The “dark side” of Industry 4.0: How to make technology more sustainable?

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Abstract

Purpose: Recent literature has highlighted several positive impacts of Industry 4.0 (I4.0) technologies on sustainability performance. In contrast, empirical research analysing the negative effects on environmental and social sustainability is still scarce and anecdotal. The goals of this study are: (1) to identify the possible negative impacts of I4.0 technologies on sustainability; (2) to highlight the underlying motivations and mechanisms; and (3) to identify actions to mitigate such impacts.

Design/methodology/approach: In line with the exploratory, interdisciplinary, and forward-looking nature of the research, the authors carried out a Delphi expert study. 43 experts from academia and practice with heterogeneous professional backgrounds, experiences and nationalities were selected. Two rounds of data collection were performed, until convergence or stability of the answers was reached.

Findings: The results show that there is a “dark side” of I4.0, highlighting various negative effects on environmental and social aspects. Moreover, the findings suggest various corrective actions at firm, supply chain and policy levels to mitigate such effects.

Originality: This study is one of the few to systematically investigate the negative impact of I4.0 technologies on sustainability performance, providing a rigorous overview and a clear vision of the future while presenting possible solutions.

Practical implications: The qualitative evidence provided can be relevant for managers to anticipate possible sustainability issues in I4.0 technologies implementation. In addition, the policy interventions highlighted might be applicable at national and international levels to mitigate the sustainability issues.

Keywords: Digital transformation, Sustainability, Delphi study, Environmental performance, Social performance

1. Introduction

In recent years, the Industry 4.0 (I4.0) concept has gained considerable interest from scholars and practitioners across technical and managerial disciplines (Dieste *et al.*, 2022). This concept is frequently labelled as the "fourth industrial revolution" and involves the digitalization of traditional manufacturing processes through the use of smart technologies such as cyber physical systems (CPS), internet of things (IoT), artificial intelligence (AI), and cloud computing. Nowadays, more and more firms are implementing I4.0 technologies to pursue greater levels of efficiency and innovation (Culot *et al.*, 2020).

Recent literature has identified several positive sustainability implications derived from the adoption of I4.0 technologies (see Beltrami *et al.*, 2021 and Birkel and Müller, 2021 for a review on the topic). Some authors suggest that new technologies such as the Internet of Things (IoT), sensors, and big data analytics can facilitate waste reduction and monitor energy consumption of manufacturing activities, leading to energy savings (Bai *et al.*, 2020). Similarly, social sustainability benefits, such as better working conditions, can also be achieved through the adoption of human-machine interaction technologies (Müller and Voigt, 2018).

In contrast, few studies have focused on the possible negative effects of I4.0 technologies on environmental and social sustainability (Ghobakhloo *et al.*, 2021). Scholars argue for instance that a fully automated production could lead to higher primary resource consumption (Stock *et al.*, 2018); that digital technologies such as blockchain or cloud computing applied in 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 data sharing used for decision making (Cirillo *et al.*, 2021). In other words, while the positive effects of I4.0 technologies on sustainability have recently attracted significant attention, extant research on the negative effects (i.e., the "dark side" of I4.0) is still scarce and anecdotal, as also highlighted by recent reviews on the topic (Birkel and Müller, 2021; Ghobakhloo et al., 2021; Beltrami et al., 2021).

This research aims to fill the lack of knowledge about the negative effects of I4.0 on sustainability by providing a systemic vision of their nature and their potential mitigation actions. The goals are therefore: (1) to identify the possible negative impacts of the I4.0 technologies (e.g., autonomous robots, cloud technologies, IoT, and additive manufacturing) on firms' environmental and social sustainability aspects; (2) to highlight the motivations and mechanisms behind them; and (3) to identify possible corrective actions to mitigate such effects.

To achieve these aims, a comprehensive review of the literature on the negative sustainability outcomes of I4.0 technologies has first been conducted. This allowed to identify 12 potential negative impacts. Then, a Delphi study involving 43 international experts was performed to assess the probability of occurrence in the next 5 years and the severity of each I4.0 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. An exploratory research methodology, such as the Delphi study approach, was selected due to the novelty and interdisciplinary nature of the research problem. The Delphi methodology is appropriate for structuring a group communication process, allowing individuals to deal with complex problems (Okoli and Pawlowski, 2004). This method turns out to be very helpful for researchers to identify the variables of interest, generate propositions, identify causal relationships and make predictions (Flynn *et al.*, 1990).

The findings highlight various negative impacts on environmental and social dimensions that are likely to occur and are considered severe problems according to the expert panel. Therefore, this study is one of the first to systematically investigate the “dark side” of I4.0, providing not only a general and prospective view of the negative effects and their possible causes, but also potential strategies to mitigate or prevent them. This research captures the opinion of I4.0 experts from academia and industry, opening a set of important avenues for future research. The findings 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 at firm, supply chain and policy-making levels to prevent or mitigate the adverse effects of digital technologies.

2. Background

In recent years, many academic and practitioners studies have been focused on exploring the interplay between I4.0 and sustainability performance (Beltrami *et al.*, 2021; Birkel and Müller, 2021). Some scholars highlight that I4.0 technologies positively affect different dimensions of firms’ environmental performance. For instance, I4.0 technologies can be used to promote resource efficiency and materials used in production processes (Müller and Voigt, 2018). Mohamed *et al.*, (2019) discuss that I4.0 - by applying optimization algorithms, modelling, and simulation - can offer different energy efficiency opportunities to the manufacturing industry. Furthermore, according to Stock et al. (2018) I4.0 has potential to avoid overproduction, reducing the total amount of waste produced by organizations. Finally, Haass et al. (2015)

propose that I4.0 technologies such as simulation and AI can promote the reduction of carbon emissions.

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

Literature on the possible effects of I4.0 technologies has unveiled several opportunities to enhance sustainability performance. Nevertheless, recent review studies such as Ghobakhloo et al. (2021) and Beltrami et al. (2021) reveal that literature is largely over-optimistic regarding the economic and socio-environmental impacts of I4.0. Various studies have already acknowledged some negative effects of I4.0 on sustainability performance. However, according to recent literature review studies there is still a need for empirical studies focusing on the negative effects of I4.0 technologies' implementation on environmental and social sustainability (Beltrami *et al.*, 2021; Birkel and Müller, 2021). Also empirical research such as Chiarini (2021) demand a deeper investigation of the environmental issues emerging from I4.0 implementation. Bai et al. (2020) broaden the scope of the study of the I4.0 impacts and suggest that it is also necessary to delve into the nature of the negative sustainability outcomes of I4.0 considering also social aspects.

In addition, studies call for investigating potential public policy and multilateral agreements to control the unforeseen environmental and social sustainability impacts of I4.0 and industrial digitalization (Beltrami *et al.*, 2021). The role of governments and public institutions is considered crucial to mitigate the negative impacts of I4.0 on sustainability through policy actions (Birkel and Müller, 2021).

For this purpose, a literature review on I4.0 negative impacts was carried out. A keyword search using Elsevier's Scopus database was performed. Considering the multifaceted, wide ranging I4.0 applications, 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; the other to sustainability. Only articles that contained the keywords in the title, abstract or keywords were selected, without specifying a time constraint:

> ("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 "Digital twin" OR "Software-defined manufacturing") AND ("Sustainab*" OR "Green" OR "Environmental Performance" OR "Social Performance").

Two researchers independently analysed the literature evidence to improve the reliability of the negative I4.0 impacts proposed. Both researchers followed a systematic approach to ensure the objectivity of the research process (Duriau *et al.*, 2007). During the analysis, validity and reliability were supported by several rounds of discussion among the research group to refine the final list of I4.0 negative sustainability effects evidenced in the literature, as well as to discuss disagreements. The authors shared their findings with three external I4.0 and sustainability experts, who were not involved in the research team therefore took the role of "resident devil's advocate" to bring a more objective view to the literature review process. Further modifications were carried out until a consensus was clarified. Finally, the literature analysis identified 12 potential negative effects of I4.0 on social/environmental sustainability (see Section 2.1).

2.1. Potential negative effects of I4.0 on sustainability

Environmental sustainability

Previous research indicates various potential negative impacts of I4.0 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]. Studies such as Müller and Voigt (2018) and Stock et al. (2018) conclude that ecological challenges may appear due to the increased energy used by data 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) captures the trade-off between traceability and sustainability and indicate that blockchain negatively impacts the environment due to its 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, in some cases, hazardous waste [E2]. Some of the firms analysed by Müller et al. (2018), point out that I4.0 adoption imposed some difficulties regarding the different automation degrees and lifecycle stages of the machinery, this caused the need to replace some machines. Ghobakhloo and Fathi (2019) carry out an in-depth five-year case study examining the digital transformation of a manufacturing firm and emphasize the high costs of dismantling outdated devices faced by the company under analysis. Birkel et al. (2019) and Di Carlo et al. (2021) also indicate that costs and time to replace obsolete machines could be unsustainable for many companies, most of the old machinery has to be discarded and ends up in landfills during I4.0 implementation.

Third, wireless technologies include components and consumables (e.g., batteries, antennas) that raise the production of waste of electrical and electronic equipment (WEEE) [E3]. The implementation of an integrated production infrastructure implies the use of wireless devices, such as sensors and actuators, which can lead to an increase electronic waste (Kagermann *et al.*, 2013). In fact, the growth in the sales of electrical and electronic devices in the past years is generating 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 their 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]. Kagermann et al. (2013) warn that "it will be necessary to calculate the trade-offs between the additional resources that will need to be invested in smart factories and the potential savings generated". According to Stock et al. (2018) and Birkel et al. (2019), technologies in I4.0 create an enormous demand for a large quantity of new and critical raw materials, used for RFID, semiconductors, displays, sensors, and micro-energy harvesting. Similarly, Chiarini (2021) agrees with a higher consumption of rare metals and other natural resources due to the adoption of I4.0 technologies in the manufacturing sector.

Fifth, several studies have pointed out that additive manufacturing (AM) is one of the most controversial I4.0 technologies in terms of environmental performance as it leads to higher energy consumption than traditional manufacturing processes [E5]. Yoon et al. (2014) indicate that AM processes may require more extensive evaluation since specific energy consumption of additive processes is estimated to be higher than conventional processes. Similarly, Ford and Despeisse (2016) argue that AM is more energy intensive per unit produced but at the same time offers higher levels of customization and less material use. Stock et al. (2018) indicate that due to the frequent use of laser technologies, AM processes are still energy inefficient.

Social sustainability

Some potentially negative social implications have been found in the literature. First, since its inception, one of the most concerning challenges of the digital transformation has been the possible negative impact on employment [S1] (Rüßmann *et al.*, 2015). According to Sung (2018) and Grigore et al. (2021), I4.0 displaces a part of the low-skilled workers who perform simple and repetitive tasks, but enhanced jobs will balance such loss. In brief, current literature cannot provide a unified perspective on whether I4.0 will cause an increase or decrease of employee numbers in industry (Müller et al., 2018; Birkel et al., 2019).

Second, some studies suggest that I4.0 technologies (e.g., CPS, IoT, cloud computing) produce employees' loss of privacy and personal autonomy [S2]. Reporting the insights of an expert group, Sugiyama et al. (2017) remark this as 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 in terms of human-machine relationship and workers' authority to intervene on the production process, I4.0 reduces room for employees' autonomy and increases forms of 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 use and privacy. According to Schneider and Kokshagina (2021), the increasing use of digital technologies has some negative implications for individuals. For instance, the authors suggest that the digital workplace can be more exhausting, requiring employees to balance work time and off-time. Moreover, the social and emotional skills required, and the difficulties managers face in leading remote works and assessing an individual's contribution could lead to further stress. This topic has gained relevance during the COVID-19 pandemic.

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]. This could imply a negative economic and social impact for developing countries. 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 cost and quality of products. Moreover, Pegoraro et al. (2022) suggest that manufacturing reshoring strategies can be underpinned by technology adoption. Barbieri et al. (2022) remark the importance of I4.0 policies to re-attract I4.0 innovative companies in their country of origin.

Fifth, some academics recognize that one of the main restrictions of robotics is the health and safety problems derived from the interaction with employees [S5]. 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, one of the main restrictions of collaborative robotics is related to safety issues. According to Dalmarco et al. (2019) the integration of this technology in the production line may offer risks when interacting with employees.

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 about dizziness. Wang et al. (2019) state that several users suffer from visual fatigue after performing maintenance using Google Glasses. Rodriguez et al. (2021) investigate the application of smart glasses in manufacturing. The findings show that it took time for users' eyes to adapt to the glasses, that the glasses felt uncomfortable to wear, and that operators had headache after some time of use. In addition, they suggest that further studies assessing possible health consequences of wearables are necessary.

Seventh, the utilization of AM in production environments produces harsh skin reactions, eye irritation and allergies to the operators involved [S7]. Ford and Despeisse (2016) conclude that AM may have several implications on social sustainability, including health and safety, and invite to further investigate the topic. Väisänen et al. (2019) measure the concentrations of gaseous and particulate contaminants originated from AM operations and post-processes in an occupational setting. The authors found that AM operations emitted potentially harmful contaminants and remark the importance of considering this issue in occupational AM and workplace design. Furthermore, Chan et al. (2020) findings suggest that emissions increase when multiple AM devices operate simultaneously and recommend adherence to good safety and hygiene practices when deploying this technology.

Table 1 summarizes the potential negative effects of I4.0 on both environmental [E1-E5] and social dimensions [S1-S7] presented above and provide supporting references.

Table 1. Preliminary evidence on the negative sustainability implications of I4.0

I4.0 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; 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; Müller et al., 2018
[E3] I4.0 wireless technologies raise the production of waste of electrical and electronic equipment	Chiarini, 2021; Garrido-Hidalgo et al., 2020; Kagermann et al., 2013
[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; Kagermann et al., 2013; Stock et al., 2018
[E5] Additive manufacturing leads to higher energy consumption than traditional manufacturing processes	Ford and Despeisse, 2016; Stock et al., 2018; Yoon et al., 2014
Social dimension	
[S1] Firms adopting I4.0 technologies have an overall negative impact on employment	Birkel et al., 2019; Grigore et al., 2021; Müller et al., 2018; Rüßmann et al., 2015; Sung, 2018
[S2] I4.0 technologies (e.g., CPS, IoT, cloud) produce employees' loss of privacy and personal autonomy	Bai et al., 2020; Cirillo et al., 2021; Sugiyama et al., 2017
[S3] Connectivity facilitated by I4.0 leads to an unhealthy work-life balance	Coldwell, 2019; Grigore et al., 2021; 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; Pegoraro et al., 2022
[S5] Autonomous robots lead to health and safety problems for workers	Dalmarco et al., 2019; Li et al., 2019
[S6] Virtual and augmented reality produce headache, dizziness, and other symptoms to operators	Rodriguez et al., 2021; Tsai and Huang, 2018; Wang et al., 2019
[S7] Additive manufacturing materials cause harsh skin reactions, eye irritation and allergies to operators	Chan et al., 2020; Ford and Despeisse, 2016; Väisänen et al., 2019

3. Methodology

A Delphi study approach was considered the most suitable research method due to the incompleteness of the available knowledge, and the exploratory, interdisciplinary and forward looking nature of the research (Linstone and Turoff, 1975).Based on gathering expert opinions in a structured manner, Delphi studies are very appropriate for structuring group communication processes, allowing individuals to deal with complex and interdisciplinary problems (Okoli and Pawlowski, 2004). This research method is recommended for research topics where little literature evidence is available (Akkermans *et al.*, 2003). Moreover, the multistakeholder approach adopted by Delphi methods considers the complexity of the topic; by the means of this methodology research "can benefit from subjective judgements on a collective basis" (Linstone and Turoff, 1975).

3.1. Selection of the expert panel

In keeping with the interdisciplinary nature of the debate and to ensure the reliability of the Delphi study, a rigorous selection of the panel of expert members was carried out. Furthermore, due to the exploratory nature of the research topic and the different profiles interested in the negative effects of I4.0 on sustainability performance, a panel size of at least 30 experts with heterogeneous backgrounds was pursued (Kembro *et al.*, 2017). Experts from both academia and practice, with different functions, of different nationalities and years of experience were considered for the research sample (Okoli and Pawlowski, 2004). Selection criteria were defined to ensure that experts were knowledgeable on I4.0 and sustainability topics.

Consistent with previous studies, initial sampling was carried out contacting academics authoring publications related to the topic and personal networking (Culot *et al.*, 2020). A combination of academic and practical expertise was considered appropriate for the context of this Delphi study since it ensures that the participants are close enough to operational practice, and it allows the involvement of researchers who are more reflective and take an aggregated perspective (Seuring et al., 2022, pp. 6-7). Additionally, professionals working with technology providers and management consultants were also considered. Further potential participants were scouted through LinkedIn social network and alumni databases.

An initial list of 150 participants was initially established, 63 individuals agreed to participate in the Delphi study. Moreover, to ensure rigor during the participants' selection process, the experts that agreed to participate were asked to self-rate their perceived level of knowledge of the topic by answering three questions regarding I4.0, sustainability and the manufacturing sector. 20 respondents were excluded because of overall low scores or incomplete responses. The final panel was composed of 43 experts from multiple sectors (e.g., machinery, automotive, apparel, food) . The characteristics of the expert panel are illustrated in Table 2. 5 participants dropped out during the second round.

Table 2. Expert panel composition.

	Participants' categorization	Number of participants (n=43)
Affiliation	Academia	7
	Machinery and equipment	5
	Automotive	5
	Manufacture of metal products	4
	Aerospace and naval	4
	Apparel	4
	Consultancy	4
	Software and support services	4
	Food industry	3
	Home appliances	3
Working experience	More than 15 years	23
	11 to 15 years	6
	6 to 10 years	11
	Up to 5 years	3
Geographical context	Europe	28
	Asia	7
	America	6
	Africa	2

3.2. 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 (von der Gracht, 2012; Linstone and Turoff, 1975). The *first round* began in early July 2021, and the feedback was collected in 5 months. An invitation letter and the link to a web-survey commercial software containing the questions for the first round were attached to an email. The Delphi questionnaire started with a short background to the study and described the scope of the project. Then, participants found various questions aimed at assessing their suitability for the panel and understanding their expertise. In addition, various demographic and qualification questions were asked. These questions were then utilized to analyse the panel composition.

Then, respondents could find a series of open-ended and rating scale questions written in an easy to comprehend writing style to avoid ambiguous statements. Panel experts were asked to assess the importance of each preliminary I4.0 negative sustainability impact previously formulated (see Table 1) in terms of probability of occurrence (over the next five years) and severity of the problem (level of impact). Questions using a five-point Likert-type scale were used for this purpose (1: Very low, 5: Very high). According to their opinion, respondents were requested to provide arguments for high and low probability/severity and illustrate the mechanisms behind each negative effect. Moreover, experts were also asked to propose corrective actions at firm, supply chain and policy levels and to comment or provide additional discussion elements. Delphi participants were asked to provide feedback within two weeks of receiving the questionnaire.

Once data were collected, the median values of probability and severity of each negative effect were calculated, and the level of consensus was determined using the Interquartile Range (IQR). 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 analysing the data and qualitative responses of the first round, a s*econd round* was performed. Individual questionnaires including structured feedback were used, thus increasing data richness and construct validity (Okoli and Pawlowski, 2004). Each participant received an invitation email with an online form including the statistics (median and IQR), arguments and his/her original assessment from the first round (Culot *et al.*, 2020). Moreover, experts could find in the questionnaire the reorganized comments and mitigation actions provided by the panel for each I4.0 negative effect. Together, the questionnaire form allowed participants to either modify their answers or maintain their original assessments and to provide additional comments (Linstone and Turoff, 1975). Data collection for the second round started on mid-January 2022 and lasted 3 months. In cases where the authors did not receive a response, multiple email reminders were sent to the panel experts for each round of the Delphi study to increase the response rate.

Finally, the research team performed data analysis in the same way for both rounds, enabling a comparison between them in terms of stability – i.e., the consistency of responses between rounds – calculating the Spearman's rank-order correlation coefficient (ρ) (von der Gracht, 2012). After the second round, the assessments of all Likert-type items reached either consensus (IQR ≤ 1) or stability ($\rho \geq 0.75$), thus making further iterations of the questionnaire with panel experts unnecessary (Culot *et al.*, 2020).

4. Results

This section presents the results of the Delphi study. First, Section 4.1 shows the descriptive statistics for the two rounds, which are summarized in Table 3. Moreover, this section provides some narratives extracted from the interviews to justify the values of probability and severity assessed by the panel of experts for each I4.0 impact (E1-E5 and S1-S7). Second, Section 4.2 illustrates the mitigation strategies proposed by the Delphi participants, these are also presented in Table 4 along with qualitative evidence obtained from the data collection.

4.1. Negative impacts of I4.0 on sustainability

The analysis of the Likert items is presented in Table 3. The median values and the IQR for both "probability" and "severity" assessments are shown for the two rounds. In addition, the stability between rounds (Spearman's ρ) is presented for the whole panel. Results of the second round suggest that there are various I4.0 negative effects that have a medium-high probability of occurrence and/or severity affecting environmental [E1, E2, E3, E4] and social [S2, S3, S6] sustainability aspects. These negative impacts reached consensus (IQR≤1) and thus suggest that experts consider there is a negative effect of I4.0 adoption on many environmental and social sustainability dimensions.

Furthermore, the results show a growing convergence of opinions through 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. It is highlighted that 4 values were slightly higher than 1, therefore close to reaching consensus. After the second round, the items reaching consensus were 15 out of 24. As expected, the "probability" values display higher median values and higher levels of agreement than the "severity" ones in both rounds. This occurs because the degree of severity of the negative effect can be seen differently depending on the sector considered and the processes involved at a firm level. Spearman's ρ confirms these results highlighting greater stability values in assessments of probability of occurrence.

Environmental dimension

According to the respondents, 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 ($Me_p = Me_s = 4$; $IQR_p = IQR_s = 1$). This was highlighted to be due to "the use of electronic components and consumables (e.g., batteries, chips, and antennas) with lifespans of around 5 to 10 years". Other important reasons highlighted include "the limited attention that manufacturers pay to forecast and optimize the use of consumables" and "the difficulties in recycling components/products that contain hazardous materials". According to panel experts this problem is especially severe since "the recycling industry may struggle to cope with the wave of new types of obsolete materials containing rare and hazardous components". Moreover, professionals from developing nations warn that this problem may become more serious in these countries due to "the lack of adequate recycling technologies and recovery systems".

Experts also agree 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 metals and other rare materials. Experts also point to the exponential increase in demand for small devices that has even led to a lack of raw materials (e.g., microelectronic chip crisis) producing "an increasing strategic dependence from producing countries". Moreover, materials' needs and consumption lead to an increase in land use for mining and landfills. Participants suggest that one of the underlying reasons for this problem is "the lack of incentives to consider sustainability issues when developing new devices". Although respondents give convincing reasons for this negative impact, some of them consider that "in the end, better technology is supposed to enable more efficient use of resources, offsetting the high consumption of raw materials" and "continued component downsizing will reduce the need for material and energy consumption". These reasons lowered the median of the severity of the problem to "medium".

Furthermore, the shorter life cycle of new devices; the lack of compatibility and limited refurbishment options of old equipment; a limited adoption of recycling and circular economy practices; and the "difficulties in recycling electronic equipment with more complex parts that are in turn more harmful to the environment" are among the main reasons to justify the increase in waste due to obsolescence of old equipment [E2]. Paradoxically, some experts suggest that the use of public funds (e.g., incentives to implement I4.0 technology) increases the rate of replacement of old technology. The participants indicate that this is a problem with a high probability of occurrence, but less agreement has been reached for 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 and more efficient recycling technologies, and the use of environmentally friendly and recyclable materials.

Besides, panel experts consider that the higher levels of energy consumption produced by connectivity and data processing is a problem of medium severity [E1] ($Me_s = 3$; $IQR_s = 1$). However, they achieve less consensus when evaluating the probability of occurrence ($Me_p = 3$; $IQR_p = 2$). Relevant arguments for both high and low probability/severity are provided. For instance, "data storage and digital waste" and "data centres and the cooling required" require a significant amount of energy; on the contrary, experts consider that I4.0 technologies "should lead to greater efficiency of the entire process" and that "newer equipment will consume less energy during data processing". Respondents from energy-intensive industries state that "the increases in energy consumption produced by I4.0 are in any case negligible".

Respondents state with a high consensus that there is low probability that AM leads to higher energy consumption compared to traditional manufacturing processes [E5]. Panel experts agree with this evidence but consider that this issue less likely to happen due to the limited implementation of AM in production operations. They consider this negative aspect to be of little concern since "current AM applications in processes such as prototyping are already leading to energy savings". AM allows end-to-end processes; uses less material; and produces less defects and wastes which means, in the end, less costs and energy ($Me_p = Me_s = 2$; $IQR_p = IQR_s = 1$).

Social dimension

Experts remark that technologies such as CPS, IoT and cloud computing could produce employees' loss of privacy and autonomy [S2]. Furthermore, I4.0 technologies may lead to an unhealthy work-life balance, stress and mental health problems [S3]. Regarding workplace safety and ergonomics, Delphi participants consider that VR and AR produce problems such headache and dizziness [S6]. For this evidence, expert opinions converge with a high consensus when assessing probability of occurrence, highlighting that these negative effects of technology may have a medium probability ($Me_p = 3$; $IQR_p = 1$). Instead, the severity values of S2 and S3 achieve less consensus ($Me_s = 3$; $IQR_s = 2$), S6 reaches a high consensus ($Me_s = 3$; $IQR_s = 1$). Some of the main reasons given for privacy and autonomy issues [S2] are that European countries have already strict regulations; this may however not be the case in developing countries. Respondents also recognise "greater traceability" as a current problem. Remote work generally provides flexibility and support to employees but may cause monotony and "fear to be closely monitored". The "stay connected" concept is being boosted and its effects has already been witnessed in other sectors such as health care in the US [S3]. Additionally, experts warn that VR and AR technologies must be used only in suitable workstations, for short periods, and for training activities due to users' discomfort; nevertheless, "the number of firms currently using VR and AR is still limited" [S6].

Table 3. Delphi study descriptive statistics.

I4.0 negative impacts on sustainability	Round 1				Round 2				Stability (Spearman's ρ)	
	Probability		Severity		Probability		Severity		Round 2 vs. Round 1	
	Median (Me_p)	IQR_p	Median (Me_s)	IQR_s	Median (Me_p)	IQR_p	Median (Me_s)	IQR_s	Probability	Severity
Environmental dimension										
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 dimension										
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

participants do not support the negative implications of autonomous robots [S5] and AM on the safety of workers [S7] (Me_p = 2; IQR_p = 1). “Robots are now much safer mainly due to the presence of sensors and limitations on the forces involved”; and the application of laws and certifications addressing this issue (e.g., ISO 10218) are some of the reasons provided. This also explains the low severity values, although with less consensus (Me_s = 2; IQR_s = 2). As for AM, its limited use in production, the use of personal protective equipment by operators, and the advances in safety of AM devices to protect the user, make this issue less likely for experts. However, the results suggest that this is a problem of medium severity that should not be underestimated due to the “possible respiratory problems and chronic diseases that AM can cause” (Me_s = 3; IQR_s = 1).

Finally, the rest of the negative effects identified in the literature were characterized by medium probability of occurrence and severity [S1, S4] (Me_p, Me_s = 3). For these topics, the experts did not find a high level of consensus and reasons provided were contrasting (IQR_p, IQR_s > 1).

4.2. Potential mitigation actions

Experts highlight various corrective actions to counteract the I4.0 adverse sustainability effects. 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 4 shows the full list of mitigation actions proposed.

To address environmental issues stemming from resource consumption and waste generation, respondents suggest several mitigation actions at the company level. For instance, participants propose accurate monitoring and forecasting of energy and waste using KPIs, compensating additional resources consumption and waste with the use of renewable resources, preventing the problem from the design phase using environmentally friendly components and materials, and gradual implementations or retrofitting/modular solutions. Regarding the supply chain, establishing recycling and reusing initiatives, using renewable energy providers, and collaborating with environmentally friendly suppliers and service providers are the most relevant mitigation actions. Furthermore, panel experts call for additional national/international economic incentives, laws and standards encouraging “green” initiatives, and remark the importance of supporting research to deal with these novel issues that are not yet fully addressed by policymakers.

Table 4. Mitigation actions proposed by Delphi panel experts.

I4.0 negative impacts on sustainability	Mitigation actions		
	Firm-level actions	**Supply chain level actions**	**Policy interventions**
Environmental dimension			
E1	1. Using electricity from renewable sources 2. Close monitoring of energy consumption by adopting standards to control equipment's utilization rate 3. Implementing I4.0 technology in an appropriate and gradual way, starting from a pilot area 4. Edge Computing, keeping data only for temporary calculations 5. Using AI to manage energy consumption 6. Employee training to promote the correct and environmentally responsible use of technologies 7. Shutting down of devices when not in use (e.g., overnight, holidays) 8. Integrating energy consumption KPIs in project phases	1. Using Green data centres utilizing energy-efficient and up-to-date technologies 2. Promoting software technologies that enable data sharing and reduce the need for multiple hardware devices for the same information 3. Collaborating with service companies that support manufacturing firms to efficiently manage energy consumption	1. Encouraging with economic incentives the use of advanced technologies to optimize energy use (e.g., AI) 2. Coupling digitalization and "green", demanding green energy purchase 3. Decarbonizing policies to force companies to adopt standards and measurement systems to reduce total energy consumption
E2	1. Accurate monitoring of obsolescence 2. Using modular systems to update obsolete devices (retrofitting) 3. Promoting the reuse of the obsolete technology internally in other processes 4. Replacing devices in a gradual, planned and manageable way	1. Establishing a recovery and recycling system 2. Reusing the obsolete technology upstream and downstream (e.g., in low-cost countries) 3. Using sustainable components and materials	1. Encouraging and rewarding virtuous behaviours in materials reuse and recycling through norms, laws and protocols 2. Making retrofitting more attractive through tax incentives
E3	1. Preventing the problem through "green design" of technology (e.g., batteries with higher energy densities, photovoltaic devices, energy harvesting) 2. Selecting durable and robust technologies	1. Developing recycling and circular economy initiatives	1. Fostering the reuse of resources through economic incentives or legal frameworks 2. Financing and investing in applied research to dispose of waste generated by the industry
E4	1. Asking for proper technical consultancies to use hardware only where it is necessary 2. Balancing and compensating resources consumption	1. Recycling and reusing initiatives 2. Carrying out responsible procurement (e.g., buying devices	1. Developing national/international regulations regarding strategic raw materials

	with renewable sources in other parts of the value chain 3. Being cautious in replacing the legacy equipment, doing it only when necessary	with a certified low level of consumption of natural resources)	2. Incentivising the production and use of machines designed to be disassembled/recycled
E5	1. Simulating AM's energy consumption through predictive models to compare it to traditional manufacturing 2. Applying AM only for selected complex products 3. Utilizing standard and reusable designs 4. Using more environmentally friendly filaments (e.g., with lower melting points) 5. Balancing and compensating energy consumption with renewable sources in other parts of the value chain 6. Optimizing product geometries at the design stage to reduce energy consumption during manufacturing 7. Improving capacity utilization of AM devices	1. Using renewable energy supply	1. Supporting R&D on lowering energy consumption of AM
Social dimension			
S1	1. Developing workforce re-skilling and up-skilling plans 2. Reducing employees working hours per week without reducing wages (assuming I4.0 will increase worker productivity). Hire more staff to cover the reduction in working hours	1. Requalifying employees with supplier development programs within the supplier network	1. Supporting training at different educational levels adapted to skills that the industry will demand in the future 2. Encouraging re-skilling and up-skilling of employees who have lost their jobs
S2	1. Defining and negotiating strict data privacy policies with unions 2. Using data ethically 3. Regularly assessing privacy compliance 4. Investing in cybersecurity, developing secure architectures, systems and components	1. Delegating the management of private data to external certified bodies	1. Developing internationally valid standards and guidelines addressing data governance and ethical use of data 2. Reviewing labour legislation to ensure sensible data protection in practice
S3	1. Preserving employees' wellbeing and fostering technology acceptance (e.g., user involvement, supervisor support, information sharing) 2. Respecting time off and right to disconnect 3. Monitoring wellbeing of workers (e.g., information	1. Outsourcing services to monitor workers' wellbeing and to support manufacturing companies in implementing specific actions	1. Reinforcing the regulations on free time, the right to disconnect and remote work 2. Developing industry standards

	overload) 4. Implementing technology in an appropriate and gradual way, starting from a pilot area		addressing psychological effects of the technology
S4	1. Considering the reduction of inequality within and among countries (SDG 10) as a true strategic value of the company	1. Supporting suppliers based in developing countries in their digital transformation process 2. Improving network coordination to enable regionalization 3. Balancing the sourcing of goods with dual/multiple sourcing strategies from developed and developing countries	1. Establishing synergies between companies and local communities (including Universities) 2. Defining international laws to avoid inequalities and preserve developing countries economy (e.g., providing financial support)
S5	1. Using only cobot technologies equipped with sensors and safety systems 2. Including interaction with robots in safety training 3. Isolating robot activities from operators 4. Applying security measures redundantly to prevent and counteract incorrect behaviour	1. Cooperating with manufacturers/integrators to ensure equipment meets safety standards and addresses hazards in the intended use	1. Strengthening of safety regulations based on accident reports to avoid health and ergonomics problems 2. Updating standards such as ISO 15066 and 10218.
S6	1. Allowing timely breaks for operators using VR/AR 2. Selecting technologies with reduced side effects (e.g., mixed reality) 3. Involving the operators in the proof of concept 4. Applying VR/AR only when/where it is necessary 5. Requesting medical advice to assess the physical ability of workers who will use VR/AR technologies 6. Implementing VR/AR gradually	1. Cooperating with manufacturers/integrators to ensure equipment meets safety standards and addresses hazards in the intended use	1. Strengthening safety regulations based on accident reports to avoid health and ergonomics problems 2. Updating and applying standards that address VR/AR applications in industry
S7	1. Wearing Personal Protective Equipment 2. Using safer materials (e.g., ecologic, hypoallergenic) 3. Building air extraction systems 4. Isolating 3D printers from operators	1. Supporting suppliers in the research and development of new, less hazardous materials	1. Integrating this issue into safety regulations 2. Supporting research and development of safer materials

Experts also provide various solutions to address the negative effects of I4.0 on the social dimension of the triple bottom line. Organizations can implement preventive actions such as investing in cybersecurity, monitoring workers' wellbeing, and using protective equipment to avoid some of the concerns produced by I4.0 technologies. The involvement of unions, employees and operators to negotiate working conditions, share information and design workplaces using I4.0 technologies is also considered relevant. According to the panel, cooperation with supply chain partners is essential to retrain and relocate employees, support and coordinate the I4.0 adoption at partner companies in developing countries, and to ensure that I4.0 equipment meets all safety recommendations. In addition, outsourcing services such as data management and monitoring of the wellbeing of workers are considered appropriate solutions. Policy interventions acquire special relevance for this sustainability dimension. Policymakers can develop international laws to prevent inequalities and preserve developing countries' economies. Moreover, institutions must support I4.0 with focused training carried out by universities and update laws and standards to protect data privacy and integrate physical and psychological risks derived from I4.0 technologies.

5. Discussion

The main goal of this study was to provide an outlook on the negative effects of I4.0 technologies on sustainability in manufacturing companies. Three negative environmental effects, related to waste production and resource consumption, appear very likely to happen and are considered severe problems according to the expert's panel. Previous studies such as Bonilla *et al.* (2018) already introduce these issues – despite only based on conceptual reasonings or anecdotal evidence – remarking that new I4.0-related devices may produce an increase in electronic and non-electronic wastes [E2, E3]. Furthermore, according to Beltrami *et al.* (2021) new I4.0-related devices require scarce raw material resources [E4], in addition to other natural resources; this is still a relevant problem that requires further attention.

Moreover, important review studies such as Ghobakhloo et al. (2021) and Birkel and Müller (2021) conclude that social sustainability implications of I4.0 are severely understudied. They invite "to identify the undesirable consequences of the digital industrial revolution and contribute to develop necessary policies to address these pressing issues proactively". Hence, this study identifies 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 utilization of AR and VR in the workplace [S6]. These issues are likely to happen and are considered severe. Respondents provided valid justifications for their reasoning and qualitative evidence to understand the mecanisms behind and how to mitigate these problems.

In contrast, some results of this research are not fully aligned with previous studies. The results suggest that that there is a low probability that the implementation of AM will produce an increase in energy consumption [E5]. Participants recognise that “producing with AM consumes more time and energy than traditional methods” which confirms previous results (Huang *et al.*, 2013). Nevertheless, the limited implementation of AM in production and the energy efficiency provided by the shortening of processes (e.g., transportation, prototyping), make this a minor issue for panel experts. Studies such as Dalmarco *et al.* (2019) point out safety problems as one of the main restrictions of collaborative robotics [S5]. Nonetheless, Delphi participants consider that due to the presence of specific safety standards and new technologies such as “proximity sensors and force limiting methods”, robots now are much safer (Liu *et al.*, 2019). 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, the results contradict this again due to the limited use of AM. Respondents also acknowledge that “current devices already provide safety measures” such as ventilation, personal protective equipment, and machine enclosures. Moreover, the risks are significantly reduced if the company “complies with safety recommendations”. Indeed, experts’ opinion is in line with the literature in recognizing the need for careful design and consistent regulation of AM environments (Arrizubieta *et al.*, 2020).

In general, after two rounds the panel experts reached a better consensus on the probability values than on the severity values (see Table 3). This is because severity is more subject to interpretation depending on the industry under analysis and the processes involved. Furthermore, greater consensus has been found for the negative impacts on environmental aspects. This occurs due to the increased awareness of the environmental effects of technology, the literature shows that social implications of I4.0 receive less attention (Ghobakhloo *et al.*, 2021), results also reflect this. The social drawbacks of I4.0 in terms of possible job losses due to automation [S1] are still controversial due to the low consensus and high stability reached in the second round. Studies such as Birkel and Müller (2021) acknowledge this trade-off between job creation and loss. Likewise, low agreement levels and high stability are obtained regarding the possible reshoring phenomenon produced by I4.0, which could increase the gap between developed and developing countries [S4]. The results agree with recent studies such as the one by Barbieri et al. (2022). However, due to the presence of respondents from both developed and developing countries and the valid supporting (i.e., I4.0 reduces costs and makes developed countries competitive again) and non-supporting reasoning provided (i.e., I4.0 allows regionalisation), the consensus achieved for this negative social impact is low. Future studies could discuss this topic in greater depth.

Panel experts also unveiled several firm, supply chain and policy mitigation actions, studies such as Birkel and Müller (2021) emphasize that it is necessary to investigate these three types of interventions. Important environmental mitigation actions at the firm level such as retrofitting the old machinery to make them ready to the I4.0 context as an alternative to replacement [E2], are in line with the existing literature (e.g., Di Carlo et al., 2021). Manufacturing companies can also address the "dark side" of I4.0 by implementing actions aimed at respecting and monitoring employees' wellbeing, privacy and time off. Recent studies such as Schneider and Kokshagina (2021) remark that the digital workplace can be more exhausting [S3], requiring specific actions enabling employees to find their balance with on-times and off-times.

Supply chain environmental actions such as "developing circular economy and recycling" seem to be adequate to mitigate the material waste generated by the I4.0 transformation. Authors such as Lopes de Sousa Jabbour *et al.* (2018) support this evidence and add that technologies such as IoT and big data may help develop a path towards the circular economy and closed loop supply chains, reducing material waste. Nevertheless, results are controversial since a large number of devices communicating with each other may generate large amounts of data which can overwhelm computer infrastructures leading to larger energy consumption (Singh and Bhanot, 2020). On the one hand, I4.0 can facilitate the circular economy through better traceability of waste, on the other hand, this can lead to more data processing and storage. This possible trade-off has been observed in the results [E1]. In addition, results indicate that the use of sensors and wireless devices for IoT implementation could increase the generation of waste [E3], counteracting the benefits of circular economy. Firms need to be cautious even when implementing I4.0 for sustainability purposes, understanding the benefits but also the problems. Various mitigation actions within the supply chain have also been proposed to reduce the negative social implications of I4.0. Measures such as outsourcing services to identify, monitor, and respond to workforce stress issues have been suggested [S3]. When deemed necessary, active intervention by mental health providers may be necessary (Coldwell, 2019).

Regarding proposed policy interventions, respondents primarily recommend incentivizing "green" behaviours through tax reductions, providing financing, and developing new targeted frameworks and roadmaps coupling digital transformation and sustainability. Moreover, respondents also recommended more regulatory actions addressing privacy and data security issues. These would support smarter and more sustainable processes according to Beltrami *et al.* (2021). Besides, Bai *et al.* (2020) suggest that sustainability trade-offs may not only exist across technologies and sustainability dimensions, but also across industries. This result has been also observed in this study. For instance, if regulators decide to support industry investments in autonomous and collaborative robots to enhance workers safety - increasing social sustainability - the resulting impact may be a higher level of obsolescence and electronic waste in the automotive industry [E2]. Thus, decreasing environmental sustainability. Currently, governments are supporting the I4.0 transition with national plans to promote competitiveness (Chiarini, 2021; Kagermann *et al.*, 2013). Results suggest that policy incentives to obtain new technology increases the rate of replacement of technology, leading to increased waste and resource use [E2, E3, E4]. Respondents recommend governments to be aware of the negative sustainability effects of I4.0 technologies while deploying I4.0-focused actions to prevent them before they occur.

An overview of Table 4 suggests that company-level actions and policy interventions seem to be the preferred mitigation actions for panel experts. The results indicate that many of the actions proposed at the supply chain level require collaboration between actors. However, previous research indicates that although I4.0 supports supply chain collaboration through increased data transparency (Müller and Voigt, 2018), this is still considered challenging even in an I4.0 context (Dieste *et al.*, 2022). In fact, supply chain actions to mitigate negative sustainability effects appear to be more problematic due to their lower relative importance.

To conclude, although some of the negative I4.0 implications to developing countries [S4] were not largely supported by the findings, panel experts have suggested several times that I4.0 may affect developing countries in diverse ways and sometimes with greater impact. Some of the highlighted problems refer to the absence of appropriate recycling systems [E2, E3], the lack of safety regulations [S2, S3, S6], and growing demand for critical raw materials from politically unstable regions [E4] (Stock *et al.*, 2018).

6. Conclusions

Previous studies call for further research on sustainability implications of I4.0 technologies. Ghobakhloo *et al.* (2021) recommend further research with a more complete consideration of the potential negative sustainability impacts of I4.0. Moreover, studies such as Beltrami *et al.* (2021) and Bai *et al.* (2020) encourage researchers to explore the "dark side" of I4.0 and acknowledge the need of further regulatory actions, including governmental policies and guidelines, to address the social and environmental sustainability downsides of technology. These research gaps have been addressed in this paper.

By contributing to the lack of research on the negative impacts of I4.0 technologies on sustainability, 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 this issue and can explore the implementation of the specific mitigation actions proposed at firm and supply chain levels. Based on the Delphi results, some severe negative socio-environmental implications are likely to occur in the coming years, and therefore I4.0 practitioners can prevent them before they become apparent. Various policy interventions are also provided to alleviate the issues presented in this research. These implications are especially relevant in the context of "Industry 5.0". This novel concept, that is being supported by the European Commission, complements the existing I4.0 providing a vision of industry that aims beyond efficiency and productivity, and reinforces the role and the contribution of industry 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".

Nevertheless, this research presented a two-round Delphi study with a large and heterogeneous sample of professionals. This methodological approach has some limitations that need to be acknowledged. First, most of the participants (around 70%) operate in European and American countries. On the other hand, the respondents represent a wide range of industries and have long experience in the field. Second, some studies recommend carrying out three rounds of data collection for Delphi studies, however only two rounds were completed after accomplishing high levels of consensus (IQR) and stability between rounds (Spearman's ρ). This approach guaranteed that participants' fatigue was kept as low as possible, which, in turn, facilitated a higher response rate and validity of the responses (von der Grach and Darkow, 2010; Mitchell, 1991).

Findings encourage researchers to further investigate the "dark side" of I4.0. Future qualitative and quantitative studies might be needed to complete a more detailed description of the relevant issues underlined in this research and provide further insights to facilitate a sustainable implementation of I4.0 technologies. In addition, it might be relevant understand the solutions to the potential trade-offs of the proposed mitigation actions as well. Researchers could also investigate the differences between developed and developing countries. Respondents of the latter seem to observe in their home countries greater trade-offs between I4.0 and the socio-environmental aspects of sustainability.

Concluding, during the two rounds of this Delphi study, experts – especially management consultants and practitioners – have stressed a great interest on the research topic by proposing evidence to demonstrate which of the proposed negative sustainability impacts have greater relevance, while providing root causes and possible solutions. According to the general opinion of the panel, there is indeed a “dark side” of 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 timely issues.

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