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The "dark side" of Industry 4.0: How can technology be made more sustainable?

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Abstract

Purpose – A positive outlook on the impact of Industry 4.0 (I4.0) on sustainability prevails in the literature. However, some studies have highlighted potential areas of concern that have not yet been systematically addressed. The goal of this study is to challenge the assumption of a sustainable Fourth Industrial Revolution by (1) identifying the possible unintended negative impacts of I4.0 technologies on sustainability; (2) highlighting the underlying motivations and potential actions to mitigate such impacts; and (3) developing and evaluating alternative assumptions on the impacts of I4.0 technologies on sustainability.

Design/methodology/approach – Building on a problematization approach, a systematic literature review was conducted to develop potential alternative assumptions about the negative impacts of I4.0 on sustainability. Then, a Delphi study was carried out with 43 experts from academia and practice to evaluate the alternative assumptions. Two rounds of data collection were performed until reaching the convergence or stability of the responses.

Findings – The results highlight various unintended negative effects on environmental and social aspects that challenge the literature. The reasons behind the high/low probability of occurrence, the severity of each impact in the next five years and corrective actions are also identified. Unintended negative environmental effects are less controversial than social effects and are therefore more likely to generate widely accepted theoretical propositions. Finally, the alternative hypothesis ground is partially accepted by the panel, indicating that the problematization process has effectively opened up new perspectives for analysis.

Originality/value – This study is one of the few to systematically problematize the assumptions of the I4.0 and sustainability literature, generating research propositions that reveal several avenues for future research.

Keywords Industry 4.0, Digitalization, Smart manufacturing, Sustainability, Problematization

Paper type Research paper

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1. Introduction

In the existing literature on Industry 4.0 (I4.0) and sustainability, the prevailing assumption is that digitalization is the key to more efficient and sustainable manufacturing companies (see Beltrami *et al.*, 2021; Birkel and Müller, 2021; Ghobakhloo, 2020 for a review on the topic). For example, some authors suggest that new technologies such as the IoT, sensors and big data analytics can reduce the resource and energy consumption of manufacturing activities through detection and data analysis (Bai *et al.*, 2020). Similarly, social sustainability benefits, such as better working conditions due to more ergonomic and safer tasks, can also be achieved through the adoption of human–machine interaction technologies (Müller and Voigt, 2018).

In contrast, some studies have highlighted possible negative unintended effects of I4.0 technologies on environmental and social sustainability (Bohnsack *et al.*, 2022; Dieste *et al.*, 2022; Ghobakhloo *et al.*, 2021). Scholars argue, for instance, that fully automated production could lead to higher primary resource consumption (Stock *et al.*, 2018); that blockchain or cloud computing applied to production and supply chain management may lead to higher energy consumptions (Singh and Bhanot, 2020); and that cloud technologies could cause the loss of employees’ autonomy due to continuous sharing of data (Cirillo *et al.*, 2021). However, while there is already some evidence challenging established knowledge about I4.0 and sustainability, no previous studies have systematically questioned the main assumptions of the literature by analyzing potential unintended sustainability impacts of I4.0 (Birkel and Müller, 2021; Ghobakhloo *et al.*, 2021; Beltrami *et al.*, 2021).

According to MacCarthy *et al.* (2013), relevant contemporary issues such as the one presented (i.e. the unintended negative impacts of I4.0 on sustainability) can be addressed through research approaches that are not gap-spotting driven, such as through a process of problematization. Therefore, this paper uses a problematization approach (Alvesson and Sandberg, 2011) to formulate alternative assumptions that challenge, rather than build on and extend an established body of literature that highlights the positive impact of I4.0 technologies on sustainability performance.

Through this approach, this paper aims to formulate and evaluate alternative assumptions that can potentially develop new research propositions regarding the sustainability impacts of I4.0. More in detail, this study: (1) identifies the possible unintended negative impacts of I4.0 technologies on firms’ environmental and social sustainability aspects; (2) highlights qualitative elements that support the alternative assumptions such as motivations, mechanisms behind and possible mitigation actions; and (3) develops and evaluates alternative assumptions about the unintended negative effects of I4.0 technologies on sustainability.

To achieve these aims, the six methodological principles for problematization proposed by Alvesson and Sandberg (2011) were fulfilled through a combined methodological approach. First, a comprehensive review of the literature on the negative sustainability outcomes of I4.0 technologies was conducted, which identified 12 unintended negative impacts challenging extant literature’s assumptions. Second, a Delphi study involving 43 international experts was performed to evaluate the alternative assumptions by assessing the probability of occurrence in the next five years and the severity of each I4.0 unintended negative effect. Moreover, Delphi participants were asked to illustrate the mechanisms behind each negative impact and to propose mitigation actions at firm, supply chain and policy levels. A Delphi study method was selected due to the exploratory and interdisciplinary nature of the research problem. As suggested by Alvesson and Sandberg (2011), a heterogeneous group of experts was involved in the problematization process.

The findings present a systematic overview and preliminary evaluation of the most important and controversial unintended negative impacts of I4.0 technologies on the environmental and social dimensions of sustainability. This evidence challenges the current state of knowledge in I4.0 and sustainability research and therefore contributes to the academic debate by opening a set of important avenues for future research. The results are also relevant to managers who plan and oversee the effective and sustainable implementation of I4.0

technologies. Furthermore, the corrective actions proposed can be valuable to policymakers, as some prevention and mitigation strategies are beyond the scope of companies.

2. Background

2.1 The problematization approach

The aim of problematization is "*to come up with novel research questions through a dialectical interrogation of the domain of literature targeted for assumption challenging, instead of spotting gaps within a literature domain*"; in doing so this method encourages the creation of new theories (Alvesson and Sandberg, 2011, p. 252). To this end, the authors developed a set of *six methodological principles* (see Table 1) on how assumptions in existing theory can be problematized and used to generate new research propositions.

In this study, the problematization approach was used to identify and challenge the assumptions underlying the existing literature on I4.0 and sustainability. Alvesson and Sandberg's (2011) principles were applied as follows: (1) identifying the literature domain and selecting influential texts on the research topic of I4.0 and sustainability; (2) identifying the assumptions underlying this literature; (3) evaluating these assumptions by identifying preliminary evidence that suggests they are worthy of being problematized; (4) developing alternative assumptions through a systematic literature review (SLR); (5) considering assumptions related to the audience through a multi-round Delphi study; and (6) evaluating the alternative assumptions' ground. The problematization process followed throughout this article is summarized in Table 1.

2.2 Underlying assumptions in the I4.0 and sustainability literature

The *first principle* of problematization involves an in-depth reading of key texts on the specific area of literature targeted. This allows for the subsequent identification of the underlying assumptions to be challenged. Some of the most relevant works in the field have suggested that I4.0 can be a significant factor in achieving improvements in sustainability performance.

Principles for identifying and challenging assumptions	Description	Article sections
1. Identifying a literature domain: What main bodies of literature and key texts make up the broader domain?	Preliminary review of key texts on I4.0 and sustainability	Section 2.2
2. Identifying and articulating assumptions: What major assumptions underlie the literature within the identified domain?	Identification of assumptions to be challenged in the I4.0 and sustainability literature	
3. Evaluating articulated assumptions: Are the identified assumptions worthy to be challenged?	Identification of preliminary evidence of negative sustainability impacts of I4.0	Section 2.3
4. Developing alternative assumptions: What alternative assumptions can be developed?	SLR on the negative sustainability impacts of I4.0 to identify and develop alternative assumptions	Sections 3.1 and 4.1
5. Relating assumptions to audience: What major audiences hold the challenged assumptions?	Selection of an expert panel and development of a 2-round Delphi study	Sections 3.2, 4.2 and 4.3
6. Evaluating alternative assumptions: Are the alternative assumptions likely to generate a theory that will be regarded as interesting and useful by the targeted audiences?	Discussion of the results of the Delphi study	Sections 5 and 6

Source(s): Adapted from Alvesson and Sandberg (2011)

Table 1. Research process based on the problematization approach

For instance, the seminal I4.0 report by Kagermann *et al.* (2013) states that smart factories will ensure that production is "simultaneously attractive and sustainable". Stock and Seliger (2016) suggest that I4.0 offers a great opportunity to achieve economic, social and environmental sustainability. Frank *et al.* (2019) suggests that various I4.0 technologies can promote sustainable manufacturing by improving energy efficiency and producing less waste than traditional manufacturing.

This evidence has paved the way for an overwhelming number of articles on I4.0 and sustainability. As recommended by Alvesson and Sandberg (2011), more recent literature was analyzed to understand whether a positive relationship between I4.0 and sustainability is still relevant. For instance, Kamble *et al.* (2018a) consider sustainability among the many elements of I4.0, concluding that smart technologies have the potential to reduce waste and energy consumption. Li *et al.* (2020), after conducting a survey of Chinese manufacturing firms, conclude that digital technologies have a positive impact on economic and environmental performance. Bai *et al.* (2020) highlight that I4.0 technologies positively affect several dimensions of firms' environmental performance, such as promoting resource efficiency and reducing the materials used in production processes. Ghobakhloo (2020) indicates that I4.0 technologies such as simulation, IoT and AI can facilitate the reduction of carbon emissions. Finally, Zheng *et al.* (2021) argue that I4.0 offers energy efficiency opportunities to the manufacturing industry by applying optimization algorithms, modelling and simulation.

In addition, recent studies have also highlighted a set of positive implications of I4.0 on social sustainability performance. For instance, Kiel *et al.* (2020) suggest that fair wage assessments, human learning and employee motivation are among the social implications of I4.0. Cagliano *et al.* (2019) indicate that workers may benefit from more autonomy in performing tasks, resulting in more social interactions and teamwork. Occupational health and safety can be positively improved due to the substitution of heavy manual work, reducing the risk of injury (Birkel and Müller, 2021).

In summary, the existing literature on I4.0 and sustainability generally assumes that smart technologies contribute to improving sustainability in manufacturing companies (Bohnsack *et al.*, 2022; Dalenogare *et al.*, 2018). Thus, according to the *second principle* of problematization, the following underlying assumptions can be formulated:

u1. There is a positive relationship between the adoption of I4.0 technologies and firms' environmental sustainability performance.

u2. There is a positive relationship between the adoption of I4.0 technologies and firms' social sustainability performance.

2.3 Evaluating the underlying assumptions in the I4.0 and sustainability literature

The *third problematization principle* suggests evaluating whether the identified assumptions (u1, u2) are worth challenging. Recent reviews such as Ghobakhloo *et al.* (2021) and Beltrami *et al.* (2021) reveal that the literature is generally over-optimistic regarding the economic and socio-environmental impacts of I4.0. Bohnsack *et al.* (2022) explain that the introduction of digital technology can have both positive and negative unintended effects that either create additional sustainable value or destroy existing sustainable value.

According to Merton's (1936) seminal paper, unintended consequences must be viewed in relation to their intended consequences. In this study, the intended consequences are defined as the improvements in socio-environmental sustainability resulting from the implementation of I4.0, according to the underlying assumptions presented in Section 2.2. Thus, the unintended consequences are those unwanted negative sustainability impacts of I4.0 technologies that are not considered intended outcomes (Sugiyama *et al.*, 2017). Various studies have, in fact, already acknowledged some unintended negative effects of I4.0 on sustainability performance. Chiarini (2021), for instance, found empirical evidence of increased energy consumption and e-waste generation and highlights the need for a deeper investigation of the environmental issues emerging from I4.0 implementation. Birkel and Müller (2021) also raise concerns about who will be responsible for increased waste and predict rising energy consumption levels due to the rapid proliferation of data centers.

Similarly, Schneider and Kokshagina (2021) recommend further investigation into I4.0 unintended negative sustainability outcomes, including consideration of social aspects. The authors discuss the replacement of workers by new digital technologies and the challenge for employees to find their own balance between on and off time. Similarly, Bai *et al.* (2020), discuss the potential ethical, privacy and autonomy issues associated with data sharing in the cloud. According to the authors, the social implications of I4.0 have been understudied.

In conclusion, several key literature reviews and empirical studies have already suggested some unintended negative impacts of I4.0 on both environmental and social dimensions of sustainability. This evidence justifies the objective of this study, that is to question the underlying assumption of a sustainable Fourth Industrial Revolution.

3. Methodology

3.1 Developing alternative assumptions through a SLR

To address the *fourth problematization principle* – i.e. developing alternative assumptions – a SLR of the negative impacts of I4.0 was conducted. Durach *et al.*'s (2017) six sequential steps for SLRs were adopted: (1) define the research question, (2) determine the required characteristics of primary studies, (3) retrieve a sample of potentially relevant literature (baseline sample), (4) select pertinent literature (synthesis sample), (5) synthesize the literature and (6) report the results.

First, it was decided that the SRL would aim to identify a set of unintended negative sustainability impacts of I4.0 technologies. The preliminary evidence gathered will shape the alternative assumptions that challenge the I4.0 and sustainability literature. Second, the inclusion and exclusion criteria are specified: both conceptual and empirical studies that focus on the relationships between I4.0 technologies and sustainability are targeted. Furthermore, only journal articles written in English and including unintended negative impacts are considered. Third, a keyword search was carried out using Elsevier's Scopus database, the most recognized online scientific database. Considering that I4.0 applications are multifaceted and wide-ranging, no restrictions in the disciplinary scope of the journals were applied. Two sets of keywords were used for the search (see the search string below). One set is related to I4.0 and the other to sustainability. Only articles that included the keywords in the title, abstract, or keywords were selected, and no time constraint was specified:

> ("Industry 4.0" OR "Industrie 4.0" OR "fourth industrial revolution" OR "4th industrial revolution" OR "Digital transformation" OR "Industrial automation" OR "Smart manufacturing" OR "Smart production" OR "Smart factory" OR "Smart industr*" OR "Cyber physical system*" OR "Cyber physical production system*" OR "Intelligent manufacturing" OR "Internet of things" OR "Digital twin" OR "Software-defined manufacturing") AND ("Sustainab*" OR "Green" OR "Environmental Performance" OR "Social Performance").

A total of 6,140 contributions resulted from the search, which made up the baseline sample.

Fourth, the inclusion/exclusion criteria were gradually applied. Papers with non-coherent abstracts were removed – that is, those articles that are not primarily focused on I4.0 and environmental and social sustainability or that discuss I4.0 and sustainability independently – leaving 269 articles in the dataset. A total of 117 publications discussing the relationship between I4.0 and sustainability were identified through full-text analysis. Consistent with other literature reviews, subsequent cross-referencing was conducted for further relevant publications (Seuring and Gold, 2012). Finally, 39 papers were selected that focused on unintended negative sustainability impacts of I4.0.

Fifth, descriptive and content analyses were conducted on the data set. The articles were classified according to the following criteria: authors, year of publication, research topic, methodology, sample used, technologies analyzed and unintended negative impacts supported. The content analysis methodology was carried out by identifying the specific findings displaying negative effects of I4.0 on sustainability performance. For each paper, specific findings regarding unintended negative sustainability impacts on both environmental and social dimensions were categorized according to the indicators included in the Global Reporting Initiative (2018) framework.

Sixth, the results were then grouped into 12 statements, 5 for environmental [E1-E5] and 7 for social [S1-S7] unintended negative impacts, which are reported in Section 4.1 with supporting arguments. A descriptive overview of the results is provided in the Appendix.

3.2 Relating assumptions to audience through a Delphi study

As mentioned in the *fifth principle*, the problematization methodology suggests considering assumptions in relation to the audience. Alvesson and Sandberg (2011) point out that the "audience" is usually not a uniform group, and therefore it is important to combine academic and practical expertise to understand their different views. A Delphi study approach was considered the most appropriate research method for this purpose due to the incompleteness of the available knowledge and the exploratory, interdisciplinary and forward-looking nature of the research (Linstone and Turoff, 1975). As Delphi studies are based on gathering expert opinions in a structured manner, they are very appropriate for structuring group communication processes, allowing individuals to deal with complex and interdisciplinary problems (Okoli and Pawlowski, 2004).Therefore, this Delphi study aims to provide a systematic assessment (probability/severity) to explore whether the interested audiences agree or disagree with the unintended negative impacts presented, thus evaluating alternative assumptions. It also aims to provide possible motivations, additional details and mitigation actions. In doing so, this study systematically collects qualitative evidence from experts that goes beyond the mostly anecdotal knowledge present in the literature.

3.2.1 Selection of the expert panel. Following the methodological suggestions above, the research sample included experts from both academia and practice, working in different functions, with different nationalities and years of experience (Okoli and Pawlowski, 2004). A rigorous selection of the panel of expert members was carried out (Landeta, 2006). A panel size of at least 30 participants with heterogeneous backgrounds was sought, as suggested by previous studies (Kembro *et al.*, 2017).

Consistent with prior research, selection criteria were defined to ensure that the experts were knowledgeable about I4.0 and sustainability topics. Initial sampling was carried out by contacting academics who had authored publications related to the topic and leveraging networks of personal contacts (Culot *et al.*, 2020). Nevertheless, most of the experts contacted were industry professionals working in the manufacturing sector such as digital transformation specialists, general managers, operations managers and supply chain managers. Management consultants working for manufacturing companies were also considered. This was done as it was intended to reach a wide range of interest groups. Further potential participants were scouted through LinkedIn social network and alumni databases.

An initial list of 150 participants was established, 63 of whom accepted to participate in the Delphi study. Moreover, to ensure rigor during the participant selection process, the experts who agreed to participate were asked to self-rate their perceived level of knowledge of the topic by answering three Likert-type scale questions (1: Very low, 5: Very high) regarding I4.0, sustainability and the manufacturing sector (Landeta, 2006). 20 respondents were excluded from the sample due to low overall scores or incomplete responses. The final panel consists of 43 experts familiar (median = 4) with I4.0, sustainability and manufacturing: Table 2 illustrates its composition. 5 participants dropped out during the second round.

	Participant categorization	Number of participants (n = 43)
Affiliation	Academia	7
	Machinery and equipment	5
	Automotive	5
	Manufacture of metal products	4
	Aerospace and shipbuilding	4
	Apparel	4
	Consultancy	4
	Software and support services	4
	Food and beverages	3
	Home appliances	3
Working experience	More than 15 years	23
	11–15 years	6
	6–10 years	11
	Up to 5 years	3
Job title	Digital transformation specialists	10
	General managers	8
	Operations managers	8
	Supply chain managers	6
	Scholars	7
	Management consultants	4
Geographical context	Europe	28
	Asia	7
	America	6
	Africa	2

Source(s): Authors' elaboration

Table 2.
Expert panel composition

3.2.2 Data collection and analysis. During a 10-month time span, reiterated rounds of data collection were carried out, as suggested for Delphi studies, to obtain convergence or stability (Linstone and Turoff, 1975; von der Gracht, 2012). The *first round* began in early July 2021, and the feedback was collected over five months. An invitation letter and the link to a web-survey commercial software containing the questions for the first round were sent. The Delphi questionnaire started with a brief background to the study and defined the scope and objectives of the project; it then moved on to various questions aimed at assessing participants' suitability for the panel. In addition, various demographic and qualification questions were asked.

Next, respondents found a series of rating-scale and open-ended questions written in a comprehensible writing style to avoid ambiguous statements. Panel experts were asked to assess the importance of each of the preliminary I4.0 negative sustainability impacts (see Section 4.1) in terms of probability of occurrence (over the next five years) and severity of the problem (level of impact). Five-point Likert-type scale questions were used for this purpose (1: Very low, 5: Very high). Respondents were requested to provide arguments for high and low probability/severity and illustrate the mechanisms behind each negative effect. Moreover, experts were asked to propose corrective actions at firm, supply chain and policy levels and to comment or provide additional discussion elements.

Once data had been collected, the median values for the probability and severity of each negative effect were calculated, and the level of consensus was determined by the interquartile range (IQR) (von der Gracht, 2012). Qualitative data were approached through a content analysis, resulting in a list of arguments supporting high and low probability/severity for each I4.0 negative impact and various relevant corrective actions at the three levels proposed.

After the data and qualitative responses of the first round were analyzed, a *second round* was performed. Each participant received an online form including the statistics (median and IQR), arguments and his/her previous assessment during the first round (Okoli and Pawlowski, 2004; Seuring *et al.*, 2022). Moreover, the second-round questionnaire contained the reorganized comments and mitigation actions provided by the panel for each I4.0 negative effect. The questionnaire form thus allowed participants to either modify their answers or maintain their initial assessments and provide additional remarks (Linstone and Turoff, 1975). The second round of data collection started in mid-January 2022 and lasted 3 months.

Finally, the research team performed data analysis consistently with the first round, enabling a comparison between the two rounds in terms of consistency of responses (i.e. stability) and calculating the Spearman's rank-order correlation coefficient (ρ) (von der Gracht, 2012). After the second round, the assessments of the 12 Likert-type items (E1-E5 and S1-S7) reached either consensus (IQR $\leq$1) or stability ($\rho \geq 0.75$), thus making further iterations of the questionnaire unnecessary (Culot *et al.*, 2020). This process resulted in some arguments with high consensus accepting or rejecting alternative assumptions (see Section 4.1), and others with contrasting results and low consensus.

3.3 Reliability and validity

Both the SLR and Delphi methods were tested for reliability and validity using different approaches. Regarding the SLR process, two researchers independently reviewed the evidence from the literature to improve the reliability of the unintended negative impacts of I4.0 found. Both researchers followed a systematic approach to ensure the objectivity of the literature review (Durach *et al.*, 2017). Moreover, several rounds of discussion were held within the research group to discuss disagreements during the coding process and to refine the final list of unintended negative I4.0 sustainability impacts identified in the literature.

For the Delphi study, before the questionnaires were sent to the panel of experts, two pre-tests were conducted with four senior experts (two academics and two practitioners) to ensure consistency and comprehensiveness for each round (von der Gracht, 2012). The tests were developed in the following manner: (1) informing the four experts about the research aims, (2) sending out the Delphi questionnaire and (3) interviewing the four experts about the clarity and the appropriateness of the questions.

During the pre-tests, various comments were extracted and discussed. The insights obtained from this process were employed to correct, rectify and validate the questionnaire. The final version of the Delphi questionnaire was reviewed one last time by the four experts involved in the pre-tests and by the research group. Subsequently, data collection was conducted in the same manner to pursue internal validity of the findings. Pre-test participants were not part of the final panel of experts.

Finally, to ensure the validity of the findings, both the first- and second-round results were presented at important operations management conferences to collect feedback and comments.

4. Results

This section is divided into three subsections. Section 4.1 presents the alternative assumption ground based on the SLR results (*fourth principle*). In Section 4.2, the evidence supporting the alternative assumptions is related to the audience through a Delphi study (*fifth principle*). Finally, Section 4.3 discusses some strategies proposed by the Delphi participants to mitigate the identified negative sustainability impacts of I4.0 technologies.

4.1 Developing alternative assumptions – SLR results

Table 3 summarizes the 12 potential unintended negative effects of I4.0 found in the literature on both environmental [E1-E5] and social [S1-S7] dimensions (literature review articles were not included in the supporting references to avoid redundancies).

4.1.1 Environmental sustainability. Previous research indicates that I4.0 may have various unintended negative impacts on the environmental performance of manufacturing companies. First, *connectivity and data processing following the adoption of I4.0 technologies in production and supply chain management (e.g. big data analytics, AI, cloud computing, autonomous robots and blockchain) lead to higher levels of energy consumption* [E1]. Müller and Voigt (2018) and Stock *et al.* (2018), conclude that ecological challenges may appear due to the increased energy used by data generation and interchange. Singh and Bhanot (2020) suggest that many devices communicating with each other generate large amounts of data which can overwhelm computing infrastructures, leading to higher energy consumption. Similarly, Biswas *et al.* (2022) capture the trade-off between traceability and sustainability and indicate that blockchain is characterized by high energy consumption.

Second, *I4.0 technologies' adoption (e.g. robots, CPS, IoT and additive manufacturing devices) imply the obsolescence and replacement of previous devices, increasing material waste,*

I4.0 unintended negative impacts on sustainability	References
Environmental sustainability	
[E1] Connectivity and data processing (e.g. big data, AI, cloud, and blockchain) following the adoption of I4.0 lead to higher levels of energy consumption	Biswas *et al.* (2022), Müller and Voigt (2018), Singh and Bhanot (2020) and Stock *et al.* (2018)
[E2] I4.0 technologies' adoption (e.g. robots, CPS, IoT, and 3D printers) imply obsolescence and material waste	Birkel *et al.* (2019), Di Carlo *et al.* (2021), Ghobakhloo and Fathi (2019) and Müller *et al.* (2018)
[E3] I4.0 wireless technologies raise the production of waste of electrical and electronic equipment	Birkel *et al.* (2019), Chiarini (2021) and Garrido-Hidalgo *et al.* (2020)
[E4] Hardware needed for I4.0 (e.g. sensors, chips, and connectivity infrastructure) requires higher consumption of natural resources	Birkel *et al.* (2019), Chiarini (2021) and Culot *et al.* (2020), Stock *et al.* (2018)
[E5] AM leads to higher energy consumption than traditional manufacturing processes	Ford and Despeisse (2016), Stock *et al.* (2018) and Yoon *et al.* (2014)
Social sustainability	
[S1] Firms adopting I4.0 technologies have an overall negative impact on employment	Birkel *et al.* (2019), Grigore *et al.* (2021), Kamble *et al.* (2018b) and Müller *et al.* (2018)
[S2] I4.0 technologies (e.g. CPS, IoT, cloud) cause a loss of employees' privacy and personal autonomy	Bai *et al.* (2020), Cirillo *et al.* (2021) and Sugiyama *et al.* (2017)
[S3] Connectivity facilitated by I4.0 leads to an unhealthy work–life balance	Coldwell (2019), Grigore *et al.* (2021) and Schneider and Kokshagina (2021)
[S4] Companies adopting I4.0 technologies will relocate production and related activities (e.g. R&D, logistics) to developed countries	Ancarani *et al.* (2019), Barbieri *et al.* (2022), Dachs *et al.* (2019), Müller and Voigt (2018) and Pegoraro *et al.* (2022)
[S5] Autonomous robots lead to health and safety problems for workers	Dalmarco *et al.* (2019) and Li *et al.* (2019)
[S6] VR and AR cause headaches, dizziness, and other symptoms among operators	Rodriguez *et al.* (2021) and Tsai and Huang (2018), Wang *et al.* (2019)
[S7] AM materials cause harsh skin reactions, eye irritation, and allergies among operators	Chan *et al.* (2020), Ford and Despeisse (2016) and Väisänen *et al.* (2019)

Source(s): Authors' elaboration

Table 3.
Preliminary evidence on the unintended negative sustainability implications of I4.0

which, in some cases, is hazardous waste [E2]. Müller *et al.* (2018) point out that the adoption of I4.0 often involves the need to replace entire production processes. In fact, it is difficult and complex to upgrade individual machines with different degrees of automation and at different life stages. Ghobakhloo and Fathi (2019) highlight, the high cost of dismantling obsolete devices. Birkel *et al.* (2019) and Di Carlo *et al.* (2021) also indicate that the time and cost required to replace obsolete equipment may be unsustainable, as most of the old machinery must be discarded and ends up in landfill.

Third, *wireless technologies include components and consumables (e.g. batteries, antennas) that raise the production of waste of electrical and electronic equipment (WEEE)* [E3]. Integrated production infrastructures involve the use of devices, such as sensors and actuators, which can lead to an increase in electronic waste (Birkel *et al.*, 2019). In fact, the recent increase in sales of electrical and electronic equipment is causing worldwide concern about the management of WEEE, according to Garrido-Hidalgo *et al.* (2020). Moreover, Chiarini (2021) outlines that managers are greatly concerned about the vast quantities of WEEE produced and its treatment.

Fourth, *hardware needed for I4.0 implementation (e.g. sensors, chips, connectivity infrastructure) requires higher consumption of natural resources (e.g. metals, water, energy) than traditional manufacturing technologies* [E4]. According to Stock *et al.* (2018) and Birkel *et al.* (2019), technologies in I4.0 require large amounts of critical raw materials used for RFID, sensors, displays, semiconductors and micro-energy harvesting. Experts believe that rare natural resources are increasingly needed in manufacturing activities and products (Culot *et al.*, 2020). Chiarini (2021) agrees that there has been higher consumption of rare metals and other natural resources due to the implementation of I4.0 technologies.

Fifth, several studies point out that *additive manufacturing (AM) particularly leads to higher energy consumption than traditional manufacturing processes* [E5]. According to Yoon *et al.* (2014), the specific energy consumption of AM processes is estimated to be higher than that of conventional processes. Similarly, Ford and Despeisse (2016) argue that while AM is more energy-intensive per unit produced, it offers higher levels of customization and less material use. Stock *et al.* (2018) indicate that, due to the frequent use of laser technologies to sinter the material, AM processes are still energy-inefficient.

In summary, the literature has already identified some preliminary evidence of unintended negative impacts of I4.0 technologies on the environmental performance of manufacturing firms. This alternative rationale challenges the existing assumption in the literature that I4.0 is the key to achieving environmental performance outcomes (i.e. u1).

4.1.2 Social sustainability. Some unintended negative social implications of I4.0 have also been highlighted by the literature. First, since its inception, one of the most concerning challenges of *I4.0 technologies* is that they *have an overall negative impact on employment* [S1] (Kamble *et al.*, 2018b). According to Grigore *et al.* (2021), I4.0 displaces some of the low-skilled workers who perform simple and repetitive tasks. However, this loss of jobs should be balanced by the increased demand for more skilled positions. Authors such as Müller *et al.* (2018) and Birkel *et al.* (2019) state that the existing literature cannot provide a unified perspective on whether I4.0 will cause an increase or a decrease in the total number of employees in manufacturing.

Second, some studies suggest that *I4.0 technologies (e.g. CPS, IoT, cloud computing) cause a loss of employees' privacy and personal autonomy* [S2]. Sugiyama *et al.* (2017) remark that this is one of the unintended side effects of the digital transition. More recently, Bai *et al.* (2020) suggest that cloud technologies and big data have a positive impact on social sustainability. However, the authors highlight potential privacy and personal autonomy issues related to sharing data in the cloud. Cirillo *et al.* (2021) conclude that I4.0 reduces employee autonomy and increases management control.

Third, *the connectivity facilitated by I4.0 technologies could lead to an unhealthy work–life balance, causing stress or mental health problems* [S3]. Coldwell (2019) suggests that the digital era allows employees to continue working even when away from the office. Bad practices associated with remote work and working outside of business hours can lead to depression and mental illness. Grigore *et al.* (2021) claim that digital technologies facilitate inclusive and flexible working practices. However, these same technologies also raise concerns regarding surveillance, exploitative employment contracts and data privacy. As reported by Schneider and Kokshagina (2021), the digital workplace can be more exhausting, requiring employees to balance work time and off-time. In addition, the social and emotional skills required and the difficulties in managing remote work and evaluating individual contributions can lead to additional stress. This topic has gained relevance as the COVID-19 pandemic inevitably prompted new ways of working that may become an integral part of the post-pandemic reality (Narayanamurthy and Tortorella, 2021).

Fourth, some recent studies suggest that *firms adopting I4.0 technologies will relocate production and related activities, such as research and development (R&D) and logistics, to developed countries* [S4]. The impact of this change is ambivalent, being positive for the countries where manufacturing will be relocated but negative for those abandoned. Ancarani *et al.* (2019) and Dachs *et al.* (2019) show a positive relationship between the adoption of I4.0 and firms' backshoring propensity. This occurs mainly due to the implications of I4.0 on the cost and quality of products. Moreover, Pegoraro *et al.* (2022) suggest that technology adoption supports manufacturing reallocation strategies. Barbieri *et al.* (2022) remark the importance of I4.0 policies to attract innovative I4.0 firms back to their country of origin.

Fifth, some scholars acknowledge that *autonomous and collaborative robots can cause health and safety issues when interacting with employees* [S5]. One of the main concerns about collaborative robotics is related to safety issues such as mechanical, electrical and thermal hazards (Leso *et al.*, 2018). Li *et al.* (2019) affirm that accidental collisions can happen in the process of human-robot interaction in a limited and shared physical space. Furthermore, according to Dalmarco *et al.* (2019), the integration of collaborative robotics in the shop floor can generate risks in interactions with workers.

Sixth, *virtual (VR) and augmented reality (AR) produce headache, dizziness and other symptoms* [S6]. Studies such as Tsai and Huang (2018) report that most smart glasses' users complained of dizziness. Wang *et al.* (2019) state that several users noticed visual fatigue after performing maintenance activities wearing Google Glasses. Rodriguez *et al.* (2021) show that it took time for users' eyes to adapt to smart glasses, that they were uncomfortable, and that operators experienced headaches after wearing them for a while.

Seventh, *the utilization of AM in production environments causes harsh skin reactions, eye irritation and allergies to the operators involved* [S7]. Ford and Despeisse (2016) conclude that AM may have several implications for social sustainability, including health and safety. Väisänen *et al.* (2019) measured the concentrations of gaseous and particulate contaminants originating from AM processes in an occupational environment and found that AM operations emitted potentially harmful contaminants. Furthermore, Chan *et al.* (2020) findings suggest that emissions increase when multiple AM devices operate simultaneously, and the authors recommend adherence to good safety and hygiene practices when this technology is deployed.

In summary, preliminary evidence from the literature challenges the current assumption that smart technologies lead to better social performance outcomes (i.e. u2). I4.0 may indeed entail various unitented negative impacts on social sustainability. This alternative assumption ground, which suggests negative unintended impacts of I4.0 on socio-environmental performance, needs to be evaluated by the relevant audiences. To this end, a Delphi study was conducted (see Sections 4.2 and 4.3).

4.2 Relating assumptions to audience – Delphi study results

The analysis of the Delphi statements is outlined in Table 4. The median values and IQR for both “probability” (*p*) and “severity” (s) assessments are shown for the two rounds. In addition, the stability between rounds (Spearman’s ρ) is indicated for the whole panel. Based on the results of the second round, several negative effects of I4.0 in the uniform opinion of experts (consensus IQR≤1) show a medium-high probability of occurring and/or severity. These effects concern aspects of both environmental sustainability [E1, E2, E3, E4] and social sustainability [S2, S3, S6].

Furthermore, the findings show a growing convergence of responses caused by the iteration of the questionnaire. After the first round, 4 out of 24 items (12 potential negative impacts assessed in terms of “probability” and “severity”) reached consensus. After the second round, consensus was reached on 15 out of 24 items. Spearman’s ρ generally shows high stability in values related to the probability of occurrence and severity.

Tables 5 and 6 present the results of the content analysis of the experts’ opinions collected during the two rounds. For each statement, the tables show:

(1) The median of the second-round probability and severity scores for the entire panel of experts;

(2) The level of agreement reached by the panel;

(3) Arguments for high and low probability and severity that emerged from the content analysis of the experts’ comments.

Regarding the unintended negative environmental impacts (Table 5), the experts suggest that wireless technologies will increase the generation of electrical and electronic equipment waste [E3]. This problem received the highest ratings in terms of probability of occurrence and severity ($Me_p = Me_s = 4$; $IQR_p = IQR_s = 1$) due to the use of electronic components and consumables with short lifespans. Experts also agreed that I4.0 leads to a higher consumption of natural resources than traditional manufacturing technologies, due to hardware needs [E4] ($Me_p = 4$, $Me_s = 3$; $IQR_p = IQR_s = 1$). In particular, the advancement of I4.0 technologies might cause an increase in the consumption of rare materials.

Furthermore, the shorter life cycle of new devices and the lack of compatibility and limited refurbishment options of old equipment are among the main reasons for the increase in waste due to the obsolescence of old equipment [E2]. The participants considered that this is a problem with a high probability of occurrence, but less agreement was reached concerning the severity, which is medium ($Me_p = 4$, $Me_s = 3$; $IQR_p = 1$, $IQR_s = 2$). The lower severity and consensus values are mainly due to the “retrofitting opportunities available”, the new recycling technologies and available recyclable materials.

Besides, panel experts considered that the higher levels of energy consumption produced by connectivity and data processing constitute a problem of medium severity [E1] ($Me_s = 3$; $IQR_s = 1$). However, they achieved less consensus when evaluating the probability of occurrence ($Me_p = 3$; $IQR_p = 2$). Relevant arguments for both high and low probability/severity were provided. For instance, “data centers and the cooling needed” require a significant amount of energy; in contrast, I4.0 technologies “should lead to greater efficiency of the entire process”.

Lastly, respondents stated with a high consensus that there is low probability that AM leads to higher energy consumption than traditional manufacturing processes [E5]. Panel experts considered that this issue is less likely to happen in the future due to the limited implementation of AM. The experts’ low level of concern about this problem was because “current AM applications are already leading to energy savings” ($Me_p = Me_s = 2$; $IQR_p = IQR_s = 1$).

As regards the unintended negative social impacts of I4.0, Table 6 shows that technologies such as CPS, IoT and cloud computing could cause loss of privacy and autonomy among employees [S2]. Respondents recognized “greater traceability” as a current problem, this may

Table 4. Delphi study descriptive statistics

I4.0 unintended negative impacts on sustainability	Round 1				Round 2				Stability (Spearman's ρ) Round 2 vs Round 1	
	Probability (p)		Severity (s)		Probability (p)		Severity (s)			
	Median (Me_p)	IQR_p	Median (Me_s)	IQR_s	Median (Me_p)	IQR_p	Median (Me_s)	IQR_s	Probability	Severity
Environmental sustainability										
E1	3.00	2.00	3.00	2.00	3.00	2.00	3.00	1.00	0.81	0.86
E2	4.00	1.00	3.00	2.00	4.00	1.00	3.00	2.00	0.94	0.82
E3	4.00	2.00	4.00	1.25	4.00	1.00	4.00	1.00	0.84	0.76
E4	4.00	1.00	3.00	2.00	4.00	1.00	3.00	1.00	0.92	0.78
E5	2.00	1.75	2.50	2.00	2.00	1.00	2.00	1.00	0.87	0.74
Social sustainability										
S1	3.00	2.00	3.00	2.00	3.00	1.75	3.00	2.00	0.84	0.89
S2	3.00	1.00	3.00	2.00	3.00	1.00	3.00	2.00	0.93	0.84
S3	3.00	2.00	3.00	2.00	3.00	1.00	3.00	2.00	0.85	0.77
S4	2.00	2.00	3.00	2.00	3.00	2.00	3.00	2.00	0.92	0.92
S5	2.00	1.75	2.00	3.00	2.00	1.00	2.00	2.00	0.81	0.79
S6	3.00	1.25	3.00	2.00	3.00	1.00	3.00	1.00	0.82	0.55
S7	2.00	1.00	3.00	2.00	2.00	1.00	3.00	1.00	0.90	0.66

Source(s): Authors' elaboration

Round 2 results	Coding	I4.0 unintended negative impacts on sustainability Environmental sustainability
Median magnitude: $Me_p = Me_s = 3$ **Agreement:** IQR_p = low, IQR_s = high	**E1**	Connectivity and data processing (e.g. big data, AI, cloud, and blockchain) following the adoption of I4.0 lead to higher levels of energy consumption
Reasons for high probability/severity	a	Energy consumed in data storage and digital waste
	b	Data center cooling systems consume significant amounts of energy
	c	Data analytics, AI, and especially blockchain are all energy-intensive
Reasons for low probability/severity	d	These technologies should lead to greater efficiency throughout the process
	e	Newer devices use less energy when processing data
	f	The resulting increase in energy consumption is negligible for energy-intensive industries
	g	Only blockchain consumes large amounts of energy, but will have limited adoption
Median magnitude: $Me_p = 4$, $Me_s = 3$ **Agreement:** IQR_p = high, IQR_s = low	**E2**	I4.0 technologies’ adoption (e.g. robots, CPS, IoT, and 3D printers) imply obsolescence and material waste
Reasons for high probability/severity	a	New devices have shorter life cycles
	b	Old equipment lacks compatibility and has limited refurbishment options
	c	Recycling and circular economy practices are rarely adopted
	d	Electronic equipment is difficult to recycle because it has complex parts that are harmful to the environment
	e	Developing countries have serious problems with waste management and access to recycling technologies
	f	Public funding (e.g. incentives to implement I4.0 technology) increases the replacement rate of old equipment
	g	Technologies like AM will completely replace “old” technologies
Reasons for low probability/severity	h	Several retrofitting options are available
	i	Many machine components are fully recyclable or environmentally friendly
	j	Many firms are currently using more advanced and efficient recycling technologies
	k	Newer technologies are often more environmentally friendly, offsetting the effect of replacement
Median magnitude: $Me_p = Me_s = 4$ **Agreement:** $IQR_p = IQR_s$ = high	**E3**	I4.0 wireless technologies raise the production of waste of electrical and electronic equipment

(*continued*)

Table 5.
Content analysis of the unintended impacts on environmental sustainability

Round 2 results	Coding	I4.0 unintended negative impacts on sustainability Environmental sustainability
Reasons for high probability/severity	a	Electronic components and consumables (e.g. batteries, chips, and antennas) have short life spans
	b	Manufacturers pay limited attention to forecasting and optimizing consumable usage
	c	Recycling obsolete components/products containing hazardous materials is difficult
	d	The recycling industry may struggle to cope with the wave of obsolete materials containing rare and hazardous components
	e	Developing countries have serious problems due to the lack of adequate recovery and recycling systems
Reasons for low probability/severity	f	Electronic consumables are rarely used in production environments
	g	New batteries have improved performance and durability
	h	Old equipment will be disposed of and recycled in accordance with recycling regulations
Median magnitude: $Me_p = 4$, $Me_s = 3$ **Agreement:** $IQR_p = IQR_s =$ high	**E4**	Hardware needed for I4.0 (e.g. sensors, chips, and connectivity infrastructure) requires higher consumption of natural resources
Reasons for high probability/severity	a	The proliferation of I4.0 technologies could lead to increased consumption of rare metals and other scarce materials
	b	The exponential demand for small devices has already led to a shortage of raw materials (i.e. the microelectronic chip crisis)
	c	Consumption of rare resources implies growing strategic dependence on producing countries
	d	The need for and consumption of materials leads to increased land use for mining and landfills
	e	Developers of new devices lack incentives to consider sustainability issues
Reasons for low probability/severity	f	Better technology should enable more efficient processes, offsetting the high consumption of raw materials
	g	Continued downsizing of components will reduce material and energy consumption
	h	Rare materials will be increasingly being replaced by more common and less expensive materials
Median magnitude: $Me_p = Me_s = 2$ **Agreement:** $IQR_p = IQR_s =$ high	**E5**	AM leads to higher energy consumption than traditional manufacturing processes
Reasons for high probability/severity	a	Manufacturing products with AM takes more time than traditional methods
	b	AM requires high energy consumption to melt the material
Reasons for low probability/severity	c	AM implementation is limited
	d	AM applications in processes such as prototyping are already leading to energy savings
	e	AM allows end-to-end processes, it uses less material and produces fewer defects and less waste, which means lower costs and less energy
	f	AM leads to zero wrong production buckets

Table 5.

Source(s): Authors' elaboration

Round 2 results	Coding	I4.0 unintended negative impacts on sustainability Social sustainability
Median magnitude: $Me_p = Me_s = 3$ **Agreement:** IQR_p = low, IQR_s = low	**S1**	Firms adopting I4.0 technologies have an overall negative impact on employment
Reasons for high probability/severity	a	Most of the physical labor-intensive jobs will be replaced
	b	Fewer employees will be needed to perform repetitive tasks
	c	The problem is re-training the existing workforce
	d	Digitalization education still lags behind
Reasons for low probability/severity	e	Layoffs will be offset by more efficient firms that will grow and hire
	f	The main effect on employment in industry occurred during automation. This time the effect is smaller
Median magnitude: $Me_p = Me_s = 3$ **Agreement:** IQR_p = high, IQR_s = low	**S2**	I4.0 technologies (e.g. CPS, IoT, cloud) cause a loss of employees’ privacy and personal autonomy
Reasons for high probability/severity	a	Developing countries will face a serious problem because labor regulations are not yet very strict
	b	Monitoring capability makes it easy to know what employees are doing (or not doing), where they are, and their exact work speed and performance
	c	Worker tracking is increasing with widespread use of wirelessly connected devices
Reasons for low probability/severity	d	In Europe, regulations to protect employee privacy are very strict
	e	Information systems provide very limited access to personal information
	f	Most of the technologies have the technical means to protect the data
Median magnitude: $Me_p = Me_s = 3$ **Agreement:** IQR_p = high, IQR_s = low	**S3**	Connectivity facilitated by I4.0 leads to an unhealthy work–life balance
Reasons for high probability/severity	a	Remote work provides flexibility and support for employees but can lead to monotony and “fear of being closely monitored”
	b	The “stay connected” concept is being promoted and its impact has already been seen in other sectors, such as healthcare in the US
	c	Monotony can increase as highly automated production processes are based on standard single operations
	d	Workers in highly mental-intensive fields, such as AI, may be affected
Reasons for low probability/severity	e	With I4.0, there are many ways to work remotely, providing flexibility for employees
	f	I4.0 helps workers simplify their tasks and automate manual and repetitive processes
	g	Digital technologies reduce the mental workload through assisting technologies or cognitive solutions
Median magnitude: $Me_p = Me_s = 3$ **Agreement:** $IQR_p = IQR_s$ = low	**S4**	Companies adopting I4.0 technologies will relocate production and related activities (e.g. R&D, logistics) to developed countries

(*continued*)

Table 6.
Content analysis of the unintended impacts on social sustainability

Round 2 results	Coding	I4.0 unintended negative impacts on sustainability Social sustainability
Reasons for high probability/severity	a	I4.0 will make developed economies competitive again
	b	I4.0 shifts competition from lower costs to higher capabilities. Reducing the impact of labor on cost can increase the probability of reshoring of manufacturing activities
	c	Better infrastructure and human capital are driving I4.0 in developed countries, leading to unemployment in developing nations
Reasons for low probability/severity	d	I4.0 enables supply chain regionalization
	e	Reshoring will only occur if developing countries do not adopt more sophisticated and efficient supply chains
	f	I4.0 has not yet led to significant reshoring, but rather to a slowdown in outsourcing projects
Median magnitude: $Me_p = Me_s = 2$ **Agreement:** IQR_p = high, IQR_s = low	**S5**	Autonomous robots lead to health and safety problems for workers
Reasons for high probability/severity	a	Robots that are not properly tested or deployed cause these problems
	b	Risk of accidents increases due to moving parts and mishandling of dangerous processes due to malfunction
	c	Workers in countries where there is no legal framework addressing this issue are at greater risk
Reasons for low probability/severity	d	Robots are now much safer, mainly due to the presence of sensors and limitations on the forces involved
	e	Autonomous robots are used in unsafe/non-ergonomic workplaces to assist workers
	f	Laws and certifications already address this issue (e.g. ISO 15066, ISO 10218)
Median magnitude: $Me_p = Me_s = 3$ **Agreement:** $IQR_p = IQR_s$ = high	**S6**	VR and AR cause headaches, dizziness, and other symptoms among operators
Reasons for high probability/severity	a	AR and VR should only be used in suitable workstations and for training purposes
	b	Overuse of VR and AR processes will likely cause such problems (e.g. there are no glasses on the market that are ideal for wearing during an 8-h shift)
	c	The probability and impact will be higher in countries where the rules are not clearly defined
	d	The number of companies using VR and AR is growing
	e	VR sickness has been a high-priority issue in the VR industry. Despite various efforts, there have been few results on how to alleviate users' discomfort
Reasons for low probability/severity	f	The number of firms currently using VR and AR is still limited
	g	VR and AR may not cause serious or long-term illnesses
Median magnitude: $Me_p = 2$, $Me_s = 3$ **Agreement:** $IQR_p = IQR_s$ = high	**S7**	AM materials cause harsh skin reactions, eye irritation, and allergies among operators

Table 6.

(*continued*)

Round 2 results	Coding	I4.0 unintended negative impacts on sustainability Social sustainability
Reasons for high probability/severity	a	The metal powders used in AM are carcinogenic and can cause chronic disease
	b	Respiratory problems increase with increased use of AM
	c	Developing countries with lower workplace safety standards will face this problem
Reasons for low probability/severity	e	AM implementation is limited
	f	Safety measures to protect the operator are already built into current AM devices
	g	Personal protective equipment must be used and operator safety recommendations must be followed

Source(s): Authors’ elaboration

Table 6.

have a greater impact on developing countries ($Me_p = Me_s = 3$; $IQR_p = 1$, $IQR_s = 2$). Furthermore, I4.0 technologies may lead to an unhealthy work–life balance, stress and mental health problems [S3]. Remote work generally provides flexibility and support for employees but may cause monotony and “fear of being closely monitored”. This has already been observed in some sectors ($Me_p = Me_s = 3$; $IQR_p = 1$, $IQR_s = 2$). Regarding workplace safety and ergonomics, the Delphi participants considered that VR and AR caused problems such as headache and dizziness [S6]. The experts warned that VR and AR technologies must be used only in suitable workstations and for short periods ($Me_p = Me_s = 3$; $IQR_p = IQR_s = 1$).

Participants did not support the negative implications of autonomous robots ($Me_p = Me_s = 2$; $IQR_p = 1$, $IQR_s = 2$) [S5] and AM on the safety of workers ($Me_p = 2$, $Me_s = 3$; $IQR_p = IQR_s = 1$) [S7]. Reasons provided included the fact that “robots are now much safer” and that laws and certifications address this issue. For AM, limited production usage and personal protection tools made this issue less likely for experts.

Finally, the experts did not reach a high level of consensus on job replacement, with some acknowledging that layoffs will be offset by more efficient companies growing and hiring ($Me_p = Me_s = 3$; $IQR_p = 1.75$, $IQR_s = 2$) [S1]. Similarly, regarding the relocation of production and related activities to developed countries [S4], participants argued that “I4.0 will make the economies of developed countries competitive again” but at the same time “allows regionalization of supply chains” ($Me_p = Me_s = 3$; $IQR_p = IQR_s = 2$).

4.3 Potential mitigation actions

The experts highlighted various corrective actions to counteract the adverse sustainability effects of I4.0. These actions were classified after the first round of the Delphi study into firm-level actions, supply chain-level actions and policy interventions. In the second round, the experts were asked to confirm the mitigation actions, comment on them and add more possible interventions. Table 7 shows the full list of mitigation actions proposed.

4.3.1 Environmental sustainability. The respondents suggested some mitigation actions at the company level [F1-F24]. For instance, participants proposed accurate monitoring and forecasting of energy and waste through key performance indicators (KPIs) [e.g. F2, F8, F9], offsetting additional resource consumption and waste by using renewable resources [F1, F16, F22], preventing issues from the design phase by using environmentally friendly components and materials [F13, F21, F23], encouraging gradual implementations or retrofitting/modular solutions [F3, F10, F12] and reusing/implementing durable technologies [F11, F14, F17].

I4.0 unintended negative impacts on sustainability	Mitigation actions Firm-level actions (F)	Supply chain-level actions (C)	Policy interventions (P)
Environmental sustainability			
E1	F1. Using electricity from renewable sources	C1. Using green data centers utilizing energy-efficient and up-to-date technologies	P1. Encouraging with economic incentives the use of advanced technologies to optimize energy use (e.g. AI)
	F2. Close monitoring of energy consumption by adopting standards to control equipment's utilization rate	C2. Sharing data throughout the supply chain and reducing the need for multiple hardware devices for the same information	P2. Requiring the purchase of green energy to power new digital devices
	F3. Implementing I4.0 technology in a gradual way, starting from a pilot area	C3. Collaborating with service companies that support manufacturing firms to efficiently manage energy consumption	P3. Applying decarbonizing policies to force companies to adopt standards and measurement systems to reduce total energy consumption
	F4. Temporary storing of the data, edge computing		
	F5. Using AI to manage energy consumption		
	F6. Employee training to promote the correct and environmentally responsible use of technologies		
	F7. Shutting down of devices when not in use (e.g. overnight, holidays)		
	F8. Integrating energy consumption KPIs in project phases		
E2	F9. Accurate monitoring of obsolescence	C4. Establishing a recovery and recycling system	P4. Encouraging and rewarding virtuous behaviors in reuse and recycling of materials through norms, laws, and protocols
	F10. Using modular systems to update obsolete devices (retrofitting)	C5. Upstream and downstream re-evaluation and recovery of non-frontier technologies before replacement	P5. Making retrofitting more attractive through tax incentives
	F11. Promoting the reuse of obsolete technology internally in other processes	C6. Purchasing sustainable components and materials	
	F12. Replacing devices in a gradual, planned, and manageable way		

(*continued*)

Table 7.
Mitigation actions proposed by Delphi panel experts

I4.0 unintended negative impacts on sustainability	Mitigation actions		
	Firm-level actions (F)	Supply chain-level actions (C)	Policy interventions (P)
E3	F13. Preventing the problem through "green design" of technology (e.g. batteries with higher energy densities, photovoltaic devices, energy harvesting)	C7. Developing recycling and circular economy initiatives	P6. Fostering the reuse of resources through economic incentives or legal frameworks
	F14. Selecting durable and robust technologies		P7. Financing and investing in applied research to dispose of waste generated by the industry
E4	F15. Asking for proper technical consultancies to use hardware only where it is necessary	C8. Recycling and reusing initiatives	P8. Developing national/international regulations regarding strategic raw materials
	F16. Balancing and compensating resource consumption with renewable sources in other parts of the value chain	C9. Carrying out responsible procurement (e.g. buying devices with a certified low level of consumption of natural resources)	P9. Incentivizing the production and use of machines designed to be disassembled/recycled
	F17. Being cautious in replacing the legacy equipment and doing so only when necessary		
E5	F18. Simulating AM's energy consumption through predictive models to compare it to traditional manufacturing	C10. Using renewable energy supply	P10. Supporting R&D on lowering energy consumption of AM
	F19. Applying AM only for selected complex products		
	F20. Utilizing standard and reusable designs		
	F21. Using more environmentally friendly filaments (e.g. with lower melting points)		
	F22. Balancing and compensating energy consumption with renewable sources in other parts of the value chain		
	F23. Optimizing product geometries at the design stage to reduce energy consumption during manufacturing		
	F24. Improving capacity utilization of AM devices		

(*continued*)

Table 7.

I4.0 unintended negative impacts on sustainability	Mitigation actions		
	Firm-level actions (F)	Supply chain-level actions (C)	Policy interventions (P)
Social sustainability			
S1	F25. Developing workforce re-skilling and up-skilling plans	C11. Requalifying employees through supplier development programs within the supplier network	P11. Supporting training at different educational levels in skills that the industry will demand in the future
	F26. Reducing employees' working hours per week without reducing wages (assuming I4.0 will increase worker productivity). Hiring more staff to cover the reduction in working hours		P12. Encouraging re-skilling and up-skilling of employees who have lost their jobs
S2	F27. Defining and negotiating strict data privacy policies with unions	C12. Delegating the management of private data to external certified bodies	P13. Developing internationally valid standards and guidelines addressing data governance and ethical use of data
	F28. Defining codes of conduct and ethical standards		P14. Reviewing labor legislation to ensure sensible data protection in practice
	F29. Regularly assessing privacy compliance		
	F30. Investing in cybersecurity and developing secure architectures, systems and components		
S3	F31. Preserving employees' wellbeing and fostering technology acceptance (e.g. user involvement, supervisor support, information sharing)	C13. Outsourcing services to monitor workers' wellbeing and to support manufacturing companies in implementing specific actions	P15. Reinforcing the regulations on free time, the right to disconnect, and remote work
	F32. Respecting time off and right to disconnect		P16. Developing industry standards addressing psychological effects of the technology
	F33. Monitoring wellbeing of workers (e.g. information overload)		
	F34. Implementing technology in an appropriate and gradual way, starting from a pilot area		

Table 7. (*continued*)

I4.0 unintended negative impacts on sustainability	Mitigation actions		
	Firm-level actions (F)	Supply chain-level actions (C)	Policy interventions (P)
S4	F35. Considering the reduction of inequality within and among countries (Sustainable Development Goal 10) as a true strategic value of the company	C14. Supporting suppliers based in developing countries in their digital transformation process C15. Improving network coordination to enable regionalization C16. Balancing the sourcing of goods with dual/multiple sourcing strategies from developed and developing countries	P17. Establishing synergies between companies and local communities (including universities) P18. Defining international laws to avoid inequalities and preserve developing countries' economies (e.g. providing financial support)
S5	F36. Using only cobot technologies equipped with sensors and safety systems F37. Including interaction with robots in safety training F38. Isolating robot activities from operators F39. Applying security measures repeatedly to prevent and counteract incorrect behavior	C17. Cooperating with manufacturers/integrators to ensure equipment meets safety standards and addresses hazards in the intended use	P19. Strengthening safety regulations based on accident reports to avoid health and ergonomics problems P20. Updating standards such as ISO 15066 and 10218
S6	F40. Allowing timely breaks for operators using VR/AR F41. Selecting technologies with reduced side effects (e.g. mixed reality) F42. Involving the operators in the proof of concept F43. Applying VR/AR only when/where it is necessary F44. Requesting medical advice to assess the physical ability of workers who will use VR/AR technologies F45. Implementing VR/AR gradually	C18. Cooperating with manufacturers/integrators to ensure equipment meets safety standards and addresses hazards in the intended use	P21. Strengthening safety regulations based on accident reports to avoid health and ergonomics problems P22. Updating and applying standards that address VR/AR applications in industry

(*continued*)

Table 7.

I4.0 unintended negative impacts on sustainability	Mitigation actions		
	Firm-level actions (F)	Supply chain-level actions (C)	Policy interventions (P)
S7	F46. Wearing personal protective equipment F47. Using safer materials (e.g. ecologic, hypoallergenic) F48. Building air extraction systems F49. Isolating 3D printers from operators	C19. Supporting suppliers in the research and development of new, less hazardous materials	P23. Integrating this issue into safety regulations P24. Supporting R&D of safer materials

Table 7.

Source(s): Authors' elaboration

Regarding the supply chain level [C1-C10], collaborating with environmentally friendly suppliers and service providers [e.g. C1, C3, C6], establishing recycling and reusing initiatives [e.g. C4, C5, C8] and sharing data to avoid hardware duplicities and thus save energy throughout the supply chain [C2] are the most relevant mitigation actions.

Furthermore, the panel experts called for policy interventions [P1-P10] such as encouraging "green" initiatives through national/international economic incentives, laws and standards [e.g. P3, P5, P8], supporting research [P7, P10] and requiring additional energy consumption to be balanced with renewable energy resources [P2].

4.3.2 Social sustainability. At company level [F25-F49], firms may implement preventive actions such as promoting cybersecurity and data privacy [e.g. F28, F29, F30], monitoring and preserving workers' wellbeing [e.g. F31, F32, F40], and using safety systems [e.g. F36, F46, F48]. In addition, the experts suggested redesigning workplaces [e.g. F38, F41, F49], implementing technology gradually [F34, F45] and developing training plans in I4.0 [F25, F37] to avoid some of the social concerns produced by I4.0 technologies.

Throughout the supply chain [C11-C19], cooperation is essential to ensure that I4.0 equipment meets all safety recommendations [C17, C18, C19], support and coordinate I4.0 adoption at partner companies in developing countries [C14, C15, C16] and to retrain and relocate employees [C11]. In addition, outsourcing services such as data management and monitoring of the welfare of workers [C12, C13] are considered appropriate solutions.

Finally, policy interventions acquire special relevance for social sustainability [P11-P24]. Policymakers could update laws and standards to protect data privacy and integrate physical and psychological risks derived from I4.0 technologies [e.g. P13, P15, P22]. Moreover, institutions should support I4.0-focused training and research [P11, P12, P24] and foster collaboration between firms and developing economies [P17, P18].

5. Discussion

The main goal of this study was to challenge the common assumptions of the I4.0 and sustainability literature (i.e. u1, u2). According to the *sixth principle* of problematization, alternative assumptions are evaluated to establish if they can generate new propositions. The results show that the Delphi panel disagrees with the underlying assumptions of the I4.0 literature. Four unintended negative environmental effects appeared likely to happen and/or were considered severe problems by the expert panel. In particular, new I4.0-related devices may produce an increase in electronic and non-electronic waste [E2, E3] and require scarce raw material resources, in addition to other natural resources [E1, E4]. Accordingly, the following alternative assumption can be proposed:

a1. I4.0 technologies may have unintended negative impacts on firms' environmental sustainability performance.

Moreover, this study highlights, through the opinions of experts, three negative social impacts related to the loss of privacy and autonomy of employees [S2], work–life balance issues [S3] and health problems derived from the use of AR and VR in the workplace [S6]. These issues are likely to happen and/or are considered severe. In light of the results, the following alternative assumption can be proposed:

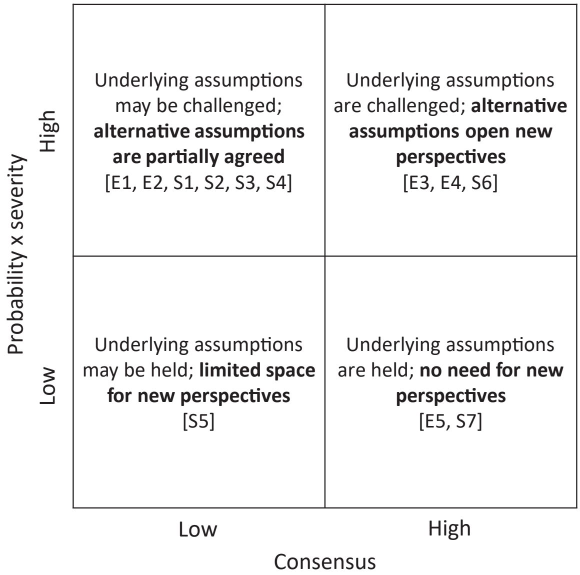
a2. I4.0 technologies may have unintended negative impacts on firms' social sustainability performance.

On the contrary, some of the results of this research are indeed consistent with the underlying I4.0-sustainability assumptions (u1, u2). For example, the increase in energy consumption associated with the implementation of AM (Huang *et al.*, 2013) was judged unlikely by experts [E5]. Studies such as Dalmarco *et al.* (2019) point to safety problems as one of the main restrictions of collaborative robotics [S5]. Nonetheless, the Delphi participants considered that, robots are much safer than they used to be and improve social sustainability by assisting workers at unsafe workplaces. Chan *et al.* (2020) suggest that emissions of particulates and volatile organic compounds (VOCs) increase when multiple 3D printers are running simultaneously, posing a risk to operators [S7]. However, due to the limited use of AM and the safety measures that have been put in place, experts are minimizing the unintended effects.

In general, greater consensus was found for the negative impacts on environmental aspects. The social drawbacks of I4.0 in terms of potential job losses due to automation [S1] are indeed still very controversial due to the low consensus on both probability and severity, and the high stability reached in the second round. Studies such as Birkel and Müller (2021) acknowledge this dilemma between job creation and loss. Likewise, low agreement levels and high stability were obtained regarding the possible reshoring phenomenon produced by I4.0, which could increase the gap between developed and developing countries [S4]. These results agree with the findings of Barbieri *et al.* (2022).

Figure 1 illustrates the results of this research from a theoretical perspective to evaluate what evidence supports or rejects the alternative assumption ground. The upper part of the figure shows the evidence supporting the alternative assumptions (a1, a2) with medium-high probability and/or severity (probability x severity ≥ 9). While the evidence with the greatest consensus is shown in the right part of the figure (IQR_p x $IQR_s = 1$). The results highlight, with high consensus on both probability and severity, several negative unintended consequences for both environmental [E3, E4] and social [S6] aspects (upper right quadrant of figure). These consequences challenge the current assumptions in the literature (u1, u2). On the other hand, some results support with high consensus the underlying hypotheses, as some unintended impacts have low probability and severity scores [E5, S7], therefore no additional perspectives are needed (right lower quadrant of the figure).

The results related to specific technologies that achieved low consensus (IQR_p x $IQR_s > 1$) but high stability during the Delphi rounds can be considered controversial. These findings are indicators of the success of the problematization approach and may stimulate the audience to take the challenging assumptions (a1, a2) seriously, generating interest and opening new research directions (see upper left quadrant of Figure 1) (Alvesson and Sandberg, 2011). Although the panel does not reach a high consensus on the probability of occurrence of connectivity and computing energy consumption [E1] and the severity of obsolescence [E2], the unintended negative impact of I4.0 on the environmental sustainability performance is partially supported by the expert panel and further research may be needed to confirm a1. On the other hand, the unintended impacts of I4.0 on social performance are more controversial due to the lower consensus reached and the contrasting evidence supporting



Source(s): Authors' elaboration

Figure 1.
Evaluation of the alternative assumption ground

and rejecting a2. Therefore, further research is needed to confirm the negative effects on privacy and personal autonomy [S2] and work–life balance [S3]. These partially support a2, but there was little consensus on the severity ratings (IQR_p x IQR_s = 2). Impacts on employment [S1] and backshoring [S4] implications are partially agreed but an even lower level of consensus was reached (IQR_p x IQR_s > 2) and therefore require further investigation.

The safety problems derived from the implementation of autonomous robots [S5] were considered of low importance (probability x severity = 4) and reached low consensus (IQR_p x IQR_s = 2). There is limited room for new perspectives, further research may confirm the underlying assumption regarding the social benefits of I4.0 (u2).

The research findings also highlight the importance of some actions to mitigate the unintended negative sustainability impacts of I4.0 at company, supply chain and policy levels. Based on the empirical evidence from the expert panel, the following alternative assumptions are proposed to reinforce the a1 and a2 alternative assumptions:

a1_1. There are actions that mitigate the unintended negative impacts of I4.0 technologies on firms' environmental sustainability performance.

a2_1. There are actions that mitigate the unintended negative impacts of I4.0 technologies on firms' social sustainability performance.

Some of the proposed actions may help prevent or mitigate some unintended negative impacts, but at the same time may unintentionally conflict with other sustainability objectives. For instance, environmental actions in the supply chain, such as "developing the circular economy and recycling", were suggested to mitigate the material waste generated by I4.0. Lopes de Sousa Jabbour *et al.* (2018) suggest that I4.0 may help develop a path towards the circular economy and closed-loop supply chains, reducing material waste. While I4.0 can facilitate the circular economy through better traceability of waste, it can also lead to more data processing with a consequent increase in energy consumption [E1] (see Table 5). The findings also indicate that the use of sensors and traceability devices could increase the generation of waste [E3], thus limiting the benefits of the circular economy. Firms need to be cautious even when implementing I4.0 for sustainability purposes, understanding the benefits but also the unintended negative impacts.

Regarding proposed policy interventions, the respondents primarily recommended incentivizing “green” behaviors through tax reductions, providing financing and developing new targeted frameworks and roadmaps coupling digital transformation and sustainability. Moreover, respondents recommended more regulatory actions addressing privacy and data security issues. Besides, Bai *et al.* (2020) suggest that sustainability trade-offs may not only exist across technology and sustainability dimensions, but also across industries, a result which was also observed in this study. For instance, if regulators decide to support industry investments in autonomous and collaborative robots to enhance workers’ safety [S5] – increasing social sustainability – the resulting unintended impact may be a higher level of obsolescence and electronic waste in the manufacturing industry [E2], thus decreasing environmental sustainability. Currently, governments are supporting the I4.0 transition with national plans to promote competitiveness (Chiarini, 2021). Respondents suggest that policy incentives to obtain new technology increase the rate of replacement of technology, leading to increased waste and resource use [E2, E3, E4]. Experts recommended that governments should be aware of the unintended negative sustainability effects of I4.0 technologies and deploy I4.0-focused actions to prevent them before they occur. In this sense, panel experts suggested further governmental actions coupling I4.0 and sustainability through standards, laws, training and research.

6. Conclusions, limitations and future research directions

Previous studies such as Bohnsack *et al.* (2022), Beltrami *et al.* (2021) and Ghobakhloo *et al.* (2021) suggest that the positive implications of I4.0 for firms do not automatically translate into positive effects for the environment or society, which raises the need to challenge the current literature on I4.0 and sustainability.

This study makes several contributions to theory, practice and policy. The research findings accept and reject some of the arguments underlying the existing literature (u1, u2). Thus, perfectly accomplishing the principles and objectives of problematization and generating further interest among the targeted audiences (Alvesson and Sandberg, 2011). A high degree of consensus has been reached on the existence of unintended environmental impacts. Social unintended consequences of I4.0 adoption remain instead controversial.

This paper contributes to the existing literature by (1) providing a structured and prospective analysis of the unintended negative effects of I4.0 technologies on sustainability performance using a problematization approach; (2) identifying the underlying mechanisms and potential mitigation strategies to such effects; and (3) providing and evaluating various alternative assumptions that challenge the literature and that may guide further research. These results can be tested or validated in extensive empirical studies. For instance, future studies might be needed to:

(1) Quantify the unintended negative impacts that are likely to occur, are severe, and have a high level of consensus [E3, E4, S6] thus going beyond general statements which lack quantitative foundations. Case study research used in conjunction with survey-based research can be useful to confirm the alternative assumption ground (a1, a2).

(2) Resolve controversial assumptions about unintended negative environmental [E1, E2] and social impacts [S1, S2, S3, S4, S5]. Survey studies may be useful to definitively support or reject alternative assumptions (a1, a2).

(3) Test the effectiveness of the proposed actions (a1.1 and a2.1) to prevent or mitigate the negative impacts of I4.0. Interview-based multiple case studies might be effective.

This study can be relevant for managers who plan and oversee the effective and sustainable implementation of I4.0 technologies. Practitioners can become more aware of the negative sustainability implications of I4.0 and may adopt the specific mitigation actions proposed by experts at the company and supply chain levels. Based on the Delphi results, some severe negative socio-environmental unintended implications are likely to occur in the coming years; therefore, I4.0 practitioners can prevent them before they become apparent.

In light of the results, policy makers can promote supply chain collaboration and international cooperation to achieve sustainability goals. The policy interventions presented are especially relevant in the context of "Industry 5.0". This novel concept, which is being supported by the European Commission, complements the existing I4.0, providing a vision of industry that aims beyond efficiency and productivity and strengthens industry's role in and contribution to society. The policymaking actions suggested by the panel of experts may help to shape this approach by transitioning to a "sustainable, human-centric and resilient industry" (European Commission, 2022) rather than the technology-oriented vision of I4.0.

This research presented a two-round Delphi study with a large and heterogeneous sample of professionals. This methodological approach nevertheless has some limitations that need to be acknowledged. First, some studies recommend three rounds of data collection for Delphi studies. In this study, two rounds were sufficient to achieve adequate levels of agreement (IQR) or stability (Spearman's ρ). This approach ensured that participant fatigue was minimized, which in turn facilitated a higher response rate and validity of responses (Mitchell, 1991). However, it is possible that a third round might have revealed additional insights. Second, respondents' perceptions may be influenced by factors such as the level and scope of digitalization, maturity, and sector of the companies in which they work. Nonetheless, one of the goals of problematization is to obtain contrasting arguments to generate interest on the topic.

To conclude, during the two rounds of this Delphi study, experts – especially management consultants and practitioners – showed great interest in the research topic, confirming the success of the problematization approach. According to the general opinion of the panel, there is indeed a "dark side" to I4.0 that needs to be mitigated with specific actions. The research findings suggest that collaboration between academia, practice and institutions is crucial to address these issues in a timely manner.

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Appendix

Table A1.
Summary of the literature reviewed

Author (s)	Year	Research subject	Research methodology	Sample	Technologies analyzed	E1	E2	E3	E4	E5	S1	S2	S3	S4	S5	S6	S7
						Unintended negative sustainability impacts supported											
Ancarani *et al*	2019	I4.0; backshoring; offshoring	Secondary data analysis	495 relocation initiatives	Bundle of I4.0 technologies									x			
Arrizubieta *et al*	2020	AM; sustainability; waste	Literature review	–	AM					x							x
Bai *et al*	2020	I4.0; sustainability; triple bottom line	Secondary data analysis	40 disruptive applications	Bundle of I4.0 technologies	x						x					
Barbieri *et al*	2022	I4.0; relocation; policies	Secondary data analysis	118 relocation initiatives	Number of patents related to I4.0 and I4.0 policies adoption									x			
Beltrami *et al*	2021	I4.0; sustainability; triple bottom line	Literature review	117 publications	Bundle of I4.0 technologies	x		x	x	x	x	x	x				
Birkel and Müller	2021	I4.0; SCM; sustainability; triple bottom line	Literature review	55 publications	Bundle of I4.0 technologies	x	x	x	x	x	x						
Birkel *et al*	2019	I4.0; sustainability; triple bottom line; risk management	Expert Interview	14 industry experts	Bundle of I4.0 technologies	x	x	x	x		x	x	x	x			
Biswas *et al*	2022	Blockchain; SCM; environmental performance	Game theory model	1 manufacturer and 1 retailer	Blockchain	x											
Bonilla *et al*	2018	I4.0; sustainability; triple bottom line	Conceptual	–	Bundle of I4.0 technologies	x	x	x	x	x				x			
Chan *et al*	2020	AM; emissions; occupational health	Experiment	2 scenarios	AM												x
Chiarini	2021	I4.0; environmental performance	Qualitative-quantitative approach	19 interviews and 260 survey responses	Bundle of I4.0 technologies			x	x	x							
Cirillo *et al*	2021	I4.0; autonomy; employment	Multiple case study	3 automotive factories	Bundle of I4.0 technologies							x					
Coldwell	2019	I4.0; workplace; employment	Secondary data analysis	–	I4.0 concept								x				

(*continued*)

Author (s)	Year	Research subject	Research methodology	Sample	Technologies analyzed	Unintended negative sustainability impacts supported E1	E2	E3	E4	E5	S1	S2	S3	S4	S5	S6	S7
Culot *et al*	2020	I4.0; value chain; scenario planning	Delphi study	76 experts	Bundle of I4.0 technologies				x					x			
Dachs *et al*	2019	I4.0; backshoring; offshoring	Survey	1700 manufacturing firms	Bundle of I4.0 technologies									x			
Dalmarco *et al*	2019	I4.0; adoption challenges; technology provider companies	Single case study	1 cluster of technology companies	Bundle of I4.0 technologies										x		
Di Carlo *et al*	2021	I4.0; retrofitting; safety; performance	Single case study	1 process plant	Bundle of I4.0 technologies		x										
Ford and Despeisse	2016	AM; sustainability; resource efficiency	Secondary data analysis	16 examples of implementation	AM					x							x
Garrido-Hidalgo *et al*	2020	IoT; circular economy; WEEE	Single case study	1 supply chain	IoT			x	x								
Ghobakhloo	2020	I4.0; sustainability; triple bottom line	Literature review	72 publications	Bundle of I4.0 technologies	x	x		x		x			x			
Ghobakhloo and Fathi	2019	I4.0; lean manufacturing; triple bottom line	Single case study	1 small manufacturing firm	Bundle of I4.0 technologies		x				x	x					
Ghobakhloo *et al*	2021	I4.0; sustainability; drivers; success determinants	Literature review	745 publications	Bundle of I4.0 technologies	x					x			x			
Grigore *et al*	2021	Digital technologies; corporate social responsibility; paradox theory	Expert interviews	39 corporate social responsibility managers	Digitalization concept						x	x	x				
Huang *et al*	2013	AM; energy consumption; social performance; occupational health	Literature review	–	AM					x							x

(*continued*)

Table A1.

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Author (s)	Year	Research subject	Research methodology	Sample	Technologies analyzed	Unintended negative sustainability impacts supported E1	E2	E3	E4	E5	S1	S2	S3	S4	S5	S6	S7
Kamble *et al*	2018b	I4.0; drivers; barriers	ISM-fuzzy MICMAC	14 experts	Bundle of I4.0 technologies						x						
Leso *et al*	2018	I4.0; workforce; occupational health; risk management	Literature review	22 publications	Bundle of I4.0 technologies						x	x	x		x		
Li *et al*	2019	Human-robot interaction; occupational health; sensors	Experiment	–	Autonomous robots										x		
Müller and Voigt	2018	I4.0; sustainability; triple bottom line; SMEs	Survey	329 manufacturing SMEs	I4.0 and Made in China 2025 concepts	x		x			x			x			
Müller *et al*	2018	I4.0; sustainability; drivers; barriers; triple bottom line	Survey	746 manufacturing companies	I4.0 concept		x				x						
Pegoraro *et al*	2022	Industrial policy; global value chain; reshoring	Single case study	1 manufacturing firm	I4.0 policies adoption									x			
Rodriguez *et al*	2021	AR; smart glasses; performance; ergonomics	Experiment	63 participants	AR											x	
Schneider and Kokshagina	2021	Digital transformation; challenges; impact	Expert interviews	7 managers	Bundle of I4.0 technologies						x		x				
Singh and Bhanot	2020	I4.0; IoT; barriers; manufacturing	DEMATEL, MMDE, ISM	10 experts	Bundle of I4.0 technologies	x											
Stock *et al*	2018	I4.0; sustainability; triple bottom line	Expert interviews	–	Bundle of I4.0 technologies	x			x	x	x						
Sugiyama *et al*	2017	Digital transition; unintended side effects; risk management	Roundtable	7 experts	Bundle of I4.0 technologies							x					
Tsai and Huang	2018	AR; user interface; safety	Experiment	20 participants	AR											x	

(*continued*)

Author (s)	Year	Research subject	Research methodology	Sample	Technologies analyzed	Unintended negative sustainability impacts supported E1	E2	E3	E4	E5	S1	S2	S3	S4	S5	S6	S7
Väisänen *et al*	2019	AM; occupational health; air emissions	Experiment	5 AM methods	AM												x
Wang *et al*	2019	AR; VR; visual fatigue; ergonomics	Experiment	30 participants	AR and VR											x	
Yoon *et al*	2014	AM; sustainability; energy consumption	Multiple case study	3 manufacturing processes	AM					x							

Source(s): Authors' elaboration

Table A1.