl H.	Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential	2018	- The state of the art in research and technology for Industry 4.0 and sustainability is outlined - The potential for sustainable value creation in Industry 4.0 is qualitatively assessed for a macro and micro perspective based on a literature review and expert interviews - The emphasis of the investigation was put on the environmental and social dimension of sustainability	- the value creation factors can positively contribute to the ecological dimension of sustainability in most cases - Critical areas with expected negative contributions are identified, namely the quantity of materials used and primary energy consumption - Benefits in the social sustainability dimension can be expected for a better integration and inclusion of employees, the enrichment of work, a more effective education of workers, as well as for a better work-life balance - Negative social impacts might occur in terms of substitution or simplification of jobs by technological systems and in terms of the controllability and complete transparency of work by ICT which might lead to exploitation and performance extortion of employees	**Environmental:** - increased quantity of materials used & primary energy consumption - enhanced resource and water management - decreased greenhouse gas emissions **Social:** - better integration and inclusion of employees - enrichment of work - more effective education of workers - better work-life balance - substitution or simplification of jobs - possible performance extortion

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Stock, T.; Seliger, G.	Opportunities of Sustainable Manufacturing in Industry 4.0	2016	- This paper will present a state of the art review of Industry 4.0 based on recent developments in research and practice - Subsequently, an overview of different opportunities for sustainable manufacturing in Industry 4.0 will be presented - A use case for the retrofitting of manufacturing equipment as a specific opportunity for sustainable manufacturing in Industry 4.0 will be exemplarily outlined	- the paradigm shift to Industry 4.0 will be a step forward towards more sustainable industrial value creation - The concept towards a holistic resource efficiency is being described as one of the essential advantages of Industry 4.0 - In connection with a smart product, retrofitted machines can decentrally schedule the material flow and are furthermore able to automatically react to any machine failures by e.g. informing the responsible worker	**Economic:** - new evolving business models - enhanced industrial symbiosis - increased operational performance and productivity **Environmental:** - more efficient allocation of resources, i.e. products, materials, energy and water - enhanced retro-fitting-opportunities - easier reuse and remanufacturing of specific product **Social:** - increased training efficiency - increased motivation and creativity
Strandhagen, JW; Buer, SV; Semini, M; Alfnes, E; Strandhagen, JO	Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain	2020	- case study of a shipbuilding supply chain, which results in the identification of its primary sustainability challenges - proposing a set of nine digital solutions to improve sustainability in shipbuilding operations	- shipbuilding supply chains should initially pay attention to the Industry 4.0 base technologies and investigate how they can be applied and pursue the least complex implementation level - This level includes cloud services, improved connectivity, monitoring and control of products, vertical integration of internal IT systems and the establishment of internal digital platforms - From there, the digital infrastructure that is needed can be built from the bottom, enabling for the pursuit of the more complex digital solutions that have been suggested in earlier sections	**Economical**: - reduced cost of production - Increased productivity and efficiency of manufacturing logistics processes **Environmental**: - increased energy-efficiency - less spare part production and stock - increased recycling opportunities **Social:** - Improved working conditions and workplace safety - job creation
Tavares, TM; Godinho, M; Ganga, GD; Callefi, MH	THE RELATIONSHIP BETWEEN ADDITIVE MANUFACTURING AND CIRCULAR ECONOMY: A SISTEMATIC REVIEW	2020	- a Systematic Literature Review was performed by applying the Method Ordination multicriteria methodology in order to map the main publications - Then, 10 articles were analyzed to obtain relevant information about the relationship between Additive Manufacturing and Circular Economy	- Additive Manufacturing has the potential to provide the advantages of sustainability and the circular production system - However, more recent studies have highlighted some barriers that can prevent this vision from becoming a reality - AM may evolve into a trend to encourage consumerism, instant gratification and disposable society, which also goes against the principles of circular economy	**Environmental:** - less waste generation during manufacturing - ability to optimize geometries and create lightweight components that reduce material consumption in manufacturing and energy consumption in use - the subsequent reduction in transportation in the supply chain - reduced inventory waste due to the ability to create spare parts on demand
Tirabeni L., De Bernardi P., Forliano C., Franco M.	How can organisations and business models lead to a more sustainable society? A framework from a systematic review of the industry 4.0	2019	- a systematic literature review is performed to investigate the most recent Industry 4.0 research streams by adopting a multi-perspective approach - insights on the key traits of an Enterprise 4.0 are analysed	- key traits found to be the recurrent, common concepts of an Enterprise 4.0 are: integration, decomposed hierarchy, flexibility, and autonomy - The following features of the phenomenon have been identified: an involved and resilient workforce, alongside 'smart' middle managers; sustainable, networked, and customer-centred business models; a lean self-organisation; and participative leadership style - the smartness of a company will probably depend on its ability to concretely adopt these features and concepts, and policy-makers could be helped to understand their role in shaping Industry 4.0, and fostering innovation and economic growth	**Economic:** - increased opportunities for novel solutions to gain competitiveness - better and more agile decision-making - increased flexibility **Environmental:** - improved operations sustainability & environmental protection **Social:** - increased autonomy and decison-making participation - increased job rotation, flexibility, team-work and interdisciplinarity - more decomposed hierarchy - advanced training opportunities

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Tiwari K., Khan M.S.	Sustainability accounting and reporting in the industry 4.0	2020	- detailed review of the key SAR (Sustainability accounting and reporting) variables under Global Reporting Initiatives and other relevant literature, and of Industry 4.0 technology and architectural features; - Mapping of Industry 4.0 capabilities with SAR variables in a multivariate model - Collecting primary data from two Focus Groups working on Industry 4.0 solutions in Delhi NCR region - Conducting interviews with five manufacturing operations heads in the city of Kanpur and Lucknow - Evolving an empirical model showing relationships between the Industry 4.0 capabilities and the relevant triple bottom-line topic areas of the Global Reporting Initiative; - Critical analyses of the empirical model, their relevance, and significance for theory and practice	- Industry 4.0 is not a complete solution for comprehensive GRI reporting because only a limited number of disclosure requirements can be implemented even if all the three levels of Industry 4.0 positioned in India are implemented - IIoT and cyber physical systems are credited to mostly environmental performance monitoring - body wearable sensors for health and safety monitoring seem not to be eligable in the future	**Economic:** - enhanced measurement of economic indicators facilitating economic improvements **Environmental:** - enhanced measurement of environmental indicators facilitating environmental improvements **Social:** - enhanced measurement of social indicators facilitating social improvements
Turner C., Moreno M., Mondini L., Salonitis K., Charnley F., Tiwari A., Hutabarat W.	Sustainable production in a circular economy: A business model for re-distributed manufacturing	2019	- In this paper, business models for re-distributed manufacture (RdM) are developed using anIDEF (Icam DEFinition for Function Modelling) description to serve as a guide for the implementation of the RdM concept in the consumer goods industry - Exploring the viability of a re-distributed business model for manufacturers employing new manufacturing technologies such as additive manufacturing as part of a sustainable and circular production and consumption system - An As-Is value chain model is presented alongside the proposed new business model for a sustainable re-distributed manufacturing system, both being illustrated via a case study drawn from the shoe manufacturing industry	- Only raw materials and data should travel long distances in a re-distributed model - the proximity of the customer to the manufacturing and servicing facilities is an important value generation opportunity - having multi-tasking facilities which can manufacture, remanufacture, and provide services all in the same location and with the same equipment, all in close vicinity to the customer, is the main generator of value to the customer and their community - Installed capacity and lead time are crucial components to the implementation of a re-distributed model, by determining installed capacity according to the particular local demands for flexibility of product and quantity	**Economic:** - increased product flexibility - decreased quantity flexibility & inventory - increased initial store-setup-costs **Environmental:** - decreased transportation and waste **Social:** - customized products - less low-cost-country-exploitation
Varela L., Araújo A., Ávila P., Castro H., Putnik G.	Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability	2019	- this research proposes a structural equation model, with six hypotheses, to quantitatively measure the effects of Lean Manufacturing and Industry 4.0, in Sustainability - 252 valid questionnaires from industrial companies of Iberian Peninsula (Portugal and Spain) are collected to statistically validate such hypotheses	- it is not conclusive that Lean Manufacturing is correlated with any of the sustainability pillars - it exists a strong relation between I4.0 and the three pillars of Sustainability, with a strongest factorial weight for Environmental Sustainability (1.482), followed by Social Sustainability (0.994), and the lowest for Economic Sustainability (0.457) - Industry 4.0 & Lean Manufacturing are correlating	**Economic:** - Increased profits, value creation, efficiency, flexibility, and competitiveness - Improved supply chains, SC management performance and security - Decreased operational costs **Environmental:** - correlation to energy consumption, circular economy, and environmental practices with partners - Decreased industrial waste, non-renewable energy and resource consumption, and global warming - Increased production of renewal energy, practice of circular economy, and collaboration with partners that follow good environmental practices **Social:** - correlation to salary remuneration, work conditions, and surrounding society - Increase participation of employees in decision-making - Decrease working accidents - Improve working conditions and conditions of the surrounding society

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Waibel M.W., Steenkamp L.P., Moloko N., Oosthuizen G.A.	Investigating the Effects of Smart Production Systems on Sustainability Elements	2017	- this research study investigates the dynamics of the next industrial revolution (Industrie 4.0) - case studies on the market, suppliers and customers are used as benchmark to identify current trends - the technical, economic, social and environmental elements of possible smart innovations were evaluated in terms of resource efficiency	- Attention should be paid to the challenges and barriers regarding Smart Production Systems and its important prerequisites, such as functioning IT security systems, an extensively, fast and stable data network, standardized process steps and not at least qualified employees	**Economic:** - ablility to produce high-tech individualized parts according to customer's requirements - flexible production adjustments - monitored and controlled production even via long distances **Environmental:** - renewable energy sources can be used more efficiently - waste and overproduction can be reduced **Social:** - more ergonomic and flexible work stations - more flexible work regarding the personal situation of the employees
Waibel, M. W.; Oosthuizen, G. A.; Toit, D. W. du	Investigating current smart production innovations in the machine building industry on sustainability aspects	2018	- This research study investigates current smart production innovations and trends in the machine building industry - the sustainability aspects and the potential of various smart innovations are outlined	- The approach of Smart Production Systems promises far-reaching improvements on every company level - To the costs of mass production parts companies will be able to produce high-tech individualized parts according to customer's requirements - On the bottom line manufacturing companies use smart innovations when these systems help them to produce a lower unit price; Falling product prices in combination with an increasing prosperity of the global population will lead to a higher consumption of goods and resources	**Economic:** - decresed cost per unit - enhanced process simulation and planning **Environmental:** - reduced necessity of on-site assemblies, and thus, reduced travel - enhanced waste reduction and resource efficiency **Social:** - improved compatibility of family and job - enhanced work safety
Yadav G., Kumar A., Luthra S., Garza-Reyes J.A., Kumar V., Batista L.	A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers	2020	- This study aims to develop a framework to improve sustainability adoption across manufacturing organisations of developing nations using Industry 4.0 technologies - enablers that strongly influence sustainability adoption are identified through a literature review - Further, a large scale survey is conducted to finalise the Industry 4.0 technologies' enablers to be included in the framework - Based on the empirical analysis, a framework is developed and tested across an Indian manufacturing case organisation - Finally, Robust Best Worst Method (RBWM) is utilised to identify the intensity of influence of each enabler included in the framework	- managerial and economical, and environmental enablers possess a strong contribution toward sustainability adoption - environmental enablers also possess a strong influence in achieving overall sustainability - the adoption of sustainable energy resources systems, adoption of sustainability supportive policies and effective sustainability performance metrics are among the top influencing enablers that support sustainability adoption - government policies favouring sustainability adoption through the execution of new technologies will have a positive impact on strengthening nations' economy - Similarly, the promotion of a sustainable energy resource system will create awareness among manufacturing organisations and help them improve their sustainable performance	**Economic:** - reduced manufacturing costs - quick product modification - improving the organisational performance - enhanced ability in keeping the inventory stocks at optimum levels **Environmental:** - enabling environmentally friendly design and disposal system - enhanced usage of sustainable and renewable energy resources - Reduction in emission **Social:** - reduce human interaction - enhanced health and safety measures
Yadav G., Luthra S., Jakhar S.K., Mangla S.K., Rai D.P.	A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case	2020	- the present study aims to develop a framework to overcome SSCM challenges through industry 4.0 and circular economy based solution measures by identifying a unique set of 28 SSCM challenges and 22 solution measures - Further, an automotive case organisation is used to test the applicability of the developed framework through hybrid Best Worst Method (BWM)-ELimination and Choice Expressing REality (ELECTRE) approach - inputs for BWM-ELECTRE approach is obtained by constructing an expert panel within the case organisation.	- managerial and organisational challenges and economic challenges emerge as most critical to SSCM adoption, followed by economic challenges, supplier challenges, process challenges, and socio-cultural challenges - lack of availability of resources including financial, technical and human, Conflict among product sustainability policy and free trade provisions, and Poor management commitment for adoption of sustainability are observed as the most critical challenges that restricts SSCM adoption	**Economic:** - enhanced potential to predict system shutdown and break in supply chain - enhanced supply chain **Environmental:** - optimized transportation - less resource consumption - less waste **Social:** - higher transparency
Yang S., Raghavendra M.R.A., Kaminski J., Pepin H.	Opportunities for industry 4.0 to support remanufacturing	2018	- This paper reviews the challenges encountered by the remanufacturing sector and discusses how the Industry 4.0 revolution could help to effectively address these issues and unlock the potential of remanufacturing - Two case studies are included in this paper to exemplify how technology enablers from Industry 4.0 can increase efficiency, reliability, and digitization of the remanufacturing process	- increased digitalization across the supply chain and enhanced cyber-physical intelligence within the factory have effectively addressed several major concerns that remanufacturers encounter	**Economic:** - tailor-made repair operations - enhanced predictive maintanance **Environmental:** - enhanced predictive maintanance and product end-of-life decision making

Appendix 12 (continued)

Author(s)	Title of Article	Year	What was done?	Author's main implications & findings	reciprocal influence per sustainability dimension
Yue, Xuejun; Cai, Hu; Yan, Hehua; Zou, Caifeng; Zhou, Keliang	Cloud-assisted industrial cyber-physical systems: An insight	2015	- this paper addresses the architecture of cloud-assisted industrial CPS, and highlights some key enabling technologies in this process - some challenges that need to be solved in the future are reviewed	- in the era of Industry 4.0, the use of some enabling technologies to link the cyber world and physical world is essential and these key enabling technologies supply a big support to the system of ICPS - the building of Industry 4.0 is a long way off, some years or even some decades; we should follow the direction of the road and develop more technologies to achieve it	**Economic:** - optimized production efficiency, production and service quality **Environmental:** - increased sustainability of processes - reduced waste and resource consumption