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


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# Sustainable digitalization: a systematic literature review to identify how to make digitalization more sustainable

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**Abstract.** With reference to sustainable digitalization, available literature reviews do not properly clarify whether digitalization is sustainable economically, environmentally and ethically - in the long period - and whether it is not. The necessity to develop this research lays its basis on the fact that, until now, sustainability researchers and digital scientists have apparently been studying in two separate tanks with few connections between them. With this paper, the authors aim at addressing this necessity. The work aims to analyze the relationship between digitalization and sustainability, and to present a framework to classify the impacts of material digitalization (production, use and disposal of hardware) and the use of digital per se (use of information systems). Subsequently, the paper will present parameters and factors that allow to identify the impacts of digitalization on sustainability and how digitalization can support sustainable growth. To do that, the authors analyzed the existing literature for deriving common understandings of digitalization-sustainability relations. Despite the large research activity on singular concepts like digitalization, digital transformation, Industry 4.0 applications, etc., not all the relevant dimensions between them have been deeply analyzed in a holistic way. The authors' ambition is to propose a general framework where some accountability could be assigned to specific plans or strategies, in a life cycle view. From such a standpoint a more integrative and sustainable perspective of digitalization effects can be foreseen.

**Keywords:** Sustainable digitalization, Digital sustainability, Digital impacts

## 1 Introduction

The digital revolution has transformed our lives and societies with unprecedented speed and scale, delivering immense opportunities as well as daunting challenges. Digital transformation can make significant contributions to realizing the Sustainable Development Goals, but positive outcomes cannot be taken for granted. By means of a systematic literature review, this study becomes the place to reflect on the key issues for a transition to a responsible and sustainable digital. It aims at presenting the nuisances generated by IT during the life of each piece of equipment: from the extraction of metals at the various stages of manufacture, to the use and the end of life. The

study of the features that allow to identify the impacts of digitalization on sustainability (whether they are positive or negative) will permit to better understand how digitalization can support companies and territories to grow sustainably. These issues will be addressed to favour practice-oriented sustainable digitalization assessments concerning ESG and ethical considerations.

First, it is necessary to share definitions of the key concepts: digitalization, sustainability, and sustainable digitalization. Several definitions of digitalization have been provided over the past few years [1-5]. For this research, the authors defined digitalization as the exploitation of new opportunities, by means of combining technologies, communications, business functions and models to achieve goals in a methodologically standardized way. The definition of sustainability relies on the original concept from the first UN conference on the environment, held in 1972. To that extent, sustainability is a development process in which natural resources exploitation, economic orientation, technological development, and social progress are in harmony with the environment that surrounds humans, thus enhancing both current and future potential [6]. Since over the time the concept of sustainability has embraced the division in three pillars [7-9], encompassing environmental (or ecological), economic and social (or ethical) factors [7;10;11], the analysis will focus on these three aspects. Even though there is still no integrative and universal definition of sustainable digitalization, for the purpose of this research the authors consider it as the ways in which technology must be designed and developed so that it actively contributes to achieving integrated sustainability goals. Moreover, authors' idea of sustainable digitalization agrees with the path to digital transformation identified by the European Union: "A [...] way that enhances our democratic values, respects our fundamental rights, and contributes to a sustainable, climate and resource neutral economy" [12]. Both definitions comply with the Brundtland report's concept of sustainable development, stating that humankind should satisfy its current needs without compromising the ability of future generations to do the same [6]. Digital technologies are often considered unpredictable, unforeseen and unanticipated [13]. Several authors have investigated how digitalization can be the enabler for a sustainable development [14-16], while others tried to understand how it deteriorates the environment and its society. A few studies wonder how digitalization can foster sustainable change [16;17;20] through energy and resource efficiency, data sharing and more transparent business processes. In the last year, aware of the impact that human being is creating on the planet day after day, several authors investigate how to reduce the environmental impacts caused by digitalization [21;22] noting how digital entire life cycle has very invasive environmental and social impacts often ignored [23-25].

The main aim of this research is to review the existing literature around the relations between digitalization and sustainability, extrapolating from it the answers to the following question: what kind of relation exists between digitalization and sustainability? The paper is structured as follows. Section 2 presents the Method based on which this study was conducted, and the sources classification. Section 3 presents the Results of the study, divided into thematic areas. Literature gaps and research limitations are discussed in Section 4. Section 5 explains the Implications of this study, both

in theory and in practice. Finally, Section 6 summarizes the Conclusions and suggests future research directions.

## 2 Method

### 2.1 Collection of relevant sources

Starting from the broad research question: “What kind of relationship exists between digitalisation and sustainability?”, a first search, from early 2000 to 2021, was conducted by the authors using Scopus and Web of Science for academic literature in English. Different combinations of key words were utilized and, considering the cross-sectoral nature of digitalization, no restrictions in the disciplinary scope of the journals were applied. Search fields included publication Title, Keywords and Abstract. The search was conducted using an AND operator between the two following groups of keywords, and the OR operator among keywords belonging to the same group:

- Digitalization-related: Digital; Digital transformation; Digital technologies; Ethics and digitalization; Ethics and technology; Ethics of digital technologies; Technical change; Information and Computing Ethics; Green IT; Sustainable digitalization; Industry 4.0; Digital impact; Digital economy; ICT impact.
- Sustainability-related: Sustainability; Environmental sustainability; Circular economy; Bioeconomy; Environmental impact; Green economy; ICT LCA; Green computing; E-waste.

Then, the search was extended on a conventional web search engine, again using the same keywords, to include contributions non-Scopus indexed. This allowed to have a more complete base of sources, given the evolving status of the topic. The filtering and screening steps were performed by the authors and led finally to 70 sources. The first screening was performed based on title and abstract; the evaluated articles have then been collected. After a careful reading of the selected articles, only interesting and suitable sources were finally included into the classification framework.

### 2.2 Classification framework

The contributions of the final sample are classified according to a framework that considers whether the impact is positive or negative, the nature of the digital solution (hardware or software), the different life cycle stage of the impact (production, use, disposal, whole life cycle), the categories of impact (the 3 sustainability pillars). The categorisations of the research were defined prior to the research according to criteria considered useful by the authors for analysis. In addition, the specificity of the study (objective and field of application) was considered. In this case categories were defined according to the topics considered by the selected papers. A comprehensive picture is given in Fig. A1 in the Appendix.

When analyzing digitization, it was considered appropriate to distinguish between hardware (H) and software (S). H refers to the physical part of an information system;

more generally, any physical component of an electronic equipment, including network structures. H related impacts are referred from the literature as related to the life cycle of the components, from material and energy inputs, to end of life issues. S is the logical/intangible layer of an information system; in computer science, this is understood as the simple data or information or, more appropriately, the source code. For S, reference will often be made to the energy impact, the possibility of sharing data and the effects that algorithms create on the choices of individuals and services.

Concerning the environmental dimension, information was extrapolated regarding the impact that the production, use and disposal of digital systems have on the environment. Speaking of the economic dimension, any fluctuation in the economy due to the advent of digitization in any of its fields described in the literature review is considered. Lastly, when talking about the social/ethical dimension, the analysis has focused on different implications expressed in the literature which link digital innovation in numerous fields: from interpersonal interaction to unemployment.

### 3 Results

#### 3.1 The relation of sustainability and digitalization over the years

The selected articles were published from the last decade of the '90s, the time when research started observing the role of digitalization in sustainability. The number of studies increased quickly from 2017 and continues to do so. Most of the sources belong to 2020, with a significant peak of studies that consider all three domains of sustainability. Considering the whole period environmental, economic and social issues were almost equally addressed, with 41, 42 and 44 occurrences, respectively. However, some differences emerge analyzing the trends. Fig. 1 shows that studies on digital's impact on the economy are present in almost every year, often associated with environmental and/or social aspects. The social dimension appears to be strong addressed at the beginning of 2000, also related to the economic one, and shows an increasing interest in the last 5-6 years as stand-alone topic or associated with the other sustainability dimensions. Finally, the environmental sphere is often left behind and considered to a lesser extent, associated sporadically to the economic one since 2014. Afterwards, environmental issues gain the interest of the scientific community and the practitioners, mainly considered with the other two sustainability pillars. Furthermore, from the analysis conducted, it is possible to note that only in recent years studies focused conjunctively on sustainability as a whole. In Fig. 2 a detail of the main topics considered in the selected papers is given. It is noticeable that in most cases the topic is treated in general terms of digitization and ICT. Fig. 3 shows the impact of each sustainability dimension. On the left, the occurrences of positive impacts overcome the negative ones in all three domains, with a net difference considering the economic sphere. On the right, it is notable how a negative impact is assigned in the most cases to the environmental aspects and never to the economic one. The social domain is the most contentious. Considering total sustainability, the greatest impacts are positive, and the only negative ones tend to disappear.

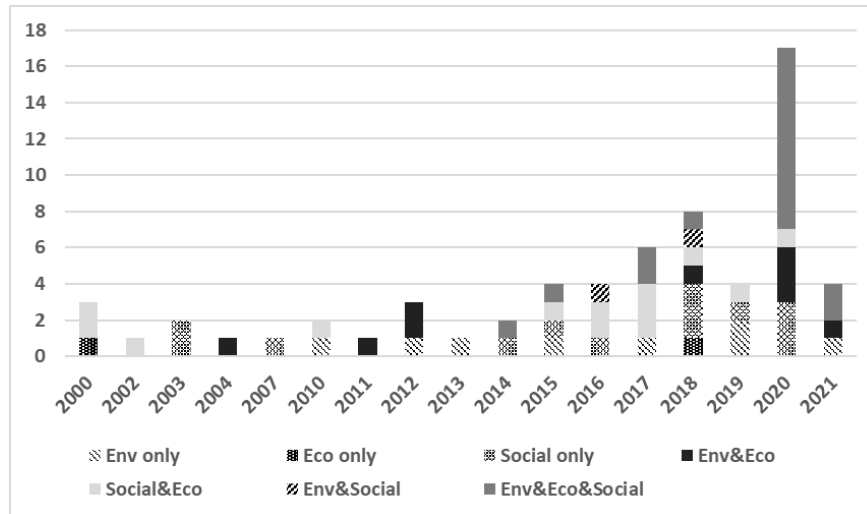


Fig. 1. Evidence of sustainability pillars trends. Year 2000 refers to the decade 1990-2000.

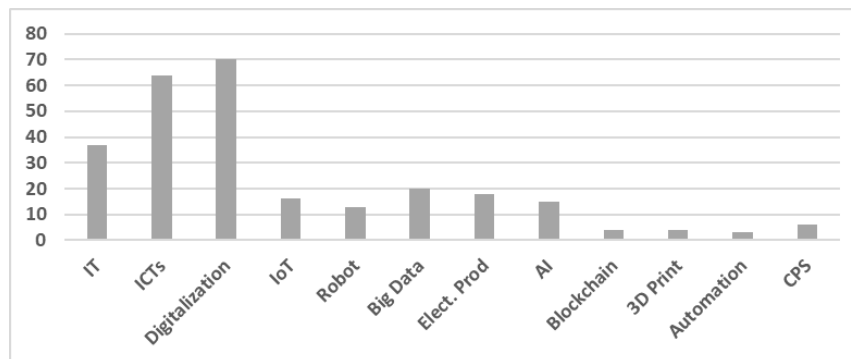


Fig. 2. Digitalization most considered topics related to sustainability.

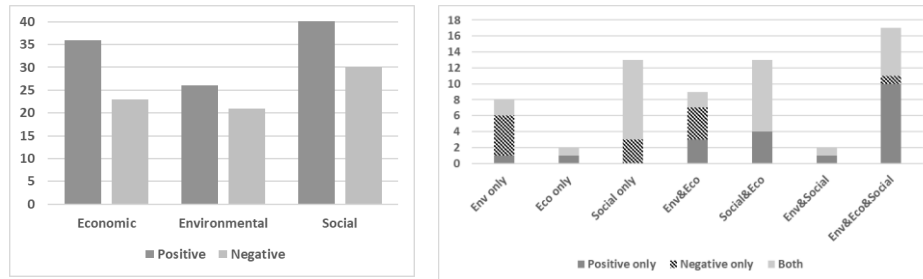


Fig. 3. Digitalization impact on sustainability pillars.

### 3.2 Economic dimension

The spread of digitalization has raised the need to understand the role that it exerts in our economy. In the literature, digitalization's positive impacts on the economy was divided between increased productivity and lowering of production and business costs. Economic sustainability is supported introducing hardware and software innovations both in production and manufacturing and for business and data sharing. Digitalization is transforming the nature of work and corporate business models as well as redefining boundaries of production, distribution, and consumption of goods and services [25], it positively bought efficiency, rationalization, and profit maximization a new face: they opened perspective of replacing people in tasks and jobs while at the same time creating new opportunities in business [25-29].

More in detail, digital technologies influence economic growth through many mechanisms [27] such as: robots have increased productivity on assembly lines within different types of industries (e.g., the automotive industry); autonomous machines increase industrial and business productivity; 3D printing has the innate ability to remove the need for assembly at some stages of production, thus printing mechanisms that are already assembled; automated maintenance scheduling, enabled by new sensors and AI, reduced production interruptions [28]. Some of its key effects are affecting relevant variables such as employment, productivity and inflation [26] lowering barriers to market entry [27]. On the contrary, the disadvantages for a company can be seen in the continuous updating required of staff and machinery, and the transparency of online customer reviews. Overall, the digitalization in economy appears positive to reduce transaction costs, maximize trading volumes, and improve the matching of supply and demand [25].

### 3.3 Environmental dimension

It is still unclear whether digitalization has more positive or negative environmental impact. Sustainable technologies development is considered one of the main components of the green economy transition [5]. Digitalization in manufacturing contributes to increasing resources and information efficiency throughout the product lifecycle, logistic management and throughout the value creation process [19;30]. It is noted how artificial intelligence [16] and digital twin can increase massively the efficiency



in production, thereby reducing consumption of resources, logistics organization and optimized distribution. Less frequent transportation requires less energy consumption and CO<sub>2</sub> emission, which are the main KPIs from environmental sustainability [30]. Analyzing the macro level, it is possible to highlight how the digitalization create interesting opportunities for digital urban factories, by offering a more customizable product at a lower cost, lower environmental impact, and shorter lead times [31].

Considering negative effects, the environmental domain is mainly compared to the energy impact caused using software and the high-impact life cycle of hardware. The *extraction* of raw materials that make up electronic products - silicon, aluminium, copper, lead and gold - contributes to increased respiratory problems for workers [29]. In addition, mining itself pollutes the water of surrounding communities through cyanide-contaminated waste ore and other toxic metals are then found in lakes, streams and the ocean, killing fish and contaminating drinking water [32]. In the *production* process it is evident how Industry 4.0 technologies are equipped with electronic components (e.g., micro-chips, semiconductors, displays, sensors, and micro-energy/harvesting) which cause a variety of undesirable environmental impacts [17] and they itself requires a massive amount of material to be produce. The production of semiconductors causes substantial air emissions (e.g., acid fumes, volatile organic compounds, and doping gases), water emissions (e.g., solvents, cleaning solutions, acids, and metals) and wastes (silicon and solvents) [17]. Also, the manufacture of electronic components is energy intensive and demands large amounts of water in cooling and rinsing [17]. The major impacts of technologies are in their *use* seen as their energy consumption and/or CO<sub>2</sub> emissions [17]. The primary energy consumption is mostly applied in ICTs for CPS with cloud technologies and data center to process big data [33]. According to some studies [30], the carbon emissions associated with data storage are approximately 35 kg of CO<sub>2</sub> per TB per year. In addition to storage, transmitting data also consumes energy [33]: a videoconference transmission between Switzerland and Japan in 2009 accounted for 200 Kwh per TB, significantly higher than the 46.33 kWh per TB estimated for storage. Considering their *end-of-life*, e-waste is the fastest growing waste stream in Europe and only less than 40% is recycled, the rest is unsorted [33]. E-waste covers a variety of different products that are thrown away after use. For many devices, the main issues are the absence of significant recycling systems (e.g., displays and sensors) due to a lack of economic efficiency or technical feasibility [33]. Therefore, the end-of-life ICT may contain hazardous metals, such as lead and cadmium [33]. Without proper recycling, a great amount of e-waste goes to landfills or incineration, generating abundant wastes, risk of exposure to hazardous materials, and harmful emissions from incineration.

### 3.4 Social dimension and Ethics

Digital technologies are at the heart of major social and ethical shifts. In the social sphere, it is considered compared with the replacement of humans by machines, algorithmic bias, and the use of data to monitor and influence human decisions. The economy has undergone a fundamental shift in recent decades: many jobs have disappeared, but many jobs have been created too [34]. Studies suggest that digitalization

may make it possible that a large portion of tasks - or entire occupations - carried out by workers, could be performed by machines [35] thus increasing the fear that computers will take over human's jobs [36]. Apparently, low-skilled workers have a higher risk of being employed in a less stable job than higher-skilled workers [37]. Indeed, digital technologies have led to restructuring and reallocation, but they have not led to higher unemployment [27]. If successfully adopted, digitalization can help increase productivity, which progressively translates into lower prices and/or new products, higher final demand, and increased employment, thus offsetting the potential displacement of jobs [28]. Moreover, much of the literature emphasizes the complementarity between humans and machines [37]. Neither large job losses nor technological unemployment are very likely due to growing digitalization. ICTs technologies are far more pervasive than they were previously: they have influence on the information flow that supports decisions and policies. Nowadays, debates in the public sphere are mediated by digital technologies and the algorithmic filtering of social media content is one of the main concerns of digital society [39]. Scholars have pointed out the Internet's shortcomings in facilitating the unfolding of deliberative democracy, the existence of a public sphere, where individuals form their social and political opinions [39]. The technological space provides a mere "public space" rather than a true "public sphere" [40;41]. Apparently, the tendency is for the Internet to promote group polarization, rather than rational-critical debate. New technologies affect our behavior and challenge human decision-making [23]. Here, the Kantian ethics assumes that human subjects are autonomous agents, while objects are merely passive tools [42], but digitalization challenges this narrative, as digital technologies are taking an active role in our lives [43]. To this extent, new technologies can be used to guide human behaviour [44] and their design should be compatible with the user's autonomy and its exercise of rational choices [45]. Within the philosophy of technology "theories have been developed to account for the fact that humans can outsource elements of their cognitive functions [...] with technological artifacts" [23]. This outsourcing of human willpower to technologies is not negative per se, since behaviour change technologies can be designed to support users [23] in cases where they are unable to perform an action, and to ease the burden of work. In this, human subjects outsource part of their agency to digital technologies (e.g., over-industrialization in production processes). How to avoid the de-skilling of human labour and how to strengthen social cohesion within the new labour chain that digitalization is creating will be the challenge of our future. With the right reorganization of work, technology can lead to the improvement of human skills, rather than their de-skilling [4].

## 4 Discussion

The proposed classification framework helps to highlight how most of the collected sources show as digital can offer both opportunities and challenges. The challenges and opportunities presented in this paragraph have been extrapolated by the authors from the literature review, and then summarized and reformulated in Tab.1. Challenges are often related to the social and environmental level, i.e., the extraction and con-

sumption of energy and hardware components [29], or regarding software in a social/ethical vision related to human alienation [43]. Instead, opportunities have been since in the support of digitalization versus a sustainable development: efficient use of resources and energy, new business models, data sharing for process planning. From the literature review emerges that the impact of technologies varies depending on their type. At least 25 sources analyzed deal with digitalization in general and other 25 in ICT; followed by specific areas of interest: IT, electronic products, AI, blockchain, big data, IoT, robotics, automation, and 3D printers. Although all these technologies show an impact, both positive and negative, the first two (general digitalization and ICTs) are found to have the most impact in terms of usage and therefore energy consumption, highlighting a balance of impact between negative and positive. Tab. 1 summarizes the opportunities and challenges offered by digitization (i.e. positive and negative impacts), further describing where these consider S or H. It is important to note that the most digital solutions are built on both H and S, so this classification is only indicative and refers to the context of the sources. Tab. 1 clearly shows that the number of opportunities listed by the analyzed papers is higher than the challenges – i.e., the analysis showed that digitalization can support sustainability in many ways. Nevertheless, a careful reading of opportunities and challenges shows that the negative impacts enumerated are much more impactful, especially at the environmental sphere. From the literature analyzed, among the authors, even those who pose the problem of digital technology impacts do not measure it in a systematic way but present the issue on a theoretical level. For the environmental domain, the impact of digital is usually measured by an LCA analysis.

**Tab. 1.** Digitalization’s opportunities and challenges related to sustainability. EN = environment, EC = economy, SO = social/ethical; H = hardware, S = software.

	Opportunities	Challenges
EN	<ul style="list-style-type: none"> <li>• Resource efficiency (S)</li> <li>• Knowledge and data sharing (S)</li> <li>• Facilitate the lifecycle of products through the value creation process (S)</li> <li>• Efficiency in resources use (water, energy, material) (S)</li> <li>• Predict impacts and find solutions (S)</li> <li>• Smart working creates less traffic, allowing lower CO<sub>2</sub> emissions (H/S)</li> </ul>	<ul style="list-style-type: none"> <li>• Water, air and soil pollution (S/H)</li> <li>• Extraction and consumption of non-renewable raw materials (H)</li> <li>• Energy consumption (S)</li> <li>• E-waste to be disposed and recycled (H)</li> </ul>

EC	<ul style="list-style-type: none"> <li>• Competitiveness of companies and territories (H/S)</li> <li>• Lower barriers to market entry (H/S)</li> <li>• Reduce transaction costs, maximize trading volumes, improve supply and demand matching (H/S)</li> <li>• Efficiency of all internal resources (materials, energy, water) (S)</li> <li>• Optimizes production and delivery times, increase overall productivity (S)</li> <li>• Less rent, energy expenditure, travel and business costs due to smart working (S)</li> <li>• More customizable products (S)</li> </ul>	<ul style="list-style-type: none"> <li>• Continued competitiveness with the market (H/S)</li> <li>• Need to stay up dated and innovative (H/S)</li> <li>• Consumer opinion is online and visible (S)</li> </ul>
SO	<ul style="list-style-type: none"> <li>• Far more reaching debates in the public sphere (S)</li> <li>• Technologies support users (H/S)</li> <li>• Improvement of human skills (H/S)</li> <li>• Better working conditions during raw materials extraction (H)</li> </ul>	<ul style="list-style-type: none"> <li>• Polarization of the debate (S)</li> <li>• Humans take a passive role towards the machine (S/H)</li> <li>• Technologies replace workers (S/H)</li> <li>• Technology as de-skilling human decision-making (S)</li> </ul>

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During the early phases of the COVID-19 pandemic outbreak, the world managed to shift rapidly to use digital technologies and replace some of our daily operations with virtual modes. It seems that the academic world is well attentive to both challenges and opportunities offered by digital technology, and now awareness among citizens and businesses is slowly increasing too. Surely, the ongoing situation have shown [46] the successful utilization of digital in the health datasets, contact-tracing apps, provision of monitory and controlling measures, resource assessment, urban heath strategies, risk assessment, transport, as well as automation, building regulating, and management perspectives. This strong and rapid increase in the use of digital support, increase the necessity to address positive and negative effects of digitalization, but also to go a step forward in measure these effects.

In the reviewed sources, some shortcomings were found. Among these, the most significant for digital sustainability studies is that of the scarce existence of tools to systematically measure digitalization's total impact – considering negative and positive aspects in the three areas of applications. Existent research tends to focus on digital sustainability dimensions separately. Moreover, considering only Scopus-indexed sources in English language had as an outcome the overall positive impact of digital, while a more extensive analysis including conventional search engines and allow different languages partially changed the outcome. The most sources presents both opportunities and challenges for the same sustainability domain or where compromises are needed between domains. Only a quantitative approach can suggest the best balance of digital solutions in each situation. In this respect, one of the future challenges will surely be to find adequate metrics to measure digital impacts - e.g., European standardization to calculate the environmental impact of ICT, since depending on the method with which the analysis is done the results may be different [47].

The results of this contribution should be viewed considering some limitations. First, the research field is evolving at a fast pace. Therefore, some of the outcomes in this study may change as new discoveries are published. Second, considering that these findings are based on a literature study, they are mainly theoretical, and their usefulness needs to be verified through case studies. Third, even though best practices for literature review were followed and Authors' background assure different point of views, the search gathering performed by the Authors itself for the classification framework is inherently affected by a certain degree of subjectivity.

## 5 Implications





Academic contributions have highlighted the importance of linking the concept of sustainability and digitalization. This research provides a framework that shows these interrelations: opportunities and challenges that were more addressed by academics and practitioners are underlined. The main contribution for research is to clearly show where there are research gaps and in which domain. Sustainability should be addressed both considering its holistic nature, and deeply investigating each specific aspect. A large part of the scientific community can contribute filling the gaps. The systematic state of the art here presented provides useful and ready-to-use information for industry [48]. This might support business owners and industry managers to implement new technologies in such ways that they can boost sustainability performances. Since after COVID-19 the digitalization of enterprises seems to be irreversible, being aware of the impacts it produces and on how they can be mitigated is essential. With respect to possible negative effects of digitalization, this study provides managers with research insights that will prompt them to monitor and correct these issues during business management practices. Understanding that digitalization affects sustainability across various dimension - environmental, economic, social/ethical - is thus fundamental. Moreover, the study provides useful food for thoughts for policy makers and public administrations that deal with the implementation of new technologies, with smart cities management and/or with the realization of the 2030 SDGs. Even though, the topic is gaining more and more awareness in the research world, the negative impact of digital deserves more attention from the manufacturing and business world. In addition, in the field of National and European policies, it would be necessary to move more quickly to encourage the certification of low-impact electronic products. To fill the gap of the end-of-life products, policies must encourage reusable products and with replaceable components. Moreover, the results of this research can be useful to raise awareness when using all digital tools, not only by using the consumption of a renewable energy and sustainable data center we implement a sustainable development, but also with certified electronic products showing low impact on raw materials, low energy consumption and human rights considered in the entire production process. In this perspective, any methodology that can guide the production process of a product or business efficiency towards a less invasive digitisation is desirable. In this respect, it is possible to consider the TRIZ methodology as a useful decision-making tool that can support sustainable development by implementing the

positive impacts linked to the life cycle and the use of electronics and the man-machine relationship. This refers both to the theoretical approach and to the realisation of matrices specifically designed to support sustainable design, considering the life cycle phases and the different performances (to be optimised and eliminated), as well as the synergies with other methodologies [49;50].

## 6 Conclusions and future work

The authors started this research by asking themselves if digitalization could support sustainability, and they concluded it by asking themselves how make digitalization increasingly sustainable not to compromise its own positive impacts on sustainability. Lowering negative impacts of digital, surely lead to a higher overall positive impact. The research was conducted considering both scientific and practitioners' community. Most papers address together the three sustainability pillars and affirm the overall positivity of digitalization. The scientific community appeared to tip the scales toward a positive impact of digital. Looking for other non-Scopus indexed sources, it was highlighted how different outcomes are found. Of the 70 sources classified, a significant majority find digital devices have a strongly negative environmental impact. The impact of digital is there: i.e., researchers are trying to develop a custom guideline towards lowering the data-center energy consumption and reducing carbon footprint, for which major digital colossal are working simultaneously. Moreover, the current literature examining the impacts of ICT equipment suffers from three major shortcomings: disagreement among studies; lack of coverage for newer products; and lack of transparency [47]. Furthermore, there is a lack of prescribed databases and approaches in place for performing comparable LCAs in a coherent manner [47]. Although the literature review has uncovered more positive impacts of digital than its negative, it is considerable to remember that the severity of the impact does not depend on its quantity but on its intensity. The following two questions rise: Is the weight of the negative such that it can be ignored? Or does digital risk become positive for our short-term goals but too impactful for long-term perspective? Together with the need of quantitative assess sustainability performances, future research should be addressed to answer the following questions. The authors strongly believe that digital and sustainable transformation could successfully take place only through a strong collaboration among all domains of science and between scientist and practitioners. Authors' plan for future work is addressed to build up some case studies to deeply investigate co-evolutions of digitalization and sustainability in specific sectors.

## Appendix

	DATA ANALYSIS	FONT	SOFTWARE HARDWARE	ECONOMIC, SOCIAL ENVIRONMENTAL	IMPACT	POSITIVE NEGATIVE	TECHNOLOGY TYPE
		3	S/H	EC	U	● ●	DIGITAL
		4	S/H	EC,S	U	● ●	AI,ROBOT
		5	S/H	EC,EN,S	EN,P,U	● ●	DIGITAL
		12	S	EC,EN,S	U	● ●	DATA
		13	S/H	S	U	● ●	DIGITAL
		14	S/H	EC,EN,S	U,EN,D	● ●	ICT
		15	S	EN,EC,S	U	● ●	ICT,IT,BLOCKCHAIN
		16	S/H	EC,S	EN,U	● ●	DATA
	HARDWARE 42	17	H	EC,EN	U,EN,P,D	● ●	ICT
	SOFTWARE 59	18	H	EC,EN,S	D	● ●	EP
		19	S/H	EN,S	U	● ●	DIGITAL
		20	S/H	EC,EN,S	U	● ●	DIGITAL
		21	S/H	S	U	● ●	DIGITAL
		22	S	EC,EN,S	U	● ●	DATA
		23	S/H	S	U	● ●	DATA
		24	S/H	EN,S	EX,U,RD	● ●	EP
		25	S/H	EC,S	U	● ●	DIGITAL
	ENVIRON. 41	26	S/H	EC,S	U	● ●	DIGITAL
	ECONOMIC 36	27	S/H	EC,S	U,P	● ●	EP,IoT,ROBOT
	SOCIAL 45	28	S	EC,S	U	● ●	DIGITAL
		29	H	EC,EN,S	EX,U,EN,D	● ●	IT,ICT
		30	S/H	EC,EN,S	EX,U,RD	● ●	IT,ICT,DATA,AI,EP
		32	H	EN,EC,S	EX	● ●	EP
		33	S	EN,EC	U	● ●	ICT
		34	S/H	EC,S	U	● ●	DIGITAL
		36	S/H	EC,S	U	● ●	ICT,IT
		37	S/H	EC,S	U	● ●	DIGITAL
	EXTRACTION 6	38	S/H	S	U	● ●	ICT, DATA
	USE 56	41	S	S	U	● ●	DATA
	ENERGY 20	43	S/H	S	U	● ●	ICT
	PRODUCTION 15	44	S/H	S	U	● ●	EP,IT
	DISPOSAL 12	45	S/H	S	U	● ●	AI
		48	H	EC,EN	U,P,D	● ●	ICT
		51	S	EC,EN	U,EN	● ●	DIGITAL
		52	S	EC,EN	EX,EN,U,P	● ●	DIGITAL
		53	S	EC,EN,S	P	● ●	DIGITAL
		54	S/H	EC,EN	U,EN,D	● ●	IT
	POSITIVE 51	55	S/H	EN	U	● ●	IT
	NEGATIVE 44	56	S	EC,EN,S	P	● ●	DIGITAL
		57	S	S	U	● ●	BLOCKCHAIN
		58	S	S	U	● ●	DATA,AI,ROBOT
		59	S/H	EC,S	U	● ●	DIGITAL
		60	S/H	EN	U,EN,D	● ●	ICT
		61	S/H	EN	U	● ●	DIGITAL
		62	S	S	U	● ●	IT,ICT
		63	S	EC,EN,S	U,EN	● ●	DIGITAL
		64	S	EC,EN,S	U,EN	● ●	DIGITAL
		65	S	EN	EN	● ●	IT
	DIGITALIZATION 24	66	S/H	EN,EC	EN,D	● ●	DATA, ICT
	ICT 21	67	S/H	EN	EN,U,P	● ●	ICT
	IT 13	68	S	S	U,P	● ●	DIGITAL
	ELECTRONIC Pr. 6	69	S	EC,EN,S	U	● ●	DIGITAL
	DATA 10	70	S/H	EN	EN,U,P	● ●	ICT, DATA
	BLOCKCHAIN 2	71	S	EC,S	U	● ●	IT,ICT
	AI 5	72	S/H	EC	U	● ●	DIGITAL
	IoT 2	73	S	EC,EN	U,EN,D	● ●	ICT
	ROBOTIC 4	74	S/H	S	U	● ●	ICT,IoT,ROBOT,AI
		75	S	EN	EN,P	● ●	ICT
		76	S/H	EC,EN,S	EX,EN,U,P	● ●	DIGITAL
		77	S/H	EN	EN,U,RD	● ●	ICT
		78	S/H	EC,EN	EN,U	● ●	DIGITAL
		79	S/H	EC,S	U	● ●	DIGITAL
		80	S/H	EC,S	U	● ●	ICT
		81	S/H	EC,EN,S	U	● ●	IT

**Fig. A1.** Classification of sources. *I Column:* Fonts numerated as bibliography; *II Column:* S (Software), H(Hardware), *III Column:* EN( Environment), EC (Economic), S(Social); *IV Column:* EX (Extraction), EN (Energy), U (Use), P (Production), D (Disposal); *V Column:* Positive (left) or/and negative (right); *VI Column:* DIGITAL (Digitalization in general), IT (Information Technology), ICT (Information and Communication Technology), EP (Electronic products), AI (Artificial Intelligence), DATA, Robot, IoT (Internet of Things), 3D printing, and Blockchain.

## Glossary

AI: Artificial Intelligence

ICT: Information and Communication Technology

IT: Information Technology

IoT: Internet of Things

LCA: Life Cycle Assessment

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