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Industry 4.0 and sustainability: Towards conceptualization and theory

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ABSTRACT

Both Industry 4.0 and sustainability have gained momentum in the academic, managerial and policy debate. Despite the relevance of the topics, the relation between Industry 4.0 and sustainability – revealed by many authors – is still unclear; literature is fragmented. This paper seeks to overcome this limit by developing a systematic literature review of 117 peer-reviewed journal articles. After descriptive and content analyses, the work presents a conceptualization and theoretical framework. The paper contributes to both theory and practice by advancing current understanding of Industry 4.0 and sustainability, especially the impact of Industry 4.0 technologies on sustainability practices and performance.

1. Introduction

Industry 4.0 – even if there is no universally accepted definition (Hofmann and Rüsch, 2017; Culot et al., 2020) – can be considered as "*the set of technologies, devices and processes [...] capable of operating in an integrated way along the several phases of the production process and along the several levels of the supply chain [...] that allow for self-sufficient production, integrated operations, decentralized decisions, minimum human intervention*" (Castelo-Branco et al., 2019). The technologies, devices and processes include the Internet of Things (IoT), Cyber-Physical Systems (CPS), autonomous robots, visualization technologies (virtual and augmented reality), cloud computing, blockchain technology, big data analytics, additive manufacturing, and digital twins (BCG, 2019; Culot, 2020; Liao et al., 2017; Tao et al., 2019).

The Industry 4.0 developments fit into a wide debate on industrial sustainability. Sustainability is a holistic concept that has been defined in many ways. The most popular definition goes back to the Brundtland report that coined the term sustainable development, meaning "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*" (Brundtland, 1987). Over the course of time, sustainability has been construed as seeking to balance economic, social and environmental performance, i.e., the triple bottom line (TBL). From a corporate perspective, the long-term success of a company relies on all three dimensions of sustainability (Elkington, 1998). These three pillars integrate different viewpoints of corporate sustainability such as corporate social responsibility or environmental management (Amini and Bienstock, 2014).

Industry 4.0 and sustainability have both gained momentum in the academic, managerial and policy debate (Kiel et al., 2017; Milano et al., 2017; de Sousa Jabbour et al., 2018b). Recent studies have sought to link Industry 4.0 and sustainability. Both complements and tensions exist. Industry 4.0 can support process optimization and positively contribute to environmental sustainability performance with efficient resource usage (Herrmann et al., 2014; Kiel et al., 2017), and a reduction in waste production (Stock et al., 2018; Beier et al., 2017). Alternatively, it can lead to increased waste production – electronic wastes, as an example – and to higher energy resources demand (Ford and Despeisse, 2016).

Industry 4.0 relates to social sustainability performance (working conditions, working hours, skills, health and safety), studies have found both positive and negative relationships (Stock et al., 2018; Bremer, 2015; Isaias et al., 2015; Beier et al., 2017). Industry 4.0 and related technologies can positively affect sustainability practices such as the circular economy (Bressanelli et al., 2018), green cloud computing, and energy monitoring (Rong et al., 2016; Tushar et al., 2018).

Recent literature reviews focus on specific aspects of the relationship between Industry 4.0 and sustainability. Examples include IoT embedded in sustainable supply chains (Manavalan and Jayakrishna, 2019), green cloud computing (Radu, 2017), artificial intelligence (AI) for humanitarian health crisis (Fernandez-Luque and Imran, 2018), optimization of sustainable energy development (Zheng et al., 2013),

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maintenance 4.0 (Franciosi et al., 2018), energy efficiency in cloud software (Procaccianti et al., 2015) and Industry 4.0 in the pharmaceutical sector (Ding, 2018), or consider sustainability among the many aspects of Industry 4.0 (Kamble et al., 2018). Others review to what extent sustainability is considered in the concept of Industry 4.0 (Beier et al., 2020).

A comprehensive evaluation and thematic analysis on the relationship between Industry 4.0 and sustainability is missing. Existing literature reviews only cover some aspects of Industry 4.0 and sustainability and do not evaluate Industry 4.0 technologies and sustainability dimensions holistically to understand their interrelated dynamics (Section 2 provides more details). Furthermore, they do not thematically analyse the relation between single technologies and sustainability and do not aim to investigate the theoretical potentials and pitfalls related to them.

Our paper fills this gap by thematically evaluating the literature to explore the interplay between Industry 4.0 and company sustainability. We analyse 117 peer-reviewed papers and develop a conceptual framework encompassing Industry 4.0 technologies, sustainability practices, sustainability performance and their moderating factors. This conceptualization helps to further construct and theory development. This study also sets the stage for critical investigations into this complex relationship full of complements and tensions.

The remainder of this paper is organized as follows. In Section 2 previous literature reviews are carefully examined. The research methodology is summarized in Section 3. Section 4 and 5 present the descriptive and thematic findings. Section 6 describes the conceptual framework on the interplay between Industry 4.0 and sustainability and identifies the main gaps of the literature. Finally, Section 7 summarizes the conclusions.

2. Perspectives from other literature reviews

The relationship between Industry 4.0 and sustainability has received increasing attention in the literature and has been reviewed using different perspectives. To explain the need for this work and to better position it, previous reviews are summarized in this section, following the approach adopted by Brandenburg et al. (2014) in their study on quantitative models for sustainable supply chain management.

In Table 1, we summarize the main literature reviews and co-citation analyses on the topic[1], highlighting the research focus, author(s) and year, time horizon, number of papers evaluated, main journals, employment of keyword search and content analysis as well as perspectives on Industry 4.0 and sustainability. Most reviews (6 out of 8) have been published in 2020.

Kamble et al. (2018) present a general review on Industry 4.0. They develop a framework, proposing that Industry 4.0 technologies aid process integration (human-machine and shop-floor), leading to economic and environmental sustainability, and automation and process safety. They mainly relate single technologies to economic outcomes (costs, flexibility, productivity etc.). In only a few cases, they show some direct relations between single technologies and environmental (e.g., IoT that leads to energy efficiency; additive manufacturing reducing the consumption of raw materials) as well as social (e.g., wearable technologies and smart glasses that make workplaces safer) performance/practices.

Three reviews focus instead on the relationship between Industry 4.0 and sustainability in a specific field, namely supply chain/logistics (Bag et al., 2018; Birkel and Müller, 2020) and manufacturing (Machado et al., 2020).

Bag et al. (2018) review how to handle supply chain sustainability in Industry 4.0 and identify relevant enabling factors, such as governmental support, collaboration with research institutes, and universities, exchange of information between supply chain actors, technological standard, management commitment that lead to increased sustainability in an Industry 4.0 context. As a result, they provide a framework that presents the enabling factors for sustainable supply chains.

Birkel and Müller (2020) study the impact of Industry 4.0 on the TBL in the context of planning and sourcing, logistics and intralogistics, and recycling logistics. They mainly focus on Industry 4.0 as a whole, without considering technologies in detail. They show some, but few direct relations between technologies and sustainability: digital twin that enables visual design and simulation, supporting product and production design along the supply chain and helping in reducing quality and resource consumption; IoT that helps coordinate logistics operation to customer demand, in order to make the whole process more flexible; virtual and augmented reality and other assistance systems that support workers and reduce repetitive and dangerous tasks, leading to stress reduction and higher satisfaction. Further, the authors review advantages of Industry 4.0 for circular economy (closed-loop) and sustainability (economic & environmental) and some possible downsides e.g., resources, energy required for recycling. They highlight that especially additive manufacturing has some controversies; on the one hand, it limits waste and reduces logistics processes; on the other hand, the production process itself consumes more energy per produced part than a conventional process would.

Similar to the other two abovementioned reviews, Machado et al. (2020), view Industry 4.0 as an overall concept and do not focus on the specific technologies. They mention relations with some (sustainable) practices such as, additive manufacturing aiding circular economy, big data and analysis for predictive maintenance, IoT supporting product life-cycle management. Further, they cite some technologies and its impact on environmental sustainability, e.g., IoT and smart sensors/smart meters or simulations for more energy efficiency. Overall, they state that some technologies (e.g, horizontal and vertical integration, IoT, big data and analytics) are directly linked to environmental (resource and energy efficiency) and economic sustainability, but they do not review them in a comprehensive way.

Ejsmont et al. (2020) conduct a bibliometric network analysis and propose a framework that links “Industry 4.0 pillars”, such as digitalization, real-time data, IoT, CPS and big data to areas in which these could contribute to sustainability, such as manufacturing, product life cycle, supply chains and value chains, and circular economy. Further, they link the aforementioned technological pillars to the TBL, but with a few exceptions (IoT for resource efficiency) they do not link single technologies to it. Thus, they do not comprehensively cluster technologies and possible environmental and social performance impacts.

Similarly, Furstenau et al. (2020) identify several clusters in which Industry 4.0 and sustainability are linked, based on a bibliometric network analysis. The authors show that Industry 4.0 can largely enhance economic and environmental performance, for example support energy efficiency or renewable-energy and ensure quality in the food industry. Additionally, these clusters imply that Industry 4.0 can support sustainable practices such as recycling, circular economy, and maintenance. Here and there the authors relate technologies (such as additive manufacturing) to practices (such as recycling) that can reduce economic and environmental impacts (e.g. raw material consumption. time to market and production costs), but they do not comprehensively review sustainable outcomes in detail.

In an Industry 4.0 context, Ghobakhloo (2020) identify a set of sustainability functions related to Industry 4.0 adoption. (e.g., business

[1] We included in the table only comprehensive literature reviews on Industry 4.0 and sustainability and excluded reviews focused on: (1) specific Industry 4.0 technologies, such as the IoT (Manavalan, and Jayakrishna, 2019) and big data analytics (Ren et al., 2019); (2) specific company areas/activities, such as maintenance (Franciosi et al., 2018), remanufacturing (Kerin and Pham, 2019), and business processes (Zheng et al., 2020); or (3) reviews in specific industries/sectors such as the palm oil industry or the pharmaceutical sector (Lim et al., 2021; Ding, 2018).

Table 1
Other literature reviews and co-citation analyses on similar topics.

Research focus	Author(s) and year	Time horizon	Number of reviewed papers	Main journals	Keyword search – content analysis – framework	Main focus on
General	Bag et al. (2018)	2004–2017[a]	53	n.a.	Yes – Yes - No	Enablers for Supply Chain sustainability in Industry 4.0 context
General	Birkel and Müller (2020)	2011–2019	55	Sustainability, Procedia Manufacturing, Process Safety and Environmental Protection	Yes – Yes – No	Industry 4.0 Supply Chain impact (plan and source, logistics and intralogistics, recycling logistics) -
General	Ejsmont et al. (2020)	2011–04.2020	162	Engineering, Environmental Science, Energy	Yes – No (Citation Network Analysis)-Yes	Industry 4.0 impact on several sustainability issues
	Furstenau et al. (2020)	2010–03.2019	894	Sustainability, Journal of Cleaner Production, Energy	Yes – No (Bibliometric Performance and Network Analysis) - No	Industry 4.0 and 12 thematic sustainability clusters
General	Ghobakhloo (2020)	n.a.	72	n.a.	Yes – Yes – Yes (only on functions for sustainability)	Industry 4.0 functions for sustainability
General	Kamble et al. (2018)	2012–2017	85	n.a.	Yes – Yes – Yes	Industry 4.0 trends
General	Machado et al. (2020)	2008–2018[a]	35	Sustainability, Entrepreneurship and Sustainability Issues, Computers in Industry	Yes – Yes - Yes	I4.0 and sustainable manufacturing
Empirical (case studies)	Margherita and Braccini (2020)	2009–2019[a]	18	n.a.	Yes – Yes - No	Industry 4.0 & organizational impacts TBL

[a] Time horizon has not been defined for the search, represents papers found in those years.

model novelty and innovation, profitability improvement, carbon/-harmful gas emission, energy and resource sustainability, and human resource development), providing mainly economic indicators, in order to study how these might be related and interdependent. They rarely link Industry 4.0 and related technologies to environmental and social performance indicators, with few exceptions (e.g., AI and data analytics helping people with career paths or augmented virtual reality for safer and faster learning environments).

In contrast, Margherita and Braccini (2020), review only empi rical-based articles and show some direct relations between technologies and the TBL, mainly focusing on the economic dimension. Few examples show the impact of single technologies on the environment (CPS and big data for energy consumption reduction, CPS for less water consumption). Such as the other reviews, they do not systematically consider single technologies and impacts.

To sum up, previous reviews have viewed Industry 4.0 and sustainability from different angles (e.g., supply chain management/logistics, sustainable production, sustainable maintenance) and different levels of detail, but mainly focusing on the concept Industry 4.0 in the context of sustainability and not on its underlying technologies. The aim of this paper is to extend existing knowledge and propose a framework that links, not only Industry overall concept but also single technologies to sustainability performance. Even though other reviews present a considerable number of aspects/performance outcomes relevant to sustainability, this study covers additional performance indicators and factors such as sustainable practices (e.g., periodic sustainable supplier evaluation, green consumer education) and moderating factors (e.g., environmental dynamism) that previous reviews have not covered and that contribute to the understanding of Industry 4.0 and sustainability. Further, this review includes more recent papers, published in 2020. See also Section 6.3 for further insides on the originality of our review.

3. Research methodology

This study uses a thematic systematic literature review (SLR). SLR is a replicable scientific process using criterion-based selection and analyses of published studies (Cook et al., 1997; Tranfield et al., 2003). It identifies homogeneity or heterogeneity within studies (Kitchenham, 2004); enabling an evidence-based summary of research investigations (Cook et al., 1997). We use the methodology recommended by (Kitchenham, 2004) and Higgins and Green (2011); outlined below.

3.1. Research question

We define the scope of the study and the research questions. The aim of this research is to evaluate literature defined interrelations between Industry 4.0 and sustainability. The research questions posited for this study is reciprocative between the two dimensions. *How does Industry 4.0 affect company sustainability practices and performance? How do sustainability goals affect Industry 4.0 adoption?*

3.2. Search strategy

To identify the studies relevant for the thematic review, we conducted a keyword search using Elsevier's Scopus data base. Considering the multi-faceted, wide ranging Industry 4.0 applications, no restrictions in the disciplinary scope of the journals were applied. Two sets of keywords set the stage for the search. One set is related to Industry 4.0; the other to sustainability – see below. Industry 4.0-related keywords have been drawn from previous literature reviews on Industry 4.0, in particular Kamble et al. (2018) and Culot et al. (2020), while sustainability-related keywords have been drawn from Seuring and Müller (2008). The keyword search includes publication keywords, title and abstract.

Industry 4.0-related-keywords ("Industry 4.0" OR "Smart Manufacturing" OR "Smart Production" OR "Cloud Manufacturing" OR

"Cloud Computing" OR "Smart Factory" OR "fourth industrial revolution" OR "4th industrial revolution" OR "Cyber-Physical System" OR "Artificial Intelligence" OR "Internet of Things" OR "Industrial Automation" OR "Smart Operations Management" OR "Smart Supply Chain" OR "Cyber-Physical Production System" OR "Intelligent Manufacturing" OR "Digital twin").

Sustainability-related-keywords (Sustainability OR Sustainable OR Green OR "Environmental Performance" OR "Social Performance").

The study time frame is the period January 2011 to December 2020. The Industry 4.0 paradigm originated in 2011 (Kagermann et al., 2011).

Only English language papers were included. We excluded conference papers, conference reviews, editorials and book chapters, as often done by literature surveys (e.g., Jia et al., 2015; Kamble et al., 2018). Consistent with previous studies (Gunasekaran et al., 2015; Centobelli et al., 2017), we controlled for publication quality by including only peer reviewed publications (Jefferson et al., 2002).

3.3. Study selection

A total number of 4645 contributions result from the search. Removing articles with non-coherent abstracts – for example papers that do not primarily focus on Industry 4.0 and social and environmental sustainability, thus that exclusively focus on economic performance, or that discuss Industry 4.0 (and synonyms such as digitalization, IIoT) and sustainability independently or related to very narrow technologic focus – left 269 studies in the data set.

Analysis of the full text results in 117 publications that fit well within the scope of this study. In cases of inclusion uncertainties, a discussion amongst the research team guided the final inclusion decision. A graphical summary of the process and the number of publications identified in each step appears in Fig. 1.

3.4. Data extraction and synthesis

We perform descriptive and content analyses of the data set. The main descriptive analysis dimensions as proposed by previous studies (e.g. Sartor et al., 2016) include: authors; publication distribution over time; publication distribution amongst journals; publication distribution by research focus – exploratory, theory building or theory testing; and publication distribution by methodology – literature review, conceptual paper, case study, survey, expert interviews, experiment, or secondary data.

The content analysis methodology relies on (Seuring and Gold, 2012). We began with a deductive approach and based our preliminary analysis on a framework of sustainability performance (Global Reporting Initiative, 2018) and sustainability practices (Rajeev et al., 2017). The categories are refined using an inductive approach resulting in the following clusters:

(1) Industry 4.0 and sustainability practices;
(2) Industry 4.0 and sustainability performance (such as energy/material consumption, emissions, waste, labour practices, human rights, productivity and profitability);
(3) Industry 4.0, sustainability practices and sustainability performance; and
(4) Factors moderating the relationship between Industry 4.0 and sustainability performance.

For each cluster, we identify a set of specific findings summarized in Tables 3–6. For cluster 2 we display potential positive (+) and negative (−) effects of Industry 4.0 technologies on sustainability performance. Positive effects mean that the society and the environment benefit from Industry 4.0 technology adoption, whereas negative impacts indicate the opposite, i.e., decreasing sustainability (see Table 4).

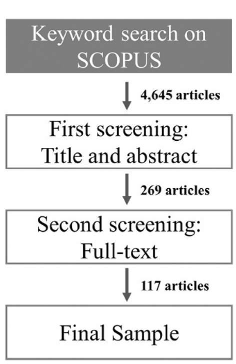

Fig. 1. Study selection process.

4. Descriptive findings

Table 2 and Fig. 2 describe the publications set. Publication distribution over time, across journals, by research focus, and by methodology appear in summary.

During the study time frame (2011–2020) an average of 11.7 articles per year with an increasing trend – peaking in 2020 with 37 studies – appears. This trend can be associated to the fact that Industry 4.0 and sustainability are both gaining momentum in the academic, managerial and policy debate.

Most of the studies – about 86% – are exploratory. Only 6% are chiefly theory building and another 8% test theory. The novelty of the research topic plays a role in this distribution.

Methodologically, approximately 33% of the studies are conceptual, 15% use surveys, and 21% case studies. The remaining studies rely on other expert interviews, simulation, experiments, modelling and secondary data – see Fig. 2.

The studies are widely distributed amongst various journals. There is fragmentation across thematic areas – engineering, technological and social change, strategy, and operations management.

The journal with most related studies – see Table 2 – is *Sustainability* with 26 studies. The *Journal of Cleaner Production* follows a distance

Table 2
Distribution of publications amongst journals.

Name of the journal	#papers
Sustainability	26
Journal of Cleaner Production	14
International Journal of Production Research	6
Computers and Industrial Engineering	6
Resources, Conservation and Recycling	4
International Journal of Production Economics	3
Process Safety and Environmental Protection	3
Technological Forecasting and Social Change	3
International Journal of Precision Engineering and Manufacturing - Green Technology	3
Benchmarking: An International Journal	2
Computers in Industry	2
IFAC-PapersOnLine	2
International Journal of Supply Chain Management	2
Production Planning and Control	2
Others (1 per journal)	39

Table 3
Industry 4.0 and sustainability practices.

		Sustainability Practices.						
		Sustainable Production	*Sustainable Purchasing*	*Sustainable performance measurement and management*	*Closed loop supply chain*	*Sustainable governance*	*Sustainable Marketing*	*Eco-Design*
Industry 4.0 Technology	Cloud Computing	Watanabe et al. (2016)		Tiwari and Khan, (2020); Xing et al., (2016)	de Sousa Jabbour et al., (2018a)	Truong and Dustdar (2012)	Tu et al. (2017)	
	Internet of Things	Ardanza et al. (2019)	Tozanlı et al. (2020)		de Sousa Jabbour et al., (2018a); Bressanelli et al. (2018); Kerdlap et al. (2019); Pham et al. (2019)			
	Additive manufacturing				de Sousa Jabbour et al., (2018a); Turner et al. (2019)			
	Big Data				Jabbour et al. (2019)			
	Cyber-Physical System	Watanabe et al. (2016)		Mörth et al. (2020)				
	Artificial Intelligence			Allaoui et al. (2019)				
	Blockchain		Tozanlı et al. (2020)	Zhang et al. (2020)				
	Human-robot collaboration	Liu et al. (2019)						
	Technological generics	Yadav et al. (2020a)	Ghadimi et al. (2019)	Qian et al. (2017) Gu et al., (2018); Yadav et al. (2020b)	de Sousa Jabbour et al. (2018a); Gu et al., (2018); Chauhan et al. (2019); Rajput and Singh (2019)			Gu et al., (2018)

behind with 14 studies. Both journals are transdisciplinary with a strong sustainability focus.

The *Sustainability* journal studies focus on global systems developments and resulting implications for environmental and social sustainability. They also measure and monitor sustainability in the Industry 4.0 context. The *Journal of Cleaner Production* studies are relatively prescriptive; proposing solutions and practices for improving environmental sustainability.

5. Thematic findings

In this section we present the main thematic findings of this study.

5.1. Industry 4.0 and sustainability practices

The initial conceptualization of the reviewed studies is across two dimensions, Industry 4.0 technologies and sustainability practices, as summarized in Table 3. Sustainability practices are classified into seven main categories: sustainable production, sustainable purchasing, sustainable performance measurement and management, closed loop supply chain, sustainable governance, sustainable marketing and sustainable design (Rajeev et al., 2017). Industry 4.0 technologies considered in this study include the IoT, CPS, robots/human robot collaboration, additive manufacturing, AI, big data (and analytics), cloud computing, augmented reality and blockchain technology (European Commission, 2018; Masood and Egger, 2019; Miller, 2018).

The preponderance of studies considers only specific technologies and sustainability practices. CPS and cloud computing (Watanabe et al., 2016) have been conceptually argued to support actions of *sustainable production.* One of the advantages purported was for quantitatively and qualitatively monitoring production system sustainability performance. The use of sensors has been mentioned for information acquisition. IoT is also strongly linked to information gathering for a sustainable production (Ardanza et al., 2019). Similarly, the use of human-collaborative robots has potential benefits for sustainable manufacturing, since collaborative robots can detect the proximity of humans and reduce the safety risk to them (Liu et al., 2019).

There have been arguments for Industry 4.0 supporting better decision-making, information and data sharing process to facilitate *sustainable purchasing* (Ghadimi et al., 2019). Interconnection and real-time information transparency for periodic sustainable supplier evaluation is a basis for improving this activity. For example, the use of intelligent IoT based products and blockchain-enabled supply chains might support sustainable purchasing through assisting better informed acquisition decisions (Tozanlı et al., 2020).

Industry 4.0-based actions and instruments can strengthen *sustainable performance measurement and management* (Xing et al., 2016; Qian et al., 2017; Yadav et al., 2020b), e.g., through the support of AI tools (Allaoui et al., 2019). Cloud-based platforms can collect life-cycle data and share information among supply chain members. This sharing can enable flexible and responsive product life-cycle assessment. Also, blockchain-based life-cycle assessments can help in tackling supply chain data, by integrating other smart technologies, such as IoT and big data (Zhang et al., 2020). Similarly, CPS can be used for performance monitoring in intralogistics (Mörth et al., 2020). Further, a cloud-based Industry 4.0 framework can enhance sustainability performance measurement by supporting reporting activities (Tiwari and Khan, 2020).

Industry 4.0 can facilitate information sharing among supply chain members for *closed loop supply chain* activities (Gu et al., 2018). The closed loop perspective has also been extended to circular economic principles. Some papers focus on studying the technological benefits and barriers of Industry 4.0 for a circular economy (Chauhan et al., 2019; Rajput and Singh, 2019). Industry 4.0 – specifically big data capabilities – can theoretically and arguably support the ReSOLVE model of a circular economy (de Sousa Jabbour et al., 2018a; Jabbour et al., 2019). The ReSOLVE model including the business model development strategies: regenerate, share, optimize, loop, virtualize and exchange, benefits from multiple Industry 4.0-technologies; furthering to reach a more sustainable decision-making in operations management. IoT has also been emphasized to help develop a path towards the circular economy

Table 4
Industry 4.0 and sustainability performance.

		Environmental Performance							
		Resource Consumption						Emissions	Waste
		Materials			Energy		Water	Emissions	Effluents and Waste
		Materials used	Recycled materials used	Consumption of toxic materials	Energy consumption	Renewable energy used			
Industry 4.0 Technology	Cloud Computing	(+) Schniederjans and Hales (2016)		(+) Schniederjans and Hales (2016)	(+) Isaias (2015)				(+) Schniederjans and Hales (2016); (+) Li et al. (2020a)
	Internet of Things	(+) Kiel et al. (2017); (+) Bressanelli et al. (2018); (+) Müller and Voigt (2018)	(+) Bressanelli et al. (2018)		(+) Kiel *et al.* (2017); (+) Beier et al. (2018); (±) Bonilla et al. (2018); (+) Bressanelli et al. (2018); (+) Müller and Voigt (2018)				(+) Jagtap et al. (2019)
	Cyber-Physical System				(±) Bonilla et al. (2018); (+) Liang et al. (2018); (+) Schulze et al. (2019)		(+) Schulze et al. (2019)		
	Additive manufacturing	(±) Ford and Despeisse (2016)			(±) Ford and Despeisse (2016); (+) Bonilla et al. (2018)				
	Big Data	(+) Bressanelli et al. (2018)	(+) Bressanelli et al. (2018)		(+) Bressanelli et al. (2018); (+) Liang et al. (2018)		(+) Braccini and Margherita (2018)		(+) Lin et al. (2020)
	Artificial Intelligence				(+) Fisher (2011); (±) Vinuesa et al. (2020)	(+) Vinuesa et al. (2020)	(±) Vinuesa et al. (2020)		
	Technological generics	(+) Beier et al. (2017); (±) Bonilla et al. (2018); (±) Stock et al. (2018); (+) Braccini and Margherita (2018); (+) Ahmad et al. (2020)	(+) Stock et al. (2018) (+) Braccini and Margherita (2018); (+) Pasi et al. (2020)	(+) Kamble et al. (2019)	(+) Beier et al. (2017); (±) Bonilla et al. (2018); (±) Stock et al. (2018); (+) Braccini and Margherita (2018); (+) Munsamy et al. (2019); (−) Birkel et al. (2019); (+) Mohamed et al. (2019); (+) Ahmad et al. (2020); (+) Pasi et al. (2020)	(+) Beier et al. (2017); (0) Stock et al. (2018); (+) Braccini and Margherita (2018)	(0/+) Stock et al. (2018); (+) Braccini and Margherita (2018)	(+) Davidsson et al. (2016); (0) Stock et al. (2018); (+) Kamble et al. (2019); (+) Munsamy et al. (2019); (−) Birkel et al. (2019); (+) Pasi et al. (2020)	(−) Bonilla et al. (2018); (+) Stock et al. (2018); (+) Braccini and Margherita (2018); Kamble et al. (2019); Li et al. (2020b); Nåfors et al. (2020); (+) Pasi et al. (2020)

		Social Performance					
		Labour Practices and Decent Work			Human Rights and Society		
		Wages and Working conditions	*Employment*	*Occupational Health and Safety*	*Ethics, Privacy and Personal Autonomy*	*Non-discrimination*	*Societal Health and Safety*
Industry 4.0 Technology	Cloud Computing				(−) Isaias (2015)		(−) Isaias (2015)
	Big Data	(+) Venkatesch et al. (2020)		(+) Venkatesch et al. (2020)	(−) Sugiyama et al. (2017)		
	Internet of Things	(+) Kiel et al. (2017); (±) Bremer (2015); (+) Venkatesch et al. (2020); (+) Müller and Voigt (2018)	(+) Kiel et al. (2017); (±) Bremer (2015); (−) Müller and Voigt (2018)	(+) Kiel et al. (2017); (+) Venkatesch et al. (2020)			
	Blockchain	(+) Venkatesch et al. (2020)		(+) Venkatesch et al. (2020)			
	Artificial Intelligence					(±) Vinuesa et al. (2020)	(±) Vinuesa et al. (2020)
	Augmented Reality			(+) Damiani et al. (2020)			
	Human-robot collaboration			(+) Gualtieri et al. (2020)			
	Technological generics	(+/0/-) Beier et al. (2017); (+) Stock et al. (2018);		(+/0/-) Beier et al. (2017); (+) Braccini and Margherita (2018);	(−) Sugiyama et al. (2017)	(+) Davidsson et al. (2016);	(+) Davidsson et al. (2016);

Table 4 (*continued*)

Social Performance						
	Labour Practices and Decent Work			Human Rights and Society		
	Wages and Working conditions	*Employment*	*Occupational Health and Safety*	*Ethics, Privacy and Personal Autonomy*	*Non-discrimination*	*Societal Health and Safety*
	(+) Nagy et al. (2018); (+) Braccini and Margherita (2018); (−) Birkel et al. (2019); (+) Cagliano et al. (2019); (−) Coldwell (2019); (+) Kamble et al. (2019); (0) Nam (2019)	(±) Beier et al. (2017); (−) Birkel et al. (2019); (0) Nam (2019); (+) Pasi et al. (2020)	(+) Kamble et al., (2019); (+) Pasi et al. (2020)		(−) Sugiyama et al. (2017)	(0) Stock et al. (2018)

		Economic Performance.						
		Profitability	Productivity	Efficiency	Costs	Quality	Flexibility	Revenue
Industry 4.0 Technology	Cloud Computing				(+) Schniederjans and Hales (2016)			
	Big data			(+) Lin et al. (2020)				
	Cyber-Physical System	(+) Watanabe et al. (2016)	(+) Watanabe et al. (2016)					
	Internet of Things	(±) Kiel et al. (2017)	(+) Nagy et al. (2018)	(+) Shrouf and Miragliotta (2015); (+) Müller and Voigt (2018)	(+) Bressanelli et al. (2018)		(+) Kiel et al. (2017)	(+) Müller and Voigt (2018)
	Additive manufacturing							(+) Ford and Despeisse (2016)
	Human-robot collaboration		(+) Gualtieri et al. (2020)					
	Technological generics	(±) Müller et al. (2018)	(+) Braccini and Margherita (2018); (+) Ahmad et al. (2020); (+) Pasi et al. (2020)	(+) Stock et al. (2018); (+) Horváthová et al. (2019); (+) Nouiri et al. (2019); (+) Pasi et al. (2020)	(+) Beier et al. (2017); (+) Nouiri et al. (2019); (+) Li et al. (2020a); (+) Ahmad et al. (2020); (+) Pinzone et al. (2020)	(+) Braccini and Margherita (2018); (+) Ahmad et al. (2020) (+) Pinzone et al. (2020)	(+) Stock et al. (2018); (+) Pinzone et al. (2020)	(+) Ahmad et al. (2020)

Table 5
Industry 4.0, sustainability practices and sustainability performance.

Industry 4.0 Technology	Sustainability Performance	Sustainability practices: Sustainable Production	Sustainable Maintenance	Sustainable performance measurement	Closed loop supply chain	Sustainable governance
Internet of Things	***Energy***	Shrouf and Miragliotta (2015); Ma *et al.* (2019);				
	Material				Mastos *et al.*, 2020	
	Waste				Mastos *et al.*, 2020	
	Emissions	Liao and Wang (2019);				
Big Data	***Energy***	Ma *et al.* (2019); Ren *et al.* (2019)			Strandhagen *et al.* (2017)	
	Emissions	Munodawafa and Johl (2019)			Strandhagen *et al.* (2017)	
	Waste	Ren *et al.* (2019)			Strandhagen *et al.* (2017) Belaud et al. (2019)	
Artificial Intelligence	***Energy***	Wang *et al.* (2019)		Främling *et al.* (2018)		Milano *et al.* (2014)
	Material					
	Emissions			Främling *et al.* (2018)		Milano *et al.* (2014)
Cyber-Physical System	***Energy***	Nouiri *et al.* (2019); Ma *et al.* (2019)				
Technological generics	***Employment and working conditions***	Matt *et al.* (2020); Mattsson *et al.* (2020); Rauch *et al.* (2017); Kamble *et al.* (2019);				
	Waste	Kamble *et al.* (2019); Jena et al. (2020); Fisher *et al.* (2020)	Johansson *et al.* (2019)		Strandhagen *et al.* (2017)	
	Energy	Jena *et al.* (2020); Fisher *et al.* (2020); Ma *et al.* (2020)			Kristoffersen *et al.* (2020); Meng *et al.* (2020);	
	Water	Jena *et al.* (2020)				
	Material	Fisher *et al.* (2020)	Johansson *et al.* (2019)		Kristoffersen *et al.* (2020)	
	Emissions				Dev et al. (2020)	
	Productivity				Kristoffersen *et al.* (2020)	

and closed loop supply chains (Bressanelli et al., 2018; Pham et al., 2019), especially supporting the concept of zero waste manufacturing (Kerdlap et al., 2019). IoT can provide real-time product information – usage or location data – enabling product end-of-life activities to support refurbishment or recycling activities. Other authors study additive manufacturing and the use of digital product data that enable a flexible and geographically distributed manufacturing and sustain the path towards sustainable and circular production (Turner et al., 2019).

While most studies examine possible Industry 4.0 and sustainability interrelations on an organizational or inter-organizational level, there are other levels of analysis that have been discussed. Cloud computing can help *sustainable governance* of facilities such as buildings, homes, cars and equipment (Truong and Dustdar, 2012). Sustainable governance can be supported by data from digital monitoring and shared within a complex system of stakeholders. This information needs techniques to manage large amounts of data. Other technical approaches can be used to effectively support policy decision making, an important aspect of *sustainable governance* (Milano et al., 2017). AI is another supportive element to integrate Industry 4.0 technologies into this governance.

IoT can greatly affect *sustainable marketing* (Tu et al., 2017). IoT can lead consumers to more sustainable purchase decisions and can support actions of green marketing. IoT can also be a suitable instrument for green consumer education.

Further, Industry 4.0 can improve *eco-design.* Information sharing among stakeholders and data exchanges during the development and manufacturing phases can indeed provide required data to make products and production processes more sustainable and environmental friendly (Gu et al., 2018).

Overall, these studies conceptually or empirically show the relationships. Many of the studies are conceptual as some of the technologies do not currently have the capabilities to fully address the sustainability concerns, requiring their further development and integration.

5.2. Industry 4.0 and sustainability performance

The literature analysis revealed two main trends. First is Industry 4.0 relating to sustainability performance. Second is sustainability as an antecedent for Industry 4.0 adoption.

A summary of Industry 4.0 and sustainable performance relationship investigations appear in Table 4. The sustainability performance categories for both environmental and social impact are from the global reporting initiative (GRI) standards. These environmental performance categories include resources – materials, energy and water – consumption, emissions, and waste. The social performance categories are instead labour practices and decent work and human rights and society (Global Reporting Initiative, 2018). Finally, economic sustainability performance categories are based on previous studies (Silveira, 2002; Grünberg, 2004): cost, quality, flexibility, productivity, revenue, and profitability.

Emergent investigations have sought to study positive and negative impacts of Industry 4.0 on sustainability performance (Bai et al., 2020; Kamble et al., 2019; Strandhagen et al., 2020). These include potential savings in resource consumption (i.e. material, energy, water and effluents) and waste management (Schniederjans and Hales, 2016; Beier et al., 2017; Kiel et al., 2017). Other studies have found improvements in employment (Stock et al., 2018). Other studies attribute possible negative environmental and social consequences from Industry 4.0 technology implementation (Bonilla et al., 2018; Bremer, 2015), see Table 3.

Many studies highlight Industry 4.0 opportunities for **resource consumption** improvement from optimization and real-time production control. Industry 4.0 technologies can facilitate efficient planning and avoid overproduction and decrease the *materials used* through improved production processes (Stock et al., 2018).

Industries set high expectations for Industry 4.0 as an opportunity to gain material savings and to improve material efficiency (Beier et al., 2017). Reviewed studies confirm for instance that IoT is expected to increase material efficiency (Beier et al., 2018; Müller and Voigt, 2018). However, they do not highlight how this efficiency can be increased. It can be assumed that the IoT-ability to monitor entire networks and to integrate in real-time with suppliers and customers (see a review by

Manavalan and Jayakrishna, 2019 for IoT attributes) helps to manage resources along the supply chain and to increase efficiency. As examples, we can think of a better coordination of material in the purchasing process or the reduction of overproduction through on-time availability of customer information.

Additive manufacturing promises environmentally sustainable benefits. Savings in *material use* occur due to extended product lifecycles resulting from product design, recycling, upcycling of waste into products (Ford and Despeisse, 2016). IoT and Big Data aid relevant product information monitoring throughout a product lifecycle (Bressanelli et al., 2018). Digital elements within a product can be easily replaced – such as through software upgrading. This updating reduces material consumption and facilitates material recycling. However, with regards to raw material consumption Zhang et al. (2019) suggest that Industry 4.0 might not have a substantial impact on the overall environmental performance of its products. In this context cloud computing is positively associated with reducing the *consumption* of *toxic materials*. Data-driven real-time support can increase the usage of environmentally friendly materials (Schniederjans and Hales, 2016).

Some studies analyse the impact of Industry 4.0 adoption on company's *energy consumption* (Munsamy et al., 2019). Industry 4.0 technologies might indeed support the collection and analysis of useful information on the energy consumption, allowing for instance to better manage the energy consumption in manufacturing (Mohamed et al., 2019). CPS, Big data analytics and intelligent learning can for instance be applied for energy-efficient machining optimization and scheduling in production (Liang et al., 2018). CPS and Big data can also aid in systematically changing system parameters (such as pump speed) to better control energy consumption (Schulze et al., 2019). Overall, we found that processes optimized through big data and AI can lead to significant savings in energy, contributing to environmental sustainability (Fisher, 2011; Bonilla et al., 2018; Vinuesa et al., 2020). Further, the interconnection ability of IoT is expected to increase energy efficiency (Müller and Voigt, 2018). Data collected by IoT and Big Data may provide relevant user instructions in the usage phase to reduce energy consumption of products (Bressanelli et al., 2018). Additive manufacturing can reduce *energy consumption* through reduced physical transport and logistics processes (Ford and Despeisse, 2016; Bonilla et al., 2018). Some studies argue that integration of digitalization – big data and analytics, IoT and CPS – may lead to an increased share of *renewable energy used* to satisfy the increasing energy consumption. This greater renewable energy sourcing might be due to cost savings (Beier et al., 2017) or improved traceability of energy sources within life cycles (Bonilla et al., 2018; Stock et al., 2018). Similarly, AI can support the integration of renewable energy sources (Vinuesa et al., 2020).

Some studies suggest that the integration of Industry 4.0 technologies might have no effect on *water consumption* and *water quality* (Stock et al., 2018). Others highlight both positive impacts of Industry 4.0 (Braccini and Margherita, 2018) or specific technologies (i.e., AI; Goralski and Tan (2020); Vinuesa et al. (2020)) and negative impacts (Vinuesa et al., 2020) on water quality. However, simulations found that Industry 4.0 can support water quality by monitoring it through CPS and Big data technologies. CPS and Big data also have the potential to reduce water demand in manufacturing by systematically changing operational control strategies (Schulze et al., 2019).

Other studies find Industry 4.0 technologies link to lower **emissions** and air pollution. For example, digital technologies can benefit public transport efficient operational and strategic planning; directly or indirectly reducing emissions (Davidsson et al., 2016). Other investigations tested or simulated AI applications and demonstrate decrease in air pollution (Nasir et al., 2014; Haass et al., 2015; Tunckaya and Koklukaya, 2015).

Data tracking and product monitoring can support recycling, reuse, the reduction of resources used, and decrease the overall **waste** production of a product (Bonilla et al., 2018; Stock et al., 2018; Li et al., 2020). Bonilla et al. (2018) argue that additive manufacturing is positively impacting the amount of waste produced, i.e. by contributing to customized products. In this context cloud computing is also positively associated with the reduction of solid waste. Cloud computing can enhance on-demand information access and collaboration which can reduce waste by better understanding of the consumer market (Schniederjans and Hales, 2016). The IoT technology is also proposed to monitor the overall amount of waste, e.g., in the food supply chains (Jagtap et al., 2019). Other authors have identified that virtual technologies with simulation of production systems, the so called "digital twin", can decrease waste by avoiding unnecessary displacements (Nåfors et al., 2020). In another way, big data analytics could reduce waste and obtain a higher production line efficiency through forecasting and analysis within the production line (Lin et al., 2020).

These technologies can also have negative environmental consequences (Bonilla et al., 2018; Stock et al., 2018). The deployment phase is especially associated with resource consumption increases. The production of electronic devices for CPS, smart products and robots raises equipment and devices demand. *Material* – many times scarce raw materials – *energy use,* and *waste production* increases. Operations in this environment use or generate significant data. Large data centres that collect and analyse this data are needed. The overall computational effort and hence the energy demand are likely to increase for this big data management situation. Other Industry 4.0 technologies such as AI or additive manufacturing will likely increase energy consumption, when compared to traditional manufacturing processes (Bonilla et al., 2018; Stock et al., 2018; Vinuesa et al., 2020).

Social sustainability includes investigations with empirical studies who see changes in **labour practices and decent work.** *Employment* (number of jobs), *working conditions and wages* and *occupational health and safety* were major work based investigations (Kiel et al., 2017; Bremer, 2015; Stock et al., 2018; Beier et al., 2017).

Studies agree that low skill jobs are likely to be replaced by automation. Three main trends are expected (Bremer, 2015; Stock et al., 2018). First, manual routine activities with high human stress levels will reduce. Automated processes are likely to replace simple tasks and affect *employment* and *working conditions* of less skilled employees. Second, more skilled workers will be employed to manage automated processes. Third, new tasks will emerge for low skill workers from intelligent assistance systems. In employment areas, it is likely that more jobs are created in research and development and less in production and assembly (Beier et al., 2017). Simplified processes – related to IoT and automation – provide benefits in working conditions (Müller and Voigt, 2018; Kiel et al., 2017), i.e. reduce psychological stress and enhance the workers well-being (Pinzone et al., 2020). Furthermore, Industry 4.0 implementation might provide workers with more autonomy in performing the tasks and increase their social interactions (Cagliano et al., 2019). Through the application of technologies i.e. blockchain, big data and IoT, labour related issues including appropriate working conditions, wages, and equity, companies' actions can be traced to prevent the abuse of those (Venkatesh et al., 2020). In some cases, Industry 4.0 could however also lead to problems of mental health or to an unhealthy work/life balance (Coldwell, 2019). For example, employees fear of losing their job (Pasi et al., 2020).

On the other hand, the integration of Industry 4.0 technologies (in particular blockchain, IoT and big data analytics) can have a positive impact on health and safety in the workplace, due to improved traceability in the supply chain (Venkatesh et al., 2020). Furthermore, the adoption of such technologies can substitute heavy manual work, reducing the risk of injuring and increasing the *occupational health and safety* (Braccini and Margherita, 2018; Pasi et al., 2020). For example, human robot collaborations can support worker's ergonomically and prevent posture problems (Gualtieri et al., 2020). Another Industry 4.0 technology that can contribute to work safety improvement is augmented reality (Damiani et al., 2020). It can provide workers with additional information—such as dangerous areas or dangerous actions—to improve work safety. In sum, the literature posits that there will be some changes in working conditions and employment, it is however not clear whether these will be positive or negative changes and how the theoretical concepts of individual technologies can be measured and applied (Nam, 2019).

Other studies relate Industry 4.0 – in particular cloud computing – to concerns about **human rights and society.** Technologies will increase *ethics, privacy and personal autonomy issues* (Gill, 2016; Isaias, 2015). Big data is creating ethical concerns, especially in the definition of AI (machine learning) algorithms (Gill, 2016). Concerns of digitalization require a redefinition of human ethics and norms. The loss of privacy and the loss of personal autonomy – making autonomous choices and not to be subjected to arbitrary restrictions – are potential big data and cloud outcomes (Sugiyama et al., 2017). Another controversial subject is the AI (Vinuesa et al., 2020); authors claim that society could potentially benefit from technologies based on AI, e.g., these technologies might support *non-discrimination* and improve *societal health and safety*. However, they can also inhibit the achievement of social sustainability; uncritically trained algorithms could in fact increase discrimination.

In some areas – such as public transport – Industry 4.0 developments relate to other positive *societal health and safety* impacts (Davidsson et al., 2016). It may also lead to increased public transport accessibility improving social equity. Accessibility allows some social groups such as elderly or disabled people to increase their participation in social life; social inclusion increases.

Some studies discuss the potential effects of Industry 4.0 technologies on firm economic and business performance. Although Industry 4.0 technology adoption poses uncertain economic risks and profitability requires careful evaluation (Kiel et al., 2017; Müller et al., 2018), Industry 4.0 is expected to increase the economic *profitability* of companies through more efficient use of resources and processes (Watanabe et al., 2016). Cyber physical production technologies may increase the *efficiency* of various activities, such as the materials selection (Horváthová et al., 2019), material reuse and recycling (Stock et al., 2018; Pasi et al., 2020), and energy management by real-time monitoring of energy consumption (Shrouf and Miragliotta, 2015; Nouiri et al., 2019).

IoT enables the interchange of real-time information within and across companies to continuously monitor physical processes that may significantly impact *productivity* (Nagy et al., 2018). Similarly, other technologies such as CPS might be implemented to increase productivity (Watanabe et al., 2016), e.g., through human-robot collaboration that increases production performance (Gualtieri et al., 2020). Several studies refer to *cost* reductions from Industry 4.0 associated with product life cycle management improvements (Nouiri et al.,2019; Li et al., 2020). Virtual technologies such as *digital twins* integrate multiple forms of information into a cloud system—such as user-related, product-related, and logistics service information—which can help map physical processes and gain closed-loop feedback. This information can not only improve the customer experience related to products and services, but also reduce resource wastes and reduce costs (Bressanelli et al., 2018; Li et al., 2020b). Costs might also be reduced through production optimization and resulting resource savings (Beier et al., 2017). For example, cloud computing can reduce energy use and operating costs (Schniederjans and Hales, 2016). Real-time data can enhance decision-making and tracking technologies such as RFID can facilitate logistics and decrease supply chain costs (Ahmad et al., 2020).

Besides a potential cost efficiency gain, Industry 4.0 technologies can have a positive impact on time efficiency and on process *flexibility* and *quality* (Braccini and Margherita, 2018; Pinzone et al., 2020). For example, additive manufacturing techniques influence maintenance and logistics while contributing to flexibility necessary for on-demand customized products (Stock et al., 2018). Similarly, IoT offers increased product customization (Kiel et al., 2017). Finally adopting a make-to-order strategy, Industry 4.0 technologies, such as IoT (Müller and Voigt, 2018) or additive manufacturing, can help improve revenue (cash) flows, i.e. when products are purchased by customers before being produced (Ford and Despeisse, 2016).

Few studies investigate the reverse relation, namely sustainability as an antecedent for Industry 4.0 adoption. Sustainability pressures pose a great challenge for manufacturers. Elements of the factory of the future – such as cloud production can overcome this challenge (Herrmann et al., 2014). An initial investigation has shown sustainability as a driver for Industry 4.0 implementation (Müller et al., 2018). Operational, social and environmental benefits associated with Industry 4.0 act as antecedents for Industry 4.0 adoption in some companies. Alternatively, it has been found that environmental pressure is not considered among the key motivation for the adoption of big data in companies (Wang et al., 2018). Scholars have found that companies are sometimes unaware of environmental benefits of Industry 4.0 (Brozzi et al., 2020) It seems that in some cases the relationship between environmentally green objectives and Industry 4.0 technologies is not perceived as strong (Chiarini et al., 2020).

Even with very early mixed results it is difficult to conclude whether sustainability is a strong antecedent for Industry 4.0 adoption. It is an area ripe for investigation.

5.3. Industry 4.0, sustainability practices and sustainability performance

Some publications explore how Industry 4.0 influences sustainability practices and the resulting effect on sustainability performance – see Table 5 for a summary. Recent investigations conceptually discuss how Industry 4.0 supports *socially sustainable production*; with a presumed result on sustainability performance. Various aspects and approaches are used in these investigations. Cognitive automation as a *sustainable production* strategy supporting Industry 4.0 operators in complex assembly have been proposed to reduce negative *working conditions* such as stress (Mattsson et al., 2020). How sustainable production such as urban production[2] mediates Industry 4.0 influence on employees and the labour market has also been investigated (Matt et al., 2020). Urban production can lead to improved working conditions for qualified workers through appropriate working models and flexible working hours to support worker well-being and equal opportunity.

On the other hand, publications discuss how Industry 4.0 enhances not only social, but also *environmentally sustainable production*, and has a positive impact on sustainability (Machado et al., 2020), e.g., decreasing *waste* production, *energy, material* and *water* consumption (Fisher et al., 2018; Jena et al., 2020). It has been argued that digitalization could support sustainable production through direct or decentralized manufacturing (Rauch et al., 2017). For example, cloud computing can incorporate collaboration with customers in the product development process; and additive manufacturing can replace the transport of physical products with virtual data-transfer through decentralized production units. Algorithms based on AI can optimize energy consumption in production by calculating the consumption of machining operations (Wang et al., 2019). Other Industry 4.0 technologies, such as IoT, CPS and big data analytics can provide new solutions to increase *energy* efficiency in production (Ma et al., 2019; Nouriri et al., 2019). For example, Industry 4.0 enabled real-time monitoring can make production environments more energy efficient (Ma et al., 2020).

Especially big data analytics are considered a key technology to achieve a more environmentally sustainable production by reducing, energy consumption, but also waste production and hence increase the sustainability, due to its capacity to process useful information (Ren et al., 2019). Big data is also referred to cleaner production through eco-innovation and to the potential in decreasing CO_2 *emissions* (Munodawafa and Johl, 2019).

Research has shown that IoT can be used for manufacturing *energy* management for energy savings and energy control (Shrouf and Miragliotta, 2015). Smart sensors and smart meter technology linked to IoT can support these sustainable production strategies. They can inform optimizing production schedules, decision-making in selecting energy efficient production machines, and benchmarking energy consumption for processes. Adopting energy management practices and integrating energy data into process design can reduce energy consumption and the

[2] Production sites reintegrated into cities in a sustainable way (Matt et al., 2020).

carbon footprint. Furthermore, IoT and CPS are used to address energy-efficient production to reduce the energy use and contribute to product life-cycle management (Nouiri et al., 2019). IoT can help reducing carbon emissions through more efficiency in production and logistics (Liao and Wang, 2019).

Kamble et al. suggest another indirect effect of Industry 4.0 on environmental performance (*waste* reduction) (Kamble et al., 2019). They found in particular that Lean Manufacturing is a strongly mediating variable of the relationship between Industry 4.0 and sustainable production. Industry 4.0 technologies can enable or enhance both lean and green supply chain paradigms that are related to sustainability performance aspects *(*Leong et al., 2020; Ramirez-Peña et al., 2020). Further studies analyse the mediating role of supplier integration between Industry 4.0 technologies (cloud computing and IoT) and sustainability performance in manufacturing (Chetthamrongchai and Jermsittiparsert, 2019; Saengchai and Jermsittiparsert, 2019).

Other publications focus on the impact of Industry 4.0 on *sustainable maintenance* and the effect on environmental performance. If maintenance is supported by digital technologies, virtual examination can replace the physical one, making maintenance more efficient. Thus, performance factors such as *waste* production and *material* consumption decrease (Johansson et al., 2019). Specifically, IoT and machine learning can be applied for real-time monitoring to detect irregularities in processes and to predict the lifetime of components, also known as predictive maintenance. Economically, predictive maintenance can reduce maintenance time, improve efficiency and customer satisfaction and, ultimately, provide an advantage over competitors (Noureddine et al., 2020).

It has been suggested that Industry 4.0 and sustainable circular approaches may positively relate (Hoosain et al., 2020). The adoption of Industry 4.0 technologies within *closed loop supply chain* practices can lead to an improvement in sustainability performance, e.g., CO2 *emissions* reduction (Dev et al., 2020) and overall, to a positive impact on the relations between society and nature (Martín-Gómez et al., 2019). Specific technologies, such as IoT, big data along with smart products and CPS can reduce material and energy use and waste production. This reduction can occur through closed loop supply chain considerations – circular economy and end-of-life activities such as reuse, recycle and remanufacturing of products and waste valorisation (Strandhagen et al., 2017; Belaud et al., 2019; Mastos et al., 2020; Meng et al., 2020). Depending on the level of implementation, Industry 4.0 might better support circularity and resource optimization, especially with the adoption of smart data analysis (e.g., artificial intelligence and machine/deep learning) (Kristoffersen et al., 2020).

Practical applications have shown that intelligent products – using AI and machine learning – can *reduce CO2 emissions* and *energy consumption* in *closed loop supply chain* environments (Främling et al., 2013). Intelligent products can aid *sustainable performance measurement* and life-cycle information exchange to influence sustainability performance.

AI can support *sustainable governance*; reducing *pollution* and *energy use* (Milano et al., 2017). Tools that can assist policy makers in all steps of this decision-making process have been developed.

5.4. Moderating factors

The relationships amongst the various factors in this study are not always static. There may be intervening contingencies and moderators that influence relationships, such as those between adoption of technologies and performance.

Studies have shown various factors that might moderate the impact of Industry 4.0 on sustainability (see Table 6). *Organizational readiness* is one of the first examples of a moderating factor.

Organizational readiness has typically been led with management commitment, understanding Industry 4.0 implications, and acquiring competency in adopting Industry 4.0 business models. Broader organizational resources requirement such as availability of research and development and a digital culture can also moderate Industry 4.0 initiatives on *sustainability practices* in the supply chain (Luthra and Mangla, 2018; de Sousa Jabbour et al., 2018b). The digital culture includes strong leadership for digital transformation, with a purpose of sustainability practice adoption (Hsu et al., 2018). Leadership and commitment include dedicating resources to build capabilities. Further, integration seems to play an important role in the relationship between Industry 4.0 and sustainability. Integration includes education and training to support the digital transformation, cooperation between organizations, and openness to strategic innovation management (Tirabeni et al., 2019). Hence, management support and an effective governance is crucial for economic-ecological-social benefits of Industry 4.0, e.g., reducing *waste* production (Luthra et al., 2020). Even if sustainability is not the first goal of Industry 4.0 adoption, digitalization can increase sustainability; whereby a strong management leadership and organizational knowledge can increase the sustainability performance (Ordieres-Meré et al., 2020).

Organizational capabilities can be built through bureaucracy reduction and investments in education (Liboni et al., 1996); through easier information sharing. These capabilities can moderate Industry 4.0 technology adoption in providing environmental protection and *occupational health and safety*. External – to the organization – contexts can also moderate the relationships. *Regulatory actions* and governmental policies that enable innovation moderate the Industry 4.0 and *occupational health and safety* relationship (Liboni et al., 1996). Policy maker regulations can support IoT for sustainable governance to improve *sustainability practices* for more environmental protection and to enhance the quality of life (Zarei et al., 2016).

Another factor that might moderate the relationship between Industry 4.0 and sustainability practices in the supply chain is the *technological readiness* (Luthra and Mangla, 2018).

This aspect is mixed with organizational and external dimensions and may include: (1) global standards and protocols in data transfer; (2) data quality; (3) a platform to integrate technology; and (4) the technological infrastructure connecting different actors. It has also been argued that specific technological capabilities such as fault-detection that share information with the system, systems of diagnosis; dynamic learning and approximate computing may also serve as moderators (Alippi and Roveri, 2017). Although some of these factors moderate specific technologies and outcomes. In this case these specific technological factors moderate the relationship between CPS and *energy* use.

The level of analysis on moderating factors can also vary. While many studies have focused on corporate sustainability implications, other studies have considered macro-economic levels of analysis (Pueyo, 2018; Cottey, 2018). In this case cooperative efforts and a degrowth-oriented *economic model* can moderate Industry 4.0 implications on various sustainability dimensions (e.g., resource - energy, material - consumption, and other environmental damage, wages and working conditions i.e. work satisfaction, employment -unemployment rate - safety, and overall social equity).

Further, there are other contextual variables within organizations that are not predictable, referred to as environmental dynamism. A study by Li et al. (2020) has identified the moderating role of environmental dynamism on both economic and environmental performance.

Industry 4.0 technologies raise both *ethical* and human issues. Technologies that are particularly involved in this social debate are AI, machine learning, and big data. There is a belief, given the sustainability theme, that society needs to find a way to *involve all stakeholders* to make sure benefits outweigh disadvantages of Industry 4.0 implementation (Stahl and Wright, 2018). Therefore, stakeholders need to be engaged in the research and innovation process of the technologies to ensure a positive impact of such technologies on social sustainability – security, health and inclusion. Policy makers, as well as research institutes and others such as involved organizations, service providers, but also users will be able to establish new standards, procedures and goals towards economic, social and environmental sustainability improvements

Table 6
Moderating factors.

	Moderating factors				
	Organizational readiness	*Regulatory actions*	*Technological readiness*	Economic model	*Involve all stakeholders and enforce collaboration*
Sustainability Practices	Luthra and Mangla (2018); de Sousa Jabbour et al. (2018b); Hsu et al. (2018); Tirabeni et al. (2019); Kumar et al. (2020) Luthra et al. (2020)	Zarei et al. (2016); Milano et al. (2017); Luthra and Mangla (2018); Luthra et al. (2020)	Luthra and Mangla (2018); Luthra et al. (2020)		Paniccia et al. (2018); Godina et al. (2020); Lardo et al. (2020); Luthra et al. (2020)
Wages and working conditions				Pueyo (2018) Cottey (2018)	Kaasinen et al. (2020)
Employment				Pueyo (2018) Cottey (2018)	
Occupational Health and Safety	Liboni et al. (2018)	Liboni et al. (2018)		Cottey (2018)	
Non-discrimination				Pueyo (2018) Cottey (2018)	
Ethics, Privacy and Personal Autonomy					Stahl and Wright (2018)
Energy use			Alippi e Roveri (2017)	Pueyo (2018) Cottey (2018)	
Material use				Pueyo (2018)	
Waste	Luthra et al. (2020)				

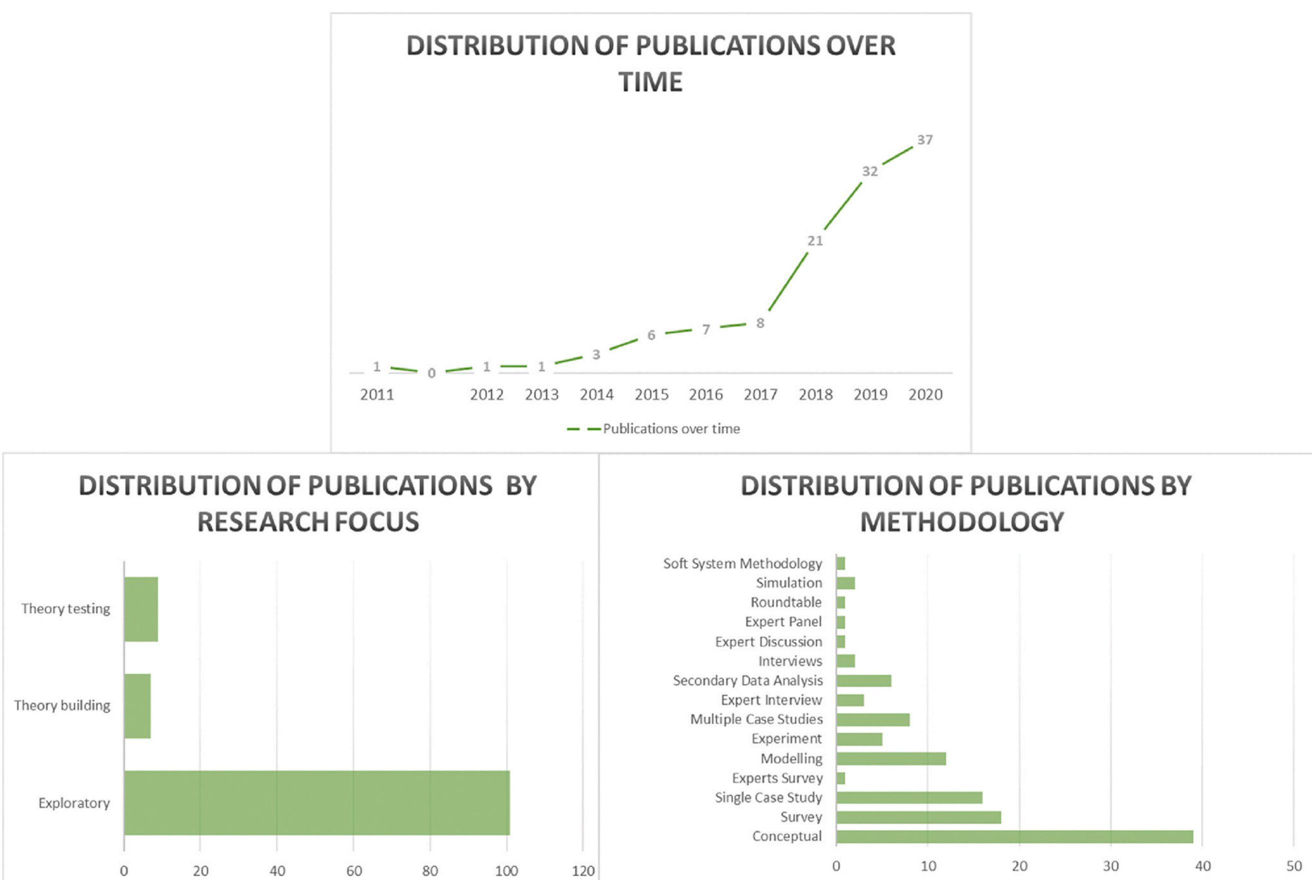

Fig. 2. Distribution of publications over time, by research focus and by methodology.

(Godina et al., 2020).

Finally, we did not find any study that sheds light on factors that moderate the impact of sustainability on Industry 4.0 adoption. This might also be related to the lack of studies focusing on this relationship.

Other broad moderating and supportive issues are effective technology transfer and a strong reciprocal relationship between stakeholders – universities, industry and governments – to positively influence digital technologies on sustainability. Coordinating resources and taking synergetic actions using shared knowledge and core values may result in improved social responsibility and well-being in local and national systems. Involving universities in the technology transfer may help in distributing scientific knowledge and creating sustainability-oriented innovative university spin-offs and start-ups that might benefit sustainable growth. In this context sustainable development based on Industry 4.0 is dependent on how stakeholders – universities, industry, and governments – synergistically interact in orienting industry and their technology towards sustainability (Paniccia and Baiocco, 2018). Similarly, *enforcing collaboration* and transparency among supply chain members (Luthra et al., 2020) and involving workers in the process towards Industry 4.0 are core issues (Kaasinen et al., 2020). In this context also technology providers have been identified as key stakeholders that determine the sustainability effects (Lardo et al., 2020).

6. Discussion

6.1. Literature gaps

This systematic review on relationships between Industry 4.0 and sustainability provides a foundation to determine areas for future research.

First of all, there is a lack of empirical studies. Most of the contributions are conceptual or qualitative; empirical studies using quantitative approaches are missing; theory-building oriented research is also rare.

Second, extant research tends to focus on sustainability dimensions separately. This situation neglects the broader relationship between Industry 4.0 and the whole TBL. Only one study empirically surveys the relationship between Industry 4.0 and the three sustainability dimensions. This study considers opportunities and challenges of Industry 4.0 influence on the TBL and whether it has have a positive or negative effect on manufacturer tendency to implement Industry 4.0 (Müller et al., 2018).

Third, publications seem to put a greater attention on positive aspects of Industry 4.0 (e.g., the profitability of Industry 4.0 technologies), forgetting its weaknesses (e.g., high implementation costs). Studies highlight that the technologies lead to a variety of environmental and social benefits (such as resource savings or health and safety gains), but they barely capture possible negative effects. Future research on the dark side of the coin is strongly needed.

Fourth, while numerous studies focus on the impact of Industry 4.0 on sustainability, only a few papers consider the opposite relation: sustainability as a driver for Industry 4.0 implementation. This perspective should be investigated intensively.

Finally, there is limited research on the organizational readiness, sustainability governance and other factors moderating the relationship between Industry 4.0 and sustainability (see Section 4.4).

6.2. Conceptualizing a framework

To guide future research on the relationship between Industry 4.0 and sustainability, in this section we develop a conceptual framework and some research propositions, using argumentation and hypotheses found in the reviewed studies. Fig. 3 summarizes the framework and relationships. Appendix A provides instead an overview of the reviewed studies and shows how they support the developed framework.

Industry 4.0 Technologies. A set of technologies that are likely to influence companies, governments and society and include IoT, CPS, robots/human robot collaboration, additive manufacturing, AI, big data (and analytics), cloud computing, augmented reality and blockchain technology (European Commission, 2018; Masood and Egger, 2019; Miller, 2018).

Sustainability practices. There are several types of supply chain sustainability practices supported by Industry 4.0 technologies. Sustainable supply chain practices include practices for *sustainable production* (Watanabe et al., 2016); sustainable *purchasing* (Ghadimi et al., 2019); sustainable *performance measurement and management* (Xing et al., 2016); *closed-loop supply chain* considerations (Jabbour et al., 2019); *sustainable governance*; and *green marketing* (Tu et al., 2017).

The investigations pretty clear that the technologies influence sustainability practices. This relationship exists without any mediation or moderation effect. Although the preponderance of research is conceptual and theoretical, the arguments made by most of the researchers are based on practical evidence and understanding. Therefore, we arrive at our first proposition.

P1. Industry 4.0 technologies have a direct impact on the adoption of sustainability practices.

Sustainability performance. When discussing sustainability performance, we rely on the triple-bottom-line dimensions of sustainability: environmental, social and economic (Elkington, 1998). We further divide environmental aspects into material use and recycled input; energy - use and renewable energy sources; water use; waste and other effluences and emissions. Social indicators incorporate impacts on labour practices, decent work, and human rights and society, those will be

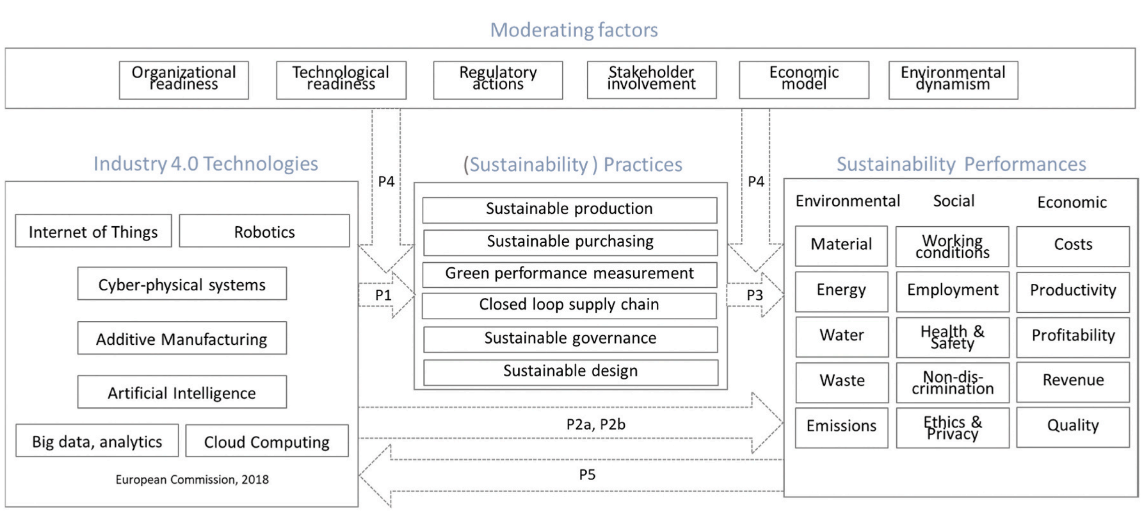

Fig. 3. A conceptual framework.

outlined later in detail.

Most environmental performance research linked to Industry 4.0 adoption focuses on material and energy use, and on waste production. These factors are critical areas that require further investigation. These technologies are expected to decrease material usage by, for example, increasing process-related quality recognition, which leads to lower failure rates and thus to less scrap and material consumption (Stock et al., 2018). The same assumption applies to energy consumption.

Digital simulations, the employment of continuous data, and independent control loops increase energy efficiency through optimization of planning, engineering and other production activities (Kiel et al., 2017). In some cases, Industry 4.0 is expected to have very high savings in resource – energy, water and raw materials - consumption through digitization (Braccini and Margherita, 2018). Overall, we conclude that the technologies will have a positive impact on environmental performance.

We do offer a caveat, fully automated production could lead to higher primary resource consumption and a negative impact on environmental sustainability through increased demand for equipment and devices that drive forward the automation process (Stock et al., 2018). Especially, since Industry 4.0 technology implementation is growing, manufacturing is facing challenges and potential sustainability problems. New Industry 4.0-related devices require scarce raw material resources, in addition to other natural resources such as water and land for the disposal of electronic waste, and reuse/recycling activities. Further, energy consumption is a relevant problem that requires increased attention (Bonilla et al., 2018).

Hence, we propose that:

P2a. Industry 4.0 technologies will have a direct (positive or negative) impact on environmental performance. This impact will depend on the level and type of technology, as well as the type of environmental sustainability measure.

Industry 4.0 adoption can have various social sustainability relationships. Published investigations identified influences on employment, wages, working conditions, occupational health and safety, discrimination, privacy and personal autonomy, social health and safety, ethics, and education.

Some studies identified social benefits such as transformation, because technology can support the sustainable development of societies in manifold ways.

A frequently discussed topic is Industry 4.0 and its potential impact on *employment*, where the emphasis is on the security of employment. New jobs are likely to emerge in technical development and management (Beier et al., 2017). Improvements in working conditions from technical assistance systems will occur while optimizing efficiencies. Industry 4.0 facilitates human-machine interaction and improve occupational safety through optimization and support processes (Kiel et al., 2017). Improved *working conditions* resulting from reduced workload and less heavy manual work that can be transferred to intelligent machines (Braccini and Margherita, 2018).

There are also some potential social sustainability downsides of Industry 4.0 technology adoption. Job losses from human substitution by technology, privacy concerns, and potential loss of human autonomy and control, are all possibilities. Industry 4.0 technology's role in this context is an open question (Sugiyama et al., 2017). There are concerns on humanity and its definition. New moral, ethical, and legal rules related to intelligent machines and human-machine relationships are also emergent concerns. We therefore propose that:

P2b. Industry 4.0 technologies have a direct – positive or negative – impact on social performance.

Industry 4.0 implementation poses economic opportunities and risks (Kiel et al., 2017; Müller et al., 2018). The reviewed publications assess the technology's economic performance in terms of profitability, productivity, revenue, costs, flexibility and quality.

Most studies relate Industry 4.0 to economic benefits, especially benefits related to efficiency increases of various activities (Horváthová et al., 2019) and improvements in production and across the product lifecycle (Nouiri et al.,2019; Li et al., 2020). These benefits are enabled by technology functionalities such as the interchange of real-time information and continuous process monitoring (Shrouf and Miragliotta, 2015; Nagy et al., 2018). Process monitoring can significantly impact *productivity* (Nagy et al., 2018) and *costs* (Nouiri et al., 2019). Studies have shown that Industry 4.0 technologies have a positive impact on *time* efficiency, process *flexibility* and *quality* (Braccini and Margherita, 2018; Pinzone et al., 2020).

Several studies discuss that economically oriented challenges, i.e. competitiveness, market position and strategic/organisational, and financial issues, such as profitability, come along with technology adoption. In the face of uncertain economic benefits of digital investments and the high costs of those investments (Kiel et al., 2017; Müller et al., 2018), we argue that:

P2c. Industry 4.0 technologies have a direct – positive or negative – impact on economic performance.

Sustainability practices and sustainability performance. Interdependencies between Industry 4.0 technologies, practices and their impact on sustainability performance have been shown to exist. Industry 4.0 adoption encourages sustainability practices within and outside the organization. This relationship includes an interaction of intelligent devices and intelligent networks for communication such as wireless objects that support energy management practices in production (Shrouf and Miragliotta, 2015).

The development and adoption of sustainability practices such as *green performance measurement* of product life-cycles may be supported by smart products that communicate with each other to reduce product environmental impact (Främling et al., 2013). Technologies such as big data analytics and CPS allow for integrating intelligent products into manufacturing and logistics systems. This integration makes product tracking and end-of life practices – such as product reuse, recycling – easier and facilitates a *closed loop supply chains* (Strandhagen et al., 2017). These practices may result in significant resource consumption and waste production efficiencies. For example, closing the loop increases *material and energy* efficiency (Strandhagen et al., 2017).

Industry 4.0 supports worker abilities to manage operational tasks influencing a social sustainability dimension – particularly employment practices. Industry 4.0 can be designed to assign physical and mental tasks between workers and technology while facilitating *working conditions* (Mattsson et al., 2020).

Overall, we can deduce that Industry 4.0 facilitates the adoption of sustainability practices. Through such practices Industry 4.0 indirectly contributes to sustainability performance. Hence, we argue that:

P3. Sustainability practices adoption mediates the Industry 4.0 technology adoption and sustainability performance relationship. That is, there is also an indirect effect between Industry 4.0 technology adoption and sustainability performance.

Moderating factors. Various investigations argue for the existence of additional factors that play a role in sustainable development given the Industry 4.0 context (de Sousa Jabbour et al., 2018a). First, organizational readiness and management commitment are important aspects for building a relationship between Industry 4.0 and sustainability. Management needs to support and accept Industry 4.0 contextual changes. The organization needs to be ready for change and expand its competencies – such as introducing environmental training for employees. Intra-organizational collaboration is also necessary. Kumar suggest that especially for SMEs management support is one of the most important challenges and that organizations need to be motivated to implement Industry 4.0 technologies for sustainable operations (Kumar et al., 2020).

Second, technological readiness must be ensured. Deficiencies in infrastructure and useable data and integrative platforms are concerns (Luthra and Mangla, 2018). Infrastructural limitations need addressing, with global standards required for many of these technologies.

Third, regulatory actions are needed. These actions include governmental policies and guidelines to support smarter and more sustainable processes development (Milano et al., 2017). Governments and regulatory actions can help make progress on policies for Industry 4.0 use and concomitant sustainable development (Zarei et al., 2016). These policy actions can propose solutions to social sustainability issues – especially data privacy and security concerns.

Fourth, macroeconomic perspectives with economic models moderate the impact of Industry 4.0 on sustainability – such as broader environmental protection and societal well-being. An example of new economic models are 'degrowth' and circular economy models. In these models our current economic model of growth needs to change radically, otherwise sustainability problems might not be solved (Cottey, 2018).

Fifth, the involvement of relevant stakeholder groups influences the positive or negative impact of Industry 4.0 technologies. When stakeholders and decision-makers are involved at an early stage of technology adoption, potential downsides for sustainability might be uncovered (Stahl and Wright, 2018).

Based on these insights we propose that Industry 4.0 can enhance sustainability performance, however provided that:

P4. The impact of Industry 4.0 on sustainability performance is moderated by external factors such as organizational and technological readiness, regulatory actions, the economic model and stakeholder involvement. The moderating factors can either negatively or positively influence the relationship.

Nascent studies also raise the importance of sustainability as an antecedent of Industry 4.0 adoption (Müller et al., 2018). Few studies contribute to the knowledge of sustainability that drives the implementation of Industry 4.0 technologies, and those who deal with it differ in opinions. This conflicting evidence requires significantly more investigation.

P5. Sustainability is a driver for industry 4.0 adoption

These propositions set the foundation for future research. The issues are manifold and complex with many uncertainties. Further research is needed for understanding how Industry 4.0 fits in our natural environment and society.

6.3. Originality of our review compared to other literature reviews

In Section 2 we reviewed previous literature reviews on Industry 4.0 and sustainability, in order to better position our research. Compared to these reviews, our systematic literature review holistically links not only Industry 4.0 as a concept, but also single Industry 4.0 technologies to various sustainability dimensions and concepts. We contribute to the existing literature by providing a conceptual framework and some testable propositions to encourage future research to better understand how single technologies relate to sustainability performance through sustainability practices. Further, the originality of our research lies in framing both positive and negative aspects for several aspects of environmental and social sustainability. In this light, our study extends the vision of existing literature reviews since our study identifies many more individual links between single technologies and specific impacts on the TBL. Further, this study covers additional performance indicators and factors such as sustainable practices (e.g., periodic sustainable supplier evaluation, green consumer education) and moderating factors (e.g., environmental dynamism) that previous reviews have not captured and that enhance the understanding of Industry 4.0 and sustainability. This is also confirmed by the relatively limited overlapping of our sample of reviewed papers with previous literature reviews on similar topics (i.e., between 0% and 15%, see Table 7), mostly due to: (1) our strong focus on the impacts of Industry 4.0 technologies on the whole TBL (while previous reviews include also papers purely focused on economic performance); and (2) our inclusion of a wide set of Industry 4.0 technologies (while previous review focus either on the Industry 4.0 overarching concept or on a limited set of technologies).

Table 7
Overlap of reviewed papers with other reviews.

Author(s) and year	Overlap
Bag et al. (2018)	53 (only list of 10 papers provided, 1 overlap)
Birkel and Müller (2020)	55 (17 overlap, ~15%)
Ejsmont et al. (2020)	162 (only ranking of top 12 cited papers provided, 11 overlaps)
Furstenau et al. (2020)	no list provided
Ghobakhloo (2020)	72 (10 overlaps ~8%)
Kamble et al. (2018)	85 (but only 16 on Industry 4.0 and sustainability, no overlap)
Machado et al. (2020)	no list on just Industry 4.0 and sustainability provided
Margherita and Braccini (2020)	18 (2 overlaps, ~2%)

7. Conclusion

This paper summarizes a current state of the art for interrelations between Industry 4.0 technologies and sustainability theory. A targeted and systematic literature review of 117 scientific contributions helped set the foundation for this investigation. We identified four focal areas: Industry 4.0 and sustainability performance; Industry 4.0 and sustainability practices; Industry 4.0, sustainability practices and sustainability performance; and moderating factors. These issues were then framed and described in detail with commensurate studies clearly identified.

Although this work was based on research publications, both implications for research and for management practice arise from the framework and propositions.

7.1. Implications for research

Current academic contributions have highlighted the importance of linking the concept of Industry 4.0 and sustainability (Beier et al., 2017; Müller et al., 2018). These are both areas that influence business, technology, society, and the natural environment. The works have suggested that Industry 4.0 is likely to play a key role in advancing sustainable development; or even potentially inhibiting it with unintended consequences.

In response to a call for further research in this field (Piccarozzi et al., 2018), we introduce a conceptual framework. This framework aims to contribute to the literature by linking Industry 4.0 and sustainability further, and providing a broader picture of their interrelation.

This conceptual model advances current understanding of Industry 4.0 and sustainability – especially the impact on sustainability practices and performance. We propose that a positive impact of Industry 4.0 on sustainability performance is not necessarily a direct one, but might be enhanced by practices that mediate and key factors that moderate this impact.

Second, the work underpins a lack of empirical studies that validate causal relationships between Industry 4.0 and sustainability. In particular, the role of sustainability as driver for Industry 4.0 adoption. This topic has rarely been investigated within the literature.

Third, we develop a number of propositions for further empirical validation. These propositions can serve as foundation for advancing research in this field; and in refinement of the conceptual framework.

7.2. Implications for management practice

The paper provides decision makers with a framework that illustrates possible interrelations between Industry 4.0 and sustainability.

The framework might support managers in their thoughts and analyses about Industry 4.0 adoption in different ways. First, by showing that Industry 4.0 technologies can aid sustainability performance improvement. This information can be valuable to managers of sustainability-oriented companies further justify the adoption of Industry 4.0 technologies. A major challenge for companies will be to know how to adopt Industry 4.0 technologies and how to retrieve their benefits in the light of sustainability. Since Industry 4.0 is based on a set of fundamental technologies, the importance of being aware of variables that link single technologies to sustainability practices and performance is crucial.

Second, on the other side, since Industry 4.0 can also have significant negative sustainability impacts, managers should carefully monitor these potential issues during Industry 4.0 implementation and management. Finally, managers should be aware of factors that moderate the relationship between Industry 4.0 and sustainability: technological readiness, management commitment, organizational readiness, training for employees and the involvement of all stakeholders.

When putting Industry 4.0 into practice it might be useful for managers to understand that the technologies can influence sustainability across various dimensions – ecologic, social and economic.

Further, our model provides implications for policy makers that deal with governmental policies and guidelines. The awareness raising of the issues requiring not only consideration of development for smarter and economical outcomes, but also more socially and environmentally sustainable processes.

7.3. Limitations

The results of our study should be viewed in light of some limitations:

(1) The research field is evolving at a fast pace. Therefore, some of the outcomes in this study may change as new contributions are published.
(2) The review was focused only on peer-reviewed journal papers indexed on Elsevier's Scopus database. Despite it is the world's largest database of peer-reviewed literature, some relevant contributions might have been missed due to this choice (e.g., non-peer reviewed journals and grey literature). This review could be more comprehensive, if more data sources were included. Nevertheless, we focused only on peer-reviewed journal papers to guarantee quality of the reviewed material (Jeffersson et al., 2002). Furthermore, future studies could also consider the current state in industry to empirically validate and extend our conceptual framework.
(3) The paper is conceptual in nature. Empirical work is therefore needed to refine and validate the model.

Declaration of competing interest

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

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Appendix A. Summary of the reviewed studies

Authors	Year	Proposition(s) [a]	Research methodology	Conceptual/Empirical
Ahmad et al.	2020	2a+, 2c+	Multiple Case Study	E
Alippi and Roveri	2017	4	Conceptual	C
Allaoui et al.	2019	1	Conceptual	C
Ardanza et al.	2019	1	Conceptual	C
Bai et al.	2020	2a+, 2b+, 2c+	Secondary data	E
Beier et al.	2018	2a+	Survey	E
Beier et al.	2017	2a+, 2b+, 2b-; 2c+	Survey	E
Belaud et al.	2019	1	Conceptual	C
Birkel et al.	2019	2a-, 2b-	Expert Interview	E
Bonilla et al.	2018	2a+, 2a-	Conceptual	C
Braccini et al.	2018	2a+, 2b+; 2c+	Single Case Study	E
Bremer	2015	2b+, 2b-	Multiple Case Study	E
Bressanelli et al.	2018	2a+, 2c+ 3	Single Case Study	E
Brozzi et al.	2020	5	Survey	E
Cagliano et al.	2019	2b+	Multiple Case Study	E
Chauhan et al.	2019	1	Conceptual	C
Chetthamrongchai and Jermsittiparser	2019	3	Survey	E
Chiarini et al.	2020	5	Survey	E
Coldwell	2019	2b-	Secondary data	C
Cottey	2018	4	Conceptual	C
Damiani et al.	2020	2b+	Experiment	E
Davidsson et al.	2016	2a+, 2b+	Conceptual	C
de Sousa Jabbour et al.	2018a	1	Conceptual	C
de Sousa Jabbour et al.	2018b	4	Conceptual	C
Dev et al.	2020	3	Modelling	C
Fisher	2011	2a+	Conceptual	C
Fisher et al.	2018	3	Conceptual	C
Ford & Despeisse	2015	2a+, 2a-	Secondary data	C
Främling et al.	2013	3	Conceptual	C
Ghadimi et al.	2019	1	Modelling	C
Gill	2016	2b-	Conceptual	C
Godina et al.	2020	4	Conceptual	C
Goralski and Tan	2020	2	Case Study (Meta-Analysis)	E
Gu et al.	2018	1	Single Case Study	E
Gualtieri et al.	2020	2b+; 2c+	Experiment	E
Haass et al.	2015	2a+	Simulation	E
Herrmann et al.	2014	5	Conceptual	C

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Authors	Year	Proposition(s) [a]	Research methodology	Conceptual/Empirical
Hoosain et al.	2020	3	Secondary Data (Case Studies)	C
Horváthová et al.	2019	2c+	Single Case Study	E
Hsu et al.	2018	4	Single Case Study	E
Isaias	2015	2a+, 2b-	Survey	E
Jabbour et al.	2019	1	Conceptual	C
Jagtap et al.	2019	2a+	Conceptual	C
Jena et al.	2020	3	Single Case Study	E
Johansson et al.	2019	3	Interviews	E
Kaasinen et al.	2020	4	Interviews	E
Kamble et al.	2019	2a+, 3	Survey	E
Kerdlap et al.	2019	1	Conceptual?	C
Kiel et al.	2017	2a+; 2c+	Multiple Case Study	E
Kristoffersen et al.	2020	3	Conceptual	C
Kumar et al.	2020	4	Expert groups	E
Lardo et al.	2020	4	Single Case Study	E
Leong et al.	2020	3	Modelling	C
Li et al.	2020a	2c+	Single Case Study	E
Li et al.	2020b	2,3,4	Survey	E
Liang et al.	2018	2a+	Simulation	E
Liao and Wang	2019	3	Single Case Study	E
Liboni et al.	2018	4	Soft System	E
Lin et al.	2020	2b+	Secondary Data & Expert Interviews	E
Liu et al.	2019	1	Experiment	E
Luthra and Magla	2018	4	Survey	E
Luthra et al.	2019	4	Survey	E
Ma et al.	2020	3	Modelling	C
Ma et al.	2019	3	Modelling	C
Machado et al.	2019	3	Conceptual	C
Martín-Gómez et al.	2019	3	Conceptual	C
Mastos et al.	2020	3	Single Case Study	E
Matt et al.	2020	3	Conceptual	C
Mattsson et al.	2020	3	Conceptual	C
Meng et al.	2020	3	Modelling	C
Milano et al.	2014	3, 4	Single Case Study	E
Mörth et al.	2020	1	Conceptual	C
Müller et al.	2018	2c+; 5	Survey	E
Müller and Voigt	2018	2a+; 2b+; 2b-; 2c+; 2c-	Survey	E
Mohamed et al.	2019	2a+	Modelling	C
Munodawafa and Johl	2019	3	Survey	E
Munsamy et al.	2019	2a+	Modelling	C
Nåfors et al.	2020	2a+, 2b+, 2c+	Multiple Case Studies	E
Nagy et al.	2018	2a+, 2b+; 2c+	Multiple Case Studies	E
Nam	2019	2b0	Secondary data	C
Nasir et al.	2014	2a+	Modelling	C
Nouriri et al.	2019	3	Experiment	E
Ordieres-Meré et al.	2020	4	Multiple Case Study	E
Paniccia et al.	2018	4	Single Case Study	E
Pham et al.	2019	1	Single Case Study	E
Pinzone et al.	2020	2b+, 2c+	Single Case Study	E
Pueyo	2016	4	Conceptual	C
Qian et al.	2017	1	Conceptual	C
Rajput and Singh	2019	1	Expert Discussion	E
Ramirez-Peña et al.	2020	3	Conceptual	E
Rauch et al.	2017	3	Conceptual	C
Ren et al.	2019	3	Conceptual	C
Saengchai and Jermsittiparsert	2019	2, 3	Survey	E
Schniederjans & Hales	2016	2a+; 2c+	Survey	E
Schulze et al.	2018	2a+	Simulation	E
Shrouf & Miragliotta	2015	3	Expert interviews	E
Stahl & Wright	2018	4	Conceptual	C
Stock et al.	2018	2a+, 2a-, 2b+; 2c+	Expert Interviews	E
Strandhagen et al.	2020	2	Single Case Study	E
Strandhagen et al.	2017	3	Conceptual	C
Sugiyama et al.	2017	2b-	Roundtable	E
Tirabeni et al.	2019	4	Conceptual	C
Tiwari et al.	2020	1	Focus group & Interviews	E
Tozanlı	2020	1	Modelling	C
Truong and Dustdar	2012	1	Conceptual	C
Tu et al.	2017	1	Multiple Case Study	E
Tunckaya and Koklukaya	2015	2a+	Modelling	C
Turner et al.	2019	1	Single Case Study	E
Venkatesh et al.	2020	2	Conceptual	C
Vinuesa et al.	2020	2	Conceptual	C
Wang et al.	2018	5	Survey	E
Wang et al.	2019	3	Experiment	E
Watanabe et al.	2016	1; 2c+	Conceptual	C

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Authors	Year	Proposition(s) [a]	Research methodology	Conceptual/Empirical
Xing et al.	2016	1	Single Case study	E
Yadav et al.	2020a	1	Survey	E
Yadav et al.	2020b	1	Expert Panel	E
Zarei et al.	2016	4	Survey	E
Zhang et al.	2019	2a0	Modelling	C
Zhang et al.	2020	1	Conceptual	C

[a] The sign + and - indicate whether the hypothesized impact on sustainability is positive (+), negative (−) or neutral (0).

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