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Digital sustainability: Ethics, epistemology, complexity and modelling

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Abstract

The growing attention to digital sustainability can arguably be linked to climate change and digital transformations as major megatrends rapidly altering our collective present and future. The current Russian-Ukrainian war and the recent pandemic, however, have both raised uncertainty over the 2030 Sustainable Development Goals (SDGs) achievement and the role of technology and innovation for sustainability. Without ignoring the dramatic consequences for people, the Ukrainian war can be deemed as a significant shift in geopolitics and global energy policies, with a short-term return to fossil fuel and commitments to renewable and clean energy transitions. At the same time, the COVID-19 pandemic acted as a catalyst for a more pervasive diffusion and adoption of information and communication technologies (ICTs) transforming our lives and notions of sustainability. By considering the disruptive impact triggered by the pandemic, this paper aims at advancing awareness and knowledge of digital sustainability and at drawing a coherent framework of arguments including ethical and epistemological issues, taking into account the approach of complexity science. This will be essentially carried out by considering digital sustainability as "the convergence of digital and sustainability imperatives that involves a trans-disciplinary approach of deploying digital technologies in tackling sustainability issues" (Pan and Zhang, 2020). Across different interpretations reflected within business and management debates (Sharma, *et al.*, 2021), this definition gives meaning to the concept or construct by specifying operations that must be performed in order to measure or manipulate the concept (Berrío-Zapata, *et al.*, 2021). This paper will focus on the profound transformations of our view of reality by ICTs acting as instrumentarian technologies, and the need to avoid determinism, rethink science-technology relations, and consider the distributed morality of multi-agent ecosystems as significant aspects to further a debate on the trans-disciplinary nature of digital sustainability, including the potential negative impacts of digital technologies on society, economy and environment.

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1. Introduction

The COVID-19 pandemic forced the adoption of extraordinary measures by countries around the world. To control and prevent viral infections, national lockdowns and “circuit breaker” measures were introduced for months or weeks, with restriction of movements and travel within and across countries depending on assessed levels of risk. These interventions aimed at reducing outdoor/indoor interactions and gatherings at schools, universities, offices, public places (stadiums, parks, playgrounds and markets), shops and sports venues. As an essential component of the production and consumption of global goods and services, human mobility and the transportation industries were the most affected (Bonaccorsi, *et al.*, 2020). With massive drops in the demand and supply of leisure-based services and in-store shopping, and impact on labour forces (del Rio-Chanona, *et al.*, 2020), the travel and tourism (Sigala, 2020), hospitality and restaurants (Dube, *et al.*, 2020), non-food retailing and events (Madray, 2020; Sheth, 2020) were affected more by partial or full business shutdowns than industries less dependent on experiential activities and capable to survive through online marketplaces.

In the continuous (re)allocation of essential and non-essential activities, the development and use of technologies defined life and work during the pandemic. The screening, tracing and forecasting of infections, deaths and recovery was possible through mobile applications, artificial intelligence (AI) and machine learning (ML) (Bullock, *et al.*, 2020; Kamalov, *et al.*, 2022). In turn, a divide emerged and expanded in relation to differing capabilities of accessing smart ICTs, fast Internet services or shifting businesses to e-commerce (Beaunoyer, *et al.*, 2020). At the social level, for example, the widespread use of videoconferencing reduced isolation during hospitalisation, quarantine and lockdowns and enabled remote participation to live events (workshops, conferences, concerts). Platforms such as Zoom and Microsoft Teams also enabled teaching and learning. The overall effects on in-person educational experiences and social interactions still requires further and in-depth investigations from both institutional and student perspectives. Similarly, the opportunity to work at home was not equally available to all forms of employment, with notable limitations and sociopsychological issues (*e.g.*, isolation and anxiety) emerging from so-called smart (or better remote) working (Barbieri, *et al.*, 2021).

The critical role played by ICTs during the pandemic can only be understood from different and multiple perspectives, including the socio-technological dimension. Unlike other viral diseases (AIDS, SARS, Ebola and MERS), the COVID-19 pandemic was characterised by an unparallel high degree of global connectedness and social complexity (Zhu, *et al.*, 2021). It was a kind of massive “experiment” concerning a sudden adjustment to online living and working, without any warning, planning or training. This experiment occurred without comparable precedents in the history of technology. Although many of the calls for profound modifications in attitudes and behaviours might seem exaggerated (Warwick, 2021), one area was deeply affected, that of online shopping (Kim, 2020). The relatively long duration of forced digital adaptation definitely and permanently formed or reinforced a familiarity with online shopping and changed attitudes and intentions (Lally, *et al.*, 2010). The view of society as a combination of complex, dynamic and networked systems is not new (Craven and Wellman, 1973; Luhmann, 1982), and evolved alongside advancements in ICTs (Martin, 1978; Castells, 1996; Sheller and Urry, 2006). With smart ICT diffusion, and an overly attention to big/open data benefits and challenges, terms like *digital transformation* [1], *digital sustainability* [2] and *smart society* [3] emerged as popular concepts in literature and in popular media (Chakravorti and Chaturvedi, 2017; Bockshecker, *et al.*, 2018). This emphasis on ICTs could be deemed as an ongoing phenomenon pre-existing before COVID-19. The pandemic acted as a catalyst for the adoption of ICTs, accelerating their enrichment and integration along with concerns for future socio-economic and environmental sustainability.

This paper will first explore the implications of digital sustainability across three pillars of sustainable development, then address ethical and epistemological issues involved along with instrumentarianism power, the role of complexity science and finally discuss the challenges imposed by simulation and modelling as essential instruments for understanding the phenomenon. Alongside positive implications, the concept of digital sustainability should also consider potential negative effects of digital technologies on the environment, economies and societies. It must be considered, in fact, that ICTs, besides having a role in solving sustainability issues, are also part of the problem (Chowdhury, 2013).

2. The pillars of sustainability

The concept of sustainable development stemmed from environmental policies and a different approach to economic growth addressing global inequalities. As a solution to the idea of progress and its adverse socio-environmental effects, the term has become popular since the Brundtland report, "Our common future" (World Commission on Environment and Development [WCED], 1987). The mainstream view of sustainable development was institutionalised around radical criticism of economic growth neglecting social and environmental issues. Over time, sustainability discourses have been assimilated by achievements of evolving sets of goals embedded in a three-pillars approach to sustainable development. Despite the continuous redefinition of Sustainable Development Goals and a recent extension to the 'common view' and the '2030 agenda' (United Nations. Department of Economic and Social Affairs, 2015; Shi, *et al.*, 2019), the tripartite approach to sustainability has gained traction and acceptance without a solid theoretical foundation (Purvis, *et al.*, 2019). The conceptual forces driving the different narratives and frameworks in sustainability literature can be broadly associated with holistic, individual and yet interrelated approaches to the three-pillar model (Josephsen, 2017; Purvis, *et al.*, 2019). As such, the social, economic and environmental dimensions have been discussed in relation to a digital and pervasive technological context in order to identify some of the most relevant implications for sustainability.

Socio-cultural

Digital technologies are meaningful and proactive agents of socio-cultural transformations. Their view as means *to an end*, or better, mere tools to achieve sustainability, does not help in fully understanding the profound influence of instrumentarian technologies. This is evident in several conceptual and empirical studies addressing the role of ICT in society. Theories conceptualised the information society (Webster, 2014) or the network society (Castells, 1996; van Dijk, 2020) or smart society (Iannone, *et al.*, 2019), often defined according to a progressive numbering of software versions (Deguchi, *et al.*, 2020; Narvaez Rojas, *et al.*, 2021). As "novel" interpretations of socio-political and cultural changes, they arose from prior theories and conceptualisations of society (Craven and Wellman, 1973; Crawford, 1983) and still needed solid theoretical underpinnings (*e.g.*, smart society). Social networks existed before the Internet, as argued by Castells (1996), and before the phrase was coined (Barnes, 1954). The importance of information and knowledge in society was also deemed ahead of the *Advent of Information Age and Knowledge Society* (Drucker, 1969; Crawford, 1983). Wireless and Web technologies transformed the mechanisms and dynamics of society, as the whole of networked relations constituting it (Floridi, 2019). Across socio-cultural and economic domains, the constant reconfiguration of social ties and relational boundaries depends on the level of technology-mediated interactions as much as access to data and information. In this respect, the pandemic provided an extraordinary example of rapid reconfigurations, with digital tracking of individual and collective health (Bullock, *et al.*, 2020; Fagherazzi, *et al.*, 2020), and remote teaching, learning and working (Williamson, *et al.*, 2020; Barbieri, *et al.*, 2021). Social transformations are not univocal or uniquely determined by digital ICTs. These transformations imply a proactive role of socio-cultural agents involved in the process with an increasingly limited autonomy resulting from data-driven predictability of behaviour and the instrumentarian power exerted by surveillance capitalists "through the automated medium of ubiquitous computational architecture of 'smart' networked devices, things and spaces." [4]

As argued by Floridi (2015), the ongoing digital transition is entrenched in social experiences and virtual-real contexts characterised by a profusion of information, hyperconnectivity, and people-nature-artefacts interactions. Cultural influences are key to understanding and effectively addressing the blurring of virtual-physical environments, primacy of interactions over entities and distinctions between human, machine and nature. Through a system of shared symbols, ethical codes, regulations, meanings and behaviour (Mead, 1934; Geertz, 1973), it is possible to make sense of a complex, dynamic and networked digital environment, in which we are living, to better foresee its sustainable implications (Levin and Mamlok, 2021). As such, digital technologies should be considered as active agents of transformation being influenced and influencing society and culture, rather than a *means to an end*. The use of ICT for health and well-being presents several ethical issues over data protection (privacy) and autonomous self-tracking and health monitoring by individuals (Burr, *et al.*, 2020). Forms of psychological and emotional conditions (anxiety [5], alienation [6] and fear of missing out [7]) are emerging from excessive use of smartphones and computers, particularly among young people (Rosen, *et al.*, 2018). Issues over technology-mediated education are related to pedagogical re-location in different space-time environments, digital literacy and an emphasis on quantifiable performances (Williamson, *et al.*, 2020; Skinner, *et al.*, 2021). ICTs are heightening problems identified decades ago, such as issues resulting from a lack of face-to-face interactions with teachers and peers (Sherry, 1995). The current work-from-home trend is raising similar issues over the negative effects on a work-life balance (Barbieri, *et al.*, 2021), a digital divide across industries and among employees (as not all jobs are “remotable”), surveillance and productivity (Aloisi and de Stefano, 2022). Public services digitisation and online public participation in decision-making also reveals issues mainly related to digital divides, social cohesion and public-private governance (Bouzguenda, *et al.*, 2019; Tomor, *et al.*, 2019).

Table 1 shows a concise account of the issues and challenges for identified socio-cultural domains, including some common and interrelated themes from the literature. As a result of hyperconnectivity and the pervasive use of data, information, algorithms and digital platforms, most of these issues tend to emerge from a blurring of traditional public and private spheres. Onlife experiences raise concerns over individual and collective rights, with norms and values often at odds with each other, requiring appropriate forms of systemic governance (Floridi, 2015; Royakkers, *et al.*, 2018; Lovett and Thomas, 2021). This applies to conflicting issues of data protection, public safety/security and surveillance (boyd and Crawford, 2012; Aloisi and de Stefano, 2022; Compagnucci, *et al.*, 2022). Major events like terrorist attacks and the recent COVID-19 pandemic clearly showed how public safety imperatives affected individual rights of control over personal data and information collection, storage and use (privacy). Through a political condition of surveillance exceptionalism (Zuboff, 2019), personal data were collected and analysed by public and private companies to predict individual behaviour. In a context of different approaches to data and information privacy, across world regions, the introduction of surveillance technologies has been accepted before considering negative consequences over privacy.

Table 1: Socio-cultural dimension.

Social domain	ICT implications	Sustainability issues	Studies
Health & well-being	Patient-centric systems; sensitive personal data monitoring; hyperconnectivity; self-assisting; health tracking; digital divide	Privacy; autonomy; accountability; anxiety; alienation; FOMO; individual/social safety; health data governance	Rosen, *et al.*, 2018; Brubaker, 2020; Burr, *et al.*, 2020; Compagnucci, *et al.*, 2022
Education	Digital literacy; digital divide; poly-synchronous teaching & learning; performance-	Access/participation/engagement; overlooking of non-quantifiable aspects (identity and values); instructors vs. educators;	Tanil and Yong, 2020; Williamson, *et al.*, 2020; Skinner, *et al.*, 2021;

	oriented pedagogy (quantitative); information overload	students/staff well-being (stress, anxiety, alienation)	Crawford & Cifuentes-Faura, 2022
Labour	Remote working; digital divide; digital skills; automation of work; Algorithmic management; ”gig economy”; data-driven labour productivity	Privacy; surveillance; work-life balance; techno-bureaucracy; high-low skills polarisation; wage inequalities; digital vulnerable groups/countries	Acemoglu & Restrepo, 2018; Vasilescu, *et al.*, 2020; Aloisi & de Stefano, 2022; Barbieri, *et al.*, 2021
Socio-cultural living	Social innovation; algorithmic management; hyperconnectivity; data and information overload; re-location of time-space; citizen participation; e-Government; digital divide; technological paternalism; digital institutions	Cohesion/inclusion/exclusion; privacy; surveillance; cyber-security; digital commons and governance; hyper-coordination of daily life; multiple identities; loss of autonomy and control over ICT; techno-bureaucracy; networked individualism vs. collective values/norms/beliefs	Floridi, 2015; Hilty, 2015; Royakkers, *et al.*, 2018; Brubaker, 2020; Burrell & Fourcade, 2021; Levin & Mamlok, 2021; Lovett & Thomas, 2021

Economic

Sustainable development discourses are historically driven by economics. An idea of prosperity based upon an effective and efficient generation and distribution of wealth guided a search for solutions and viable alternative approaches to address the socio-environmental effects of economic growth (Jackson, 2009). This view of growth underpinning neoliberal market-based economies has been assimilated into sustainable development debates. The problem of growth and progress gradually turned into “manageable” solutions (Purvis, *et al.*, 2019), with early radical critiques of capitalist economic expansion resurfacing in degrowth, circular economy and green economic discourses (Meadows, *et al.*, 1972; Belmonte-Ureña, *et al.*, 2021). In focusing on prosperity (*degrowth*), waste and pollution (*circular economy*) and ecological implications (*green economy*), however, the approaches to sustainability tend to rely on an instrumental view of ICTs in production and consumption dynamics. This view has applied blockchain technology for circular economy benefits (Kouhizadeh, *et al.*, 2020; Upadhyay, *et al.*, 2021), or in green economy narratives (Howson, 2021; Parmentola, *et al.*, 2022). Aside from socially constructed views of technology by degrowth advocates (Kerschner, *et al.*, 2018), ICTs are mostly associated with a correction of market-based failures unable to address related ecological threats (Avgerou, 2003; Hess, 2012). Technology is identified as enabler and a solution to the socio-environmental effects of global production, distribution and consumption of goods and services. Digital transformation and the Industry 4.0 [8] approach are thought by some to somehow contribute to economic and environmental sustainability (Ghobakhloo, 2020). This is mainly true if this approach is better refined and evolved as stated by Dixson-Declève, *et al.* (2022):

> “Industry 4.0 paradigm, as currently conceived, is not fit for purpose in a context of climate crisis and planetary emergency, nor does it address deep social tensions. On the contrary, it is structurally aligned with the optimisation of business models and economic thinking as the root causes of the threats we now face. The current digital economy is a winner-takes-all model creating technological monopoly or oligopoly and giant wealth inequality.” [9]

A small number of dominant digital players control their core markets and receive the majority of profits by neutralising the ability of capitalism to innovate, destroy and reinvent itself. There is currently little chance to succeed in challenging Google’s dominance in online searching or disrupt the Apple and Google’s wireless operating system duopoly, because of both time and capital needed.

Industry 4.0 lacks key design and performance dimensions that are indispensable in making systemic transformations possible and to ensure a necessary decoupling of resource and material use from negative environmental, climate and societal impacts. What is really needed is a vision of ICTs and “smart technologies” as tools that need to be applied only after a thorough reconsideration and revision of organizational and operational processes in any industry or social entity tested over a long period of time. A holistic and systemic account of socio-economic issues raised by the digital economy has been hardly considered in the literature (Cricelli and Strazzullo, 2021).

In terms of ideal Pareto efficiency (Sen, 1975), the role of technology and innovation in the steady shift of the production-possibility frontier is consistent with market-based growth of financial and economic systems (Mankiw, 2015) [10]. Digitisation of our socio-economic world (online shopping and other forms of financial/economic transactions) has also become one of the key drivers of neoliberal forms of globalisation (Yeganeh, 2019). Global e-commerce drives increased consumption and a creation of more disposable waste creating further concerns developing from digital economies (Dwivedi, *et al.*, 2022). By expanding digital trends, post-pandemic economies will likely further a dematerialisation of payments, transactions and work activities. The creation of central bank digital currencies (CBDCs) as a more stable alternative to private cryptocurrencies and the use of non-fungible tokens (NFTs) are some examples of transformations to international monetary systems and value chains (Echarte Fernández, *et al.*, 2021; Parham and Breitinger, 2022). Similarly, various flavors of remote working will eventually transform urban economies through diverse ways of travelling, teaching, learning and living (Batty, 2022).

Considering current and forecasted inflation rates and higher costs of living, due to the pandemic and the Russia-Ukraine war (Seller, 2022), socio-economic inequities cannot be ignored in digital economies. These are often defined by oligopolistic competition, intangibles and complex network effects in multi-sided and data-driven markets (Nuccio and Guerzoni, 2019; Smyrnaios, 2018; Osburg and Lohrmann, 2017). Self-learning algorithms are changing the nature of labour as we know it, with concerns over social security, welfare and circumvented legislation typical of the “gig economy”. Alongside a commodification of labour, with a high degree of flexibility and decreasing levels of protection for workers (de Stefano, 2017), the uneven production and distribution of wealth appears to be expanding with concentration in the hands of a few digital global players parallel the exponential growth of online retailers (Huws, 2014; Stark and Pais, 2020).

The digital economy clearly generates both positive and negative externalities, as described in Table 2. Alongside a negative impact on social welfare, labour market instability and abuse of market power (de Stefano, 2017; Goldfarb and Tucker, 2019), positive externalities concern the growth of human and social capital nurtured by explicit and tacit knowledge flows (knowledge spillover), lessening informational gaps and assisting decision-making on some socio-economic issues (Spence, 2021). However, the paradoxical nature of the digital economy suggests that early dilemmas of economic growth still exist today. Despite promises from technological innovation for productivity growth, the current trend of some significant structural factors (*i.e.*, decline in labour-force participation, population aging and migration flows) revived arguments for secular stagnation, in turn questioning assumptions of perpetual growth (Jackson, 2019; Probst, 2019; Magnani, 2022). Inequities, risks, security and economic vulnerability are likely to emerge from an exponential growth of e-commerce, financial technology (fintech) and digital market expansion. While inequalities and vulnerability might be broadly associated with an expansion of existing economic disparities, digital divide and fintech (Mogaji, *et al.*, 2021; Yue, *et al.*, 2022), the growing rate of cybercrime coupled with a massive collection and monetisation of consumer data raises the level of risks and security for people, groups and even countries unable to afford adequate skills and protection (Najaf, *et al.*, 2021; Jung, *et al.*, 2022). By considering current and future inequalities, market power concentration and governance in digital economies, policies and regulations need to address the challenging complexity of ever-changing digital ecosystems to achieve socio-economic sustainability, without overlooking the commodification of labour, market power concentration and algorithmic lending (Hindman, 2018; Bruckner, 2018; Hiller and Jones, 2022).

Table 2: Economic dimension.

Economic domain	ICT implications	Sustainability issues	Studies
Commerce	Global e-commerce platforms; electronic payments (Web & mobile); data-driven marketing and analytics; disintermediation; mobile/Web advertising; recommendation systems; consumer analytics (algorithm/AI); dark Web	Consumerism; Privacy and safety/security; Digital divide-inequalities; physical vs virtual commerce trade-offs; socio-economic inequalities; environmental impact trade-offs (logistics, energy, waste); illegal products/services trade	Kucuk, 2016; Dost and Maier, 2018; Lutz, 2019; Bandara, *et al.*, 2020; Gregorczuk, 2022
Markets	Disintermediation; gig economy; data-driven markets; changes in traditional business models; dark Web	Price discrimination (market structure Oligopoly); market failures; commodification of labour; cybercrime markets	Nuccio and Guerzoni, 2019; Economides and Lianos, 2021; Jung, *et al.*, 2022
Finance (fintech)	Cryptocurrencies (public & private); NFT; digital payments; digital banking; transactional data systems (electronic data	Personal/systemic financial risks; digital literacy; digital security/safety; consumer credit scoring (vulnerables);	Fry and Cheah, 2016; Bruckner, 2018; Mogaji, *et al.*, 2021;

	interchange systems [EDI]); consumer credit reporting	digitally vulnerable people/countries; financial inclusion/exclusion	Najaf, *et al.*, 2021; Yue, *et al.*, 2022
Production, distribution & consumption	Digital transformation (Industry 4.0); e-commerce; disintermediation; dematerialisation	Economic leakage; wealth gap (more profit to fewer people); labour and workers; frugal innovation; circular economy	Stewart and Stanford, 2017; Hindman, 2018; Kouhizadeh, *et al.*, 2020; Ghobakhloo, 2020
Policy/regulations	Dark Web; gig economy; remote working; big/open data; digital rights management (DRM); digital marketing; e-retailers; digital footprint	Intellectual property (IP) rights; credit scores; labour regulations; competition laws; consumer laws	Chertoff, 2017; Stewart and Stanford, 2017; Aloisi and de Stefano, 2021; Economides and Lianos, 2021; Hiller and Jones, 2022

Environmental

Different views of environmental sustainability emerged from ecological concerns the digital transformation of societies and economies. Smart technology is often recognised as a solution for climate change and renewable resources through efficient transportation, energy use, water utilization, agriculture, manufacturing, and general consumption systems (Osburg and Lohrmann, 2017; Mondejar, *et al.*, 2021). An emphasis on green technologies is essentially driven by innovations and practices mitigating environmental effects. The virtualization of physical objects and digitization of information (dematerialisation), along with changes in energy consumption patterns and algorithmic efficiency, to name a few, are contributing to sustainability through a complicated mix of software, hardware, and diverse client devices (Fuchs, 2017; Fors, 2019). With constant scientific and technological developments broadening our actions and understanding, environmental issues tend to occur at a global scale and extend beyond the scope of human concerns. Hence, there is a need to consider socio-technological and socio-economic complexities to effectively assess the contributions of “clean” technologies in reducing environmental externalities. As observed by Lee, *et al.* (2013), public and private commitments to ICTs for “greening” purposes tend to follow different agendas and strategies of countries mirroring their respective diffusions of technologies and governmental efforts for effective environmental initiatives. An agreed upon global policy framework would, in fact, facilitate the identification of actions required at national and international levels to remove contextual and systemic socio-economic barriers preventing the adoption and diffusion of “green” technologies (Waisman, *et al.*, 2019). Technology should be assessed from multiple perspectives, beyond overly optimistic assumptions about assumed positive contributions. This view arises from research on the growing debate over the role of ICTs as both a solution and a problem (Dwivedi, *et al.*, 2022). Alongside the positive contributions of smart ICTs enabling better management of resources (*e.g.*, water and energy use) and governance, it is also essential to address and assess negative impacts of technologies increasing, for example, levels of energy consumption, e-waste, and CO_2 emissions. A more critical and balanced approach is therefore required because digital computing and ICT advantages have been broadly recognised to a greater extent than disadvantages (Li and Wang, 2017; Walsh, *et al.*, 2020).

The pervasive diffusion and adoption of connected devices and energy-intensive systems (like blockchain) has indeed shifted consumption patterns, with an often overlooked effects on the environment (Howson and de Vries, 2022). Overall demand of electricity will be increasingly driven by the production and application of smart technologies, with related energy accounting for 20 percent of global demand by 2030. Data centres alone will account for one-fifth of global electricity consumption by 2050 (Li, *et al.*, 2020; Acun, *et al.*, 2023). Despite initiatives and efforts supporting a demand for "clean" technologies (Dwivedi, *et al.*, 2022), various rebound effects could also result from increasing energy efficiencies of ICTs and the growth of services on top of existing ones, rather than replacing them (Lange, *et al.*, 2020). As noted by Galvin (2015) and Coroamă and Mattern (2019), overall gains yielded by energy-saving technological innovations are outbalanced by increasing energy consumption due to enduring lower costs in consuming more of the same or other digital resources. The pervasive nature of ICTs enables the spread of both energy efficiency gains and rebound effects across sectors, products and processes. Hence, there are growing concerns over significant contributions of ICTs to greenhouse gas emissions (GHGEs) and global warming (Freitag, *et al.*, 2021). Digital living affects the environment and extends across devices, platforms, systems and behaviours, from smart home appliances to videoconferencing, social media and e-mail (Griffiths, 2020; Greengard, 2021). Any Internet carbon footprint evaluation through single online activities can lead to misleading interpretations over actual emissions. Estimation is tricky since it depends "on which parts of the chain of consumer devices, wireless networks, data centres and Internet backbone you include in your calculations" and "how much of the energy being used by each piece of infrastructure is attributable to your task." [11] The use of ICTs should be assessed relative to their production, shipment, disposal and energy requirements. Constant upgrades of hardware and software has progressively reduced the lifespans of digital ecosystem components, with overlooked implications for e-waste management. The replace-over-repair logic, with insufficient recovery of scarce and valuable materials (*i.e.*, gold, platinum, silver, copper and rare earth elements) are actually driving health and environmental hazards from discarded electronic products. According to Forti, *et al.* (2020), the amount of e-waste collected and recycled globally (17.4 percent) is still very limited compared to a five-year growth rate at 21 percent and an overall impact of 53.6 million metric tonnes (Mt) generated worldwide in 2019. To date, most recycling is occurring in countries with ineffective or non-existent regulations, by workers exposed to toxic pollution and other hazards (Okeme and Arrandale, 2019).

Except for proactive views of degrowth (Kerschner, *et al.*, 2018), discussion about ICTs have been very limited and controversial as a meaningful agent in the quest for strong sustainability (Weiss and Cattaneo, 2017; Lenz, 2021). Research on the sustainability effects of a digital transformation of society and Industry 4.0 is still too limited to corroborate highly optimistic narratives on environmental benefits (Ghobakhloo, 2020; Cricelli and Strazzullo, 2021). However there is a growing body of literature addressing negative impacts of ICTs on non-renewable resources, pollution and climate change (Dwivedi, *et al.*, 2022). As shown in Table 3, common issues revolve around different forms of pollution, GHGs emissions and exploitation of natural resources associated with increasing production, distribution and consumption of digital equipment, requiring the mining and processing of minerals as well as energy, mostly derived from fossil fuels. The problem with energy consumption, and its impact on global warming, can also be extended to data centres (Li, *et al.*, 2020; Acun, *et al.*, 2023) and e-waste recycling (Forti, *et al.*, 2020). Alongside indirect and direct rebound effects of ICTs in terms of "pure" energy efficiency gains (Gossart, 2015), the contribution of green technologies to renewable and clean energy production has to consider challenges of power supply continuity often ensured by conventional energy sources or storage. With reference to all of the examined pillars of sustainability so far, the 2030 agenda seems not to fully embrace the complexities of sustainable development outcomes, their dynamics, as well as problematic simultaneous operationalisations of all goals in diverse contexts, at different levels of socio-economic and environmental trade-offs (Selomane, *et al.*, 2019; Gentili, 2021). Hence, there is a need to address the problems of determinism, along with ethical and epistemological issues, before examining various complexities and modelling.

Table 3: Environmental dimension.

Environmental domain	ICT implications	Sustainability issues	Studies
Climate change & global warming	Pervasive diffusion of ICT infrastructure and devices; data-intensive infrastructure; cloud computing; green IT; transportation of finished products; data computing and sharing; electric vehicles	GHG emission; fossil fuel/chemicals and raw material for hardware and software manufacturing & distribution; greenwashing; carbon footprint measuring; indirect impact from poor systems designing	Li and Wang, 2017; Belkhir and Elmeligi, 2018; Rice and Friday, 2020; Freitag, *et al.*, 2021; Lannelongue, *et al.*, 2021; Dwivedi, *et al.*, 2022
Pollution & waste	Hardware/software production and consumption, Planned obsolescence, Pervasive wireless systems	e-Waste; health hazard; Recycling; electromagnetic field (EMF) pollution; air and water pollution; developing countries exploitation	Bandara and Carpenter, 2018; Okeme and Arrandale, 2019; Forti, *et al.*, 2020
Natural resources (non-renewable)	Mineral-intensive technologies; planned obsolescence; data and information infrastructure; digital artifacts creation and use; digital institutions for common-pool resources management; electric vehicles	Mining minerals (rare earth elements) effects on forests; water/soil/land use for servers and data warehouses; resource exploitation of developing countries; polycentric and participatory governance; local vs. global resource	Stuermer, *et al.*, 2017; Lovett and Thomas, 2021

		commons	
Energy production, distribution & consumption	Servers and data warehouses; sensor-based technologies; growing Energy and electricity demand for manufacturing and use; declining cost/price of electronic goods; power grid digitisation and efficiency	Direct/indirect rebound effects; direct/indirect fossil fuel use; power continuity in production, distribution, and storage (batteries)	Gossart, 2015; Coroama and Mattern, 2019; Li, *et al.*, 2020; Lange, *et al.*, 2020; Howson and de Vries, 2022; Acun, *et al.*, 2023

3. Determinism, ethics and epistemological issues

Digital sustainability is a recent *portmanteau* for positive and negative effects of technology on sustainability and sustainable development. Over the last two decades, overall attention to social, ethical and epistemological issues could have been higher, in spite of a growing body of interdisciplinary knowledge and critical views (Zuboff, 2019; Sharma, *et al.*, 2021). The disruptive forces of current ICTs are greater than those of previous technological revolutions, including an earlier shift to the digital age (Arendt, 1958: McLuhan, 1962). Through the concept of *hyperhistory*, Floridi (2016) recognised the power of ICTs in reshaping reality in profoundly different ways. Russo [12] clarified that current challenges and issues "emerge precisely because digital technologies have brought about changes that are ontological and epistemological in the first instance, with implications at the ethical level." By considering sustainable development as a process to achieve the goals of sustainability (Mensah, 2019; Sparviero and Ragnedda, 2021), the epistemological challenges and ethical implications of digital sustainability will be discussed in relation to distributed morality, ethics of technology, and importance of avoiding technological neutrality and determinism.

Socio-technological determinism and neutrality

Technologies have traditionally produced conflicting views about their roles and influences, with reactions spanning across a utopian-dystopian dichotomy. It is no less true for current digital transformations and pervasive computing, which are often treated as either enablers of socio-cultural development, economic growth and efficiency, or disablers of a sustainable economy and environment (Lee, 2021). This binary understanding of ICTs is not beneficial for a better understanding of digital sustainability, because of a natural tendency to polarize the debate around taken-for-granted visions overlooking certain complexities. As grounded in science and technology history (McLuhan, 1962; MacKenzie, 1984), determinism stresses "the autonomy of technological change and the technological shaping of society" [13]. Clearly, the common traits of both hard and soft determinism can be found in the normative role of ICTs and their regenerative dynamics resulting in socio-economic adaptation and evolution (Marx, 1987; Ziman, 2000). In short, this evolutionary view embraces an idea of progress based on socio-economic changes driven by technology and positive visions of the future as predominant over negative/dystopian perspectives.

On the other hand, social determinism shifts the focus away from the transformational powers of technology to stress the superior role of social factors in driving changes. Coherent with reversing a technology-society causal relationship, this form of determinism assumes that technologies and their development, use and effects depend on human actions, socio-cultural interactions and power structures of society (Pinch and Bijker, 1984; Matthewman, 2011). This position emerged within science and technology studies (STS) as a new turn in the social studies of technology and evolved along a constructivist criticism of unilinear technological paradigms, with an aim of treating technological knowledge in the same manner as scientific facts are treated from a sociological perspective. The main arguments shifted away from initial social determinism of views on the social construction of technology (SCOT) to consider the mutual relationship of technology and society embedded in complex and networked ecosystems (Lynch, 2016). Attention gradually moved from the products to the processes of science, innovation and technological changes, with an emphasis on their societal implications. Large-scale technological systems (LTS) and actor-network theory (ANT) studies, in fact, address interactions between physical and non-physical components of socio-technological ecosystems and the roles of human/non-human agents (Latour, 2005; Arnaboldi and Spiller, 2011). As with technological determinism, it is possible to find a distinction between hard and soft determinism in different sociological approaches to ICTs, with clear attempts to overcome both forms of determinism by proposing neutral positions for the causal relationship of society and technology. The integration of structural, social, economic and cultural elements into socio-technological discourses, along with social determinism critiques (Dafoe, 2015), has fuelled balanced approaches to examining the effects of ICTs on society and nature (Feenberg, 1999; Antonsen and Lundestad, 2019).

Given that any form of determinism related to technology should be avoided, the main issues and challenges across all approaches to digital sustainability can be identified in a linkage of progressive technological (r)evolutions, views of ICTs as neutral and value-free agents and an oversimplification of socio-technological phenomena. In this sense, technological determinism raises more concerns than recent theoretical and empirical applications of social studies to technology. If the basic assumptions of technological determinism were true, then there would be no need for discourses ensuring that ICTs will develop *motu proprio* (Bennato, 2012). On the contrary, technology profoundly needs ideology, cultural entities, socio-political structures and values to be recognised, integrated and accepted in society (Wasilewski, 2020). In the light of a pervasive diffusion of smart ICTs, exacerbated during the pandemic, their diverse use and applications based on extant values across societies cannot be associated with instrumentalist views. It is even harder to define social changes and progress as consecutive stages of technical development. As noted by Vespignani [14], we need to recognise that we are living within complex and dynamic techno-social systems consisting of "large-scale physical infrastructures (like transportation systems and power distribution grids) embedded in a dense Web of communication and computing infrastructures whose dynamics and evolution are defined and driven by human behaviour". The large-scale patterns of social interactions and energy consumption in and across self-organising ecosystems are essentially "independent of human planning and engineering of the system", which makes control and predictions of their effects more challenging [15]. This aligns with the complexity and "unintended consequences" of rapid and extensive technological changes in society (Winner, 1996; Lane, *et al.*, 2009). To move away from determinism and consider the implications for digital sustainability, it is helpful to address technology relations to progress, values, morality and science at ethical and epistemological levels.

Ethical and epistemological digression

Technology has historically raised ethical concerns. From Plato's complaints in *Phaedrus* about the technologies of writing [16] to recent technomoral virtue ethics to address issues like "global climate shifts, the emergence and spread of new pathogens" [17], technologies have been always questioned for their disruptive effects on people, society and environments. The fact that values permeate any form of technology makes ethical reflections on society, morality, progress, science and responsibility inevitable and important (Winner, 1996; Feenberg, 1999; Floridi, 2013), specifically for digital sustainability (Sparviero and Ragnedda, 2021). In ethical terms, ICTs are problematic because of their close relationship to decisions and actions, which are not politically and culturally neutral as much as the technology in itself. This is clear in how social media are influencing politics and social relations and how decisions are often guided by data-driven technologies and algorithms. Social media, like Facebook and Twitter, generate revenues from what people do and see on their platforms by utilizing our attention, collecting data linked to digital traces left through likes, views, shares and comments, and selling information to third parties. Some sensors in smartphones can track and predict online behaviour for some activities on social media, which in turn utilize algorithms and machine learning to parse data to target users with specific content for commercial and other goals. The resulting influence on society and social relations develop from a commodification of interactions, attention and personal data (Zuboff, 2019; Haidt, *et al.*, n.d.), with, in some cases, resulting in polarisation around shared narratives and viral misinformation (Quattrociocchi, *et al.*, 2014; Falkenberg, *et al.*, 2022). As such, digital technologies convey values embedded in specific socio-cultural systems in the form of shared moral meanings (Griswold, 2012; Chandler and Fuchs, 2019). The large array of values at play entails choosing among diverse values involved in the production, diffusion and use of technologies leading, in some cases, to socio-political decisions.

Reflecting on the relationship between science and technology can help broaden a view on ethics to better consider implications for digital sustainability. Even if there is no clear-cut distinction between science and technology, it is commonly believed that technology is the product (application) of science (knowledge) and, as such, exposed to determinism and ethical questions. This distinction, however, is consistent with narratives excluding socio-political influences on scientific progress and the emergence of techno-science. By suggesting a rethinking of science and technology relations, Russo [18] argued that “Galilean and Baconian science is highly technologized and politicized” because “the invention and production of technological artifacts lead to know, to better understand, and to control nature — in sum, it leads to improving on the human condition”. The separation and superordination of science (not ethically/morally questionable) over technology (ethically/morally questionable) could even appear antithetical to current profound socio-technological transformations. Heidegger (1977), Arendt (1958) and Gehlen (1980) foresaw the entwined relations between science and technology arising from the power of technology (*téchne*) over science (*epistème*) and creative-productive (*poiesis*). In our societies, human activities, extending beyond their ends (*poiesis*), are no longer defined by a synthesis between theory and practice, because technical actions are characterised more by proper doing (*téchne*) than proper acting (*praxis* as practical knowledge) in a functional and a-finalistic way (Galimberti, 2008). The attitude to reduce scientific knowledge and theories to specific or siloed knowledge, for example, have shown that the technical intents at the heart of both science and technology have become the “universal condition through which all aims are satisfied” [19]. The primacy of *téchne* over *praxis* tends to disrupt their relationship with *poiesis*, and even more importantly for digital sustainability, changes the way we understand the nature of problems and how we secure knowledge to deal with ethical and moral issues raised by ICTs.

The greatest impact of ICTs concerns unprecedented changes of the existing environment and the creation of new realities. Through a process of abstraction (dis-embedding) and return to local context (re-embedding), for example, social media and videoconferencing platforms enable time and space conflation (Castells, 1996; Wang and Tucker, 2016). Similarly, the Internet of Things (IoT) and extended reality (XR) create an environment where everything is interconnected, and in which humans are not necessarily part of technological interactions. ICTs will act as non-neutral and proactive agents like humans, who are often delegating to diverse technologies all sorts of routine activities, knowledge and memories. While transforming our ordinary environment and the world as we know it (*re-ontologization*), technologies create new realities characterised by ontologically-equal agents and interactions that are equally digital (Floridi, 2016; 2007). This complex and multi-agent reality presents epistemological challenges critical to digital sustainability for two main reasons related to ethical/moral and socio-technological aspects.

First, there is a problem of maintaining responsibility and accountability in dynamic, networked and hyperconnected physical-virtual ecosystems. It is difficult to locate the agency, responsibility and accountability of artificial/autonomous entities (algorithms) acting within contexts of highly distributed interactions with human, non-human and hybrid agents. According to a distributed morality and identification of agents in terms of interactivity, autonomy and adaptability (Floridi, 2013), however, “non-human agents cannot be held responsible even if they are accountable for certain actions as long as they do not exhibit intentionality are considered in separation” [20]. Even if accountability could be shared with digital agents with reality less anthropocentric, our responsibility cannot be delegated or ignored when creating technologies that will effect us and future generations (Jonas, 1985). More attention should be therefore placed on epistemic responsibility in ICTs to better address challenges of assuming or attributing responsibilities to actions and decisions by human and non-human agents (Simon, 2015). As such, our understanding of ICTs for sustainability cannot ignore that epistemic practices are intrinsically ethical and political in their connotation.

Second, a hybrid multi-agent reality contrasts with the common view of ICTs as instrumental to achieve sustainability and meet SDGs, rather than proactive entities. Critical discourses about the positive and negative effects of technologies on climate change (Dwivedi, *et al.*, 2022), and across all pillars of sustainable development (Sparviero and Ragnedda, 2021), are largely anchored in technological development, innovation and predictive capabilities (Moon, 2017; Sharma, *et al.*, 2021). This opens two lines of interrelated epistemological arguments concerning scientific-technological progress and the use of ICTs to inform actionable decision-making. In the science-technology dialectic, the latter (*téchne*) tends to prevail on the former (science), even if one informs another. Scientific progress is increasingly driven by sophisticated technologies that are not entirely controlled by humans, but still considered as means to an end. “Smart” and “green” technologies are created and implemented as solutions to preserve natural ecosystems by reducing the carbon footprint or for their efficiency in, consuming, producing, and distributing energy (Singh and Kumar, 2017; Andressen, *et al.*, 2019). As discussed earlier, digital interactive artefacts cannot be deemed as mere neutral and passive tools to attain desired ends, even if they are indeed the result of human activities. The improvement of sustainability through technology continues to be challenged by an ensuing loss of control over ICTs (any recovery will likely fail) and misinterpreted notions of instrumentality and causation. An assumption of a linear relationship between means and ends through a mastering of technologies could be valid for simple artefacts or socio-technical systems (with nature and its laws accepted as universal and invariable), not for current complex and unpredictable digital ecosystems. Specific knowledge and interpretation of this digitally transformed reality is therefore essential to attain information guiding meaningful decisions and actions for sustainability. There is a real need for analytical knowledge and skills to address a real epistemological issue of patterns of data, rather than more technological solutions that will only generate more data requiring in turn techniques and technologies (Floridi, 2016; Balazka and Rodighiero, 2020).

In essence, digital transformation needs profound ethical and philosophical reflections on the roles played by ICTs for sustainability as well as changes in how we understand a hybrid reality through them. Rethinking the nature of technology and interactions across all moral entities of virtual-physical ecosystems helps us to see changes and processes. The old and still dominant conceptions of technologies as utilitarian, instrumental and anthropocentric tools for an end do not ultimately consider that they are indeed means of interpreting reality (Heidegger, 1977) as well as moral agents interacting as ‘active mediators’ rather than ‘passive intermediaries’ [21]. Hence, there is a need to avoid determinism and question the prominence of technology over knowledge (*epistème*), to rebalance science-technology-ethics relations that affect socio-political decisions related to sustainability. The former decision-making power of politics has turned into a kind of brokering governed by economic forces mutually influenced by technologies and technical progress (Labini, 1990; Loeber, 2018). The traditional role of politics in democracy has been shifting from challenging powerful groups at the top of society and making decisions in the interest of current and future generations to representing and mediating new economic and technocratic classes (Diamond, 2015; Bertsou and Caramani, 2020). In this, instrumentarian technologies, like AI and social media, have acted as a ubiquitous brokering system while enabling this socio-political and economic transformation of society and us “into means to others’ market ends” [22]. Placing an emphasis on *poiesis* beyond digital tools, as suggested by Russo [23], can ‘help us bridge ontology/epistemology and ethics’, and thereby decisions and actions based on ‘specific ethical choices’. Ethical and philosophical questioning of technologies to enhance the digital sustainability discourses, however, should benefit from critical contributions of complexity science considering large-scale issues and solutions.

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4. Instrumentarianism, morality and the modification of reality

Instrumentarian power is the key tenet of Zuboff's (2019) arguments on surveillance capitalism. As a new market form and logic for accumulating data, information and human experiences, alongside capital and assets, surveillance capitalism emerged from a deterministic view of Big Tech to provide a means to people's ends while tracking, predicting and modifying their behaviours. Even if the phenomenon is not new (Gill, 1995), the recent combination of geopolitical events and technological advancements enabled the current systemic control and monetisation of mass behavioural data (Lawrence, 2018). The digital infrastructure serves as a platform for the mass collection and transformation of information resulting eventually in profits and power (Srnicek, 2017). Smart infrastructure systems, retail and e-commerce digital Web platforms and mobile telecommunications are instrumental to a power that "knows and shapes human behaviour toward others' ends [...] and that works its will through the automated medium of an increasingly ubiquitous computational architecture of 'smart' networked devices, things and spaces" [24]. Such power from instrumentarian technologies has ethical and epistemological implications, which will be briefly discussed here in terms of morality and interpretation of reality.

Individual human autonomy, privacy and the potential for exploitation are the main concerns of instrumentarian morality. Data scientists contend that the insights gained from data-driven analysis can lead to better decision-making, improved services and enhanced efficiency (*e.g.*, Provost and Fawcett, 2013). However, critical data studies (Kitchin and Lauriault, 2018) argue that privacy can be eroded and personal agency restricted, by the pervasive monitoring of individuals, with amplification of power imbalances between those who control data and those subject to its manipulation. With decisions over how and what to disclose concentrated in surveillance capitalism, "privacy is not eroded but redistributed" [25], like as the morality of human, artificial and hybrid agents of digital-physical ecosystems (Floridi, 2013). Given the challenging trade-offs between individual rights and societal benefits, it is essential to find a balance between harnessing the potential of data-driven insights and safeguarding fundamental human rights and values. This balance can be achieved through a robust legal and ethical framework preventing threats posed by instrumentarian power. As such, the debate over the morality of instrumentarianism appears to be centred around the transparency of data collection and use, the need of appropriate informed consent from individuals, and dis-automation of our moral agency alongside ethical principles ensuring the development and implementation of ubiquitous technologies in an accountable and responsible manner (Zuboff, 2019; Wade, 2021).

As described by Latour and Venn [26], technology cannot be distinguished from morality because they "happen to be indissolubly mingled" as a "particular form of exploring existence and being". The notion of technical mediation, or intermediation, is thus not appropriate to embrace the *folding* of time, spaces and agents within technology, and to understand how the external world can be shaped, modified and interpreted. As intrumentarian tools, *smart* and *predictive* ICTs affect our world and its perception by mapping, reducing and augmenting realities through the extraction and analysis of real-time data and experiences. The distinction between real and virtual worlds does not apply to surveillance capitalism, since the blending of virtual and physical worlds can actually create new connected experiences based on the unilateral scale and scope of technical knowledge shaping behaviour and to predict behaviour for revenues, market control and political decision-making (Zuboff, 2019, 2015). Such pervasive *intervention* in the nature of reality is evident, for example, in the execution of control for public safety and security during the COVID-19 pandemic (Aloisi and de Stefano, 2022), influences on important socio-political decisions like Brexit (Bond, *et al.*, 2012; Cadwalladr and Graham-Harrison, 2018) and a potential loss of an ability to self-govern smart cities (Mann, *et al.*, 2020). Within the realm of human *onlife* experiences claimed as "free raw material targeted for rendering into behavioral data" (Zuboff, 2019), instrumentarian ICTs enable what Eagle and Pentland (2006) call "reality mining", as a collection and analysis of data linked to experiences and social behaviour, for the prediction of future behaviour, ultimately to meet specific corporate objectives while increasing profitability. Considering the active roles of increasingly autonomous technologies, acting as moral agents, and the diminishing autonomy and self-determination of individuals, the role of advanced ICTs like AI in shaping reality for commercial benefits or private interests should be also questioned and discussed relative to our relationships with them and the complexities involved.

5. A complexity science approach to sustainability

Social, economic and environmental (ecological) systems, at the basis of sustainability discourse, are well known to be complex adaptive systems. They are archetypal examples that any work on complexity puts forward. Although no generally accepted and precise definition of complexity exists, a complex adaptive system is commonly described as one having a certain number of interconnected elements whose relationships are of a non-linear nature. These systems exhibit some fundamental properties: self-organization, that is their capacity to form some kind of overall order arising from local interactions between parts; emergence, properties or behaviors that might be absent in their parts and show up when certain parts interact; robustness and fragility, in response to external or internal shocks or events. A complex system is adaptive; its configuration dynamically changes due to interactions with an external environment (Bertuglia and Vaio, 2005; Brodu, 2009).

The digital world is a well-known example of an environment made of complex adaptive systems. The global digital infrastructure, IoT, robotic automated processes, digital platforms, social media and other digitally assisted ecosystems drive complexity with their hyper-connections and shared ties to human actors, technological products, processes, organizations and institutions. In this technological environment, complex sociotechnical systems feature some distinctive traits. In physical or social systems complexity is mainly originated by material processes or human actions. Technological environments are embedded in a society where the differences between a "real" and a "virtual" worlds are quite blurred, so that some have coined a new term: "onlife" (Floridi, 2015). The complexity of these systems arises on one side from the fact that they can never be complete, closed or correct (Allen and Varga, 2006); on the other side it stems from dynamic combinations of social (humans), material (machines and physical objects interacting with them) and algorithmic (computational procedures) elements (Benbya, *et al.*, 2020).

A complex system has also been said to be at the "edge of chaos", meaning that its features position it between order and complete randomness. Any dynamic system can exist and evolve through different states, from a region characterized by great stability to one almost completely chaotic. The region between these extremes is the region of complexity. The evolution can be followed by "measuring" some characteristic internal parameter (order parameter) that accounts for the critical transition (Gleick, 1987; Lewin, 1999).

All these traits are quite amplified when more and diverse systems are coupled and coevolve, as occurs in the real world (Liu, *et al.*, 2007). Complexity science provides a framework that permits a better understanding of systems, actions and processes, providing appropriate concepts and tools.

Complex systems are irreducible. There is no possibility to diminish them to a combination of smaller parts, or to simplify them with high-level generalizations grounded on macro-observations of structural continuity. The interactions between all subsystems are able to generate emergent structures and behaviors not evident *a priori*. A systemic approach is the only possibility for developing multi-level representations, making sense of some of its dynamic characteristics.

Two important consequences stem from these considerations. The first is that predicting the behavior of a complex system is almost impossible, or, better, quite limited and only if the system exhibits good "inertia" (Boffetta, *et al.*, 2002). The second is that in managing such systems great care must be taken since their self-organization properties can defeat many interventions. More importantly, the contemporary robustness and fragility are such that even small actions could result in great disruptive events, while seemingly large ones could go almost unnoticed (Carlson and Doyle, 2002).

When it comes to the attempts at implementing actions for establishing or improving sustainable behaviors this means that systems exhibit a certain &lodquo;policy resistance”. Their complexity overcomes our capabilities to fully understand them and solutions that might seem obvious have a great risk of worsening a situation or failing altogether. Moreover, the combined effects of different elements at play do not allow us to find simplistic, “linear” solutions, but force us to consider many trade-offs necessary to ensure a common level of satisfactory configurations (Bowen, *et al.*, 2017).

Aiming at maximum possible “sustainability” of a certain dynamic setting means being prepared to embrace an adaptive approach to the governance of that given setting. The complexity of the systems involved, with their inherent unpredictability, at least in the medium and long term, further compels to consider the use of a number of scenarios. These scenarios identify different situations that may occur, delineate critical uncertainties, evaluate effects and outline plans and actions for dealing with some circumstances (Lindgren and Bandhold, 2003; Meyerowitz, *et al.*, 2018). This approach, however, suffers from a certain “staticity”, as scenarios are built once and cannot be easily and swiftly changed as a situation may require. A better possibility is provided by an adaptive pathways approach (Haasnoot, *et al.*, 2013). The notion is to elicit a number of scenarios, define actions needed to respond to various conditions, identify indicators to be checked for assessing, during the evolution, whether the actions used are able to reach given objectives, and define possible alternatives, evaluating costs and benefits. These “tipping points” trigger changes in plans. Rather obviously the natural choice for indicators is the set of Sustainable Development Indicators proposed by the United Nations and adopted by many institutions and countries (United Nations, 2007).

For what concerns the structure of the systems involved, their interactions and possible responses to actions aimed at ensuring sustainable development practices in all interested domains, the complexity of systems, processes, reactions and modifications definitely call for the design and implementation of suitable models that, if well set, allow different kinds of simulations that can ease the tasks of preparing meaningful scenarios.

6. Modelling and simulations for digital sustainability

Sustainability science recognizes the complex and dynamic reality of global ecosystems and the need of valid models and simulations to better understand these systems in order to make decisions about specific socio-economic and environmental issues. The complex systemic approaches to sustainability and the well-established use of simulation modelling are mainly grounded in economic and environmental dimensions (Rice, 2013; Moon, 2017). With the recent incorporation of social sciences (Leemans, 2016), the transdisciplinary move beyond multidisciplinarity still requires an integration of diverse methods into a shared framework and an empowerment of all stakeholders to effectively address complex problems at hand (Brandt, *et al.*, 2013; Lock and Seele, 2017). Given the overall complexity, the scale of variables and agents involved, it is difficult to establish a common research basis for transdisciplinarity and create all-encompassing models resulting in productive computer simulations. Modelling and simulations are work-in-progress in sustainability research. Rather than specific procedures, techniques, or environments, some of the general issues concerning the quality, choice, design and implementation of simulation models are addressed here.

Moon (2017) and Moallemi, *et al.* (2021) noted that simulation modelling applications for sustainability span across diverse areas (manufacturing, health, energy, ICTs, tourism), with the social dimension being rather limited and the potential to incorporate socio-technical dimensions. Modelling does not occur in a “vacuum” for observers and targeted phenomena influence model designs and their applications. As representative abstractions of reality, models can only be built for an intended purpose, and “when a model (or a model component) turns out to be useful for more than one purpose it needs to be re-justified with respect to each of the claimed purposes separately (and it will probably require recoding).” [27] With a specific aim and objective, systems and phenomena are modelled in a viable, accurate and concise way to meet a specific goal. Any change will affect descriptions of future ecosystems, their components, and predictive interpretations of their behaviour. A model designed to estimate the socio-ecological effects of ICTs through behaviours and technological co-evolution during the pandemic, for example, cannot be used to run simulations after the pandemic, even if applied to the same specific context. To design an effective model, the role of the researcher is essential in selecting the most relevant elements for a "*simplified*" representation of the problems (Frigg and Hartmann, 2006), in choosing the appropriate methodology for a correct and meaningful interpretation of outcomes based upon both qualitative and quantitative approaches (Sætra, 2017) and producing a conceptual model to describe structure, objectives, assumptions and constraints as guidance for all activities (Gabriel, *et al.*, 2022). The use of computerised computational tools has increased philosophical debates around models crafted to simulate their targets and real-world reference systems correlations. This empirical validation requires ontological agreements on how key concepts in models relate to reality as well as an epistemological framework clearly and precisely showing how the object of study can be understood (Hofman, 2013; Graebner, 2018). This is crucial to the representation of ambitious holistic frameworks addressing the complexities of sustainable ecosystems with intrinsic limitations that are common to scientific model building (Box, 1979). As such, "*a model works as a mediator between theory-building and empirical research*" [28], built on a series of steps familiar to any researcher scientifically investigating phenomena. A detailed account of each and all steps lies beyond the scope of this paper, but some considerations are relevant here to the operationalisation of models, mirroring, analysing and predicting behaviours of complex ecosystems and their components.

First, by overcoming the qualitative-quantitative dichotomy, modelling can benefit from the symbiotic contribution of quantitative analyses explaining the structure and dynamics of selected ecosystems or phenomena combined with their qualitative description (often as conceptual models) and in-depth interpretation of results (Espinosa and Walker, 2011; Liu, *et al.*, 2018). In light of integrating different methods for real and complex problems (Johnson, *et al.*, 2007), the adoption of mixed methods is coherent with current transdisciplinary trends in sustainability research and related pragmatic or realistic approaches (Popa, *et al.*, 2015). Second, the gradual development of a model can help in reducing possible errors by assisting in an understanding of reproduced systems or phenomena. Researchers and simulation modellers suggest starting from a 'keep it simple stupid' (KISS) approach and gradually enhance a model by checking its overall coherence and consistency (Axelrod, 1997; Edmonds, 2017), with the possible adoption of the 'take a previous model and add something' (TAPAS) strategy for problems similarly addressed in previously implemented models (Frenken, 2006). These approaches can help avoid conceptualisations overly complicated (Sun, *et al.*, 2016), but they also entail risks of unwittingly excluding significant element from a model or adopting and adapting an existing model not fully appropriate for complex problems at stake (Harrison, 2002; Pyka and Werker, 2009). Clearly, there are no right or wrong strategies. Their implementation depends on modelling purposes and specific individual choices by modellers.

This also holds true to the third and final consideration about software. Data are the core of modelling and simulation, which cannot be performed without the help of software applications. Bearing in mind that no single tool can fulfil all needs and interoperability limitations, different levels of simulation modelling guide choices and applications of effective computer programs. As single or integrated methods, system dynamic models, network models and agent based modelling (ABM) are widely applied in simulation modelling for sustainability (Moallemi, *et al.*, 2021). Alongside the rise of hybrid modelling (Moon, 2017), increasingly ML and deep learning algorithms are used for large and high-dimensional datasets (Ladi, *et al.*, 2022; Rolnick, *et al.*, 2022). Augmenting the complexities of simulations, "black box" models are the main risks involved (Rudin, 2019). Maeda, *et al.* (2021), for example, referred to the case of climate change modelling which proved to be too complex to be interpreted by all stakeholders, failing to convince policy-makers and the public. Beyond explaining complex findings in simple terms, counterarguments mainly point to evaluation processes through calibration, verification and validation of computational models to respectively determine the best parameters that represent, as close as possible, reality by verifying internal and external consistencies (Balbi, *et al.*, 2013; Law, 2014). Robinson [29] and Moon [30] warned that "it is not possible to prove that a model is absolutely correct" and that "the process of validation is not an exact science", requiring "significant efforts and creativity to ensure that people who adopt simulation models are sufficiently convinced in the validity of the models."

As computational power grows, as hybrid approaches become more common, as modelers develop a deeper knowledge of simulation software (von Rueden, *et al.*, 2020), our understanding of complex ecosystems dynamics and behaviour is inevitably dependent upon ICTs and software development (Gomes, *et al.*, 2019). Despite the prominent and pervasive role of digital tools in simulation modelling, questions into software engineering sustainability are still limited across the entire production life cycle (Lannelongue, *et al.*, 2021; Swacha, 2022). Likewise, digital sustainability has not been widely addressed in simulation modelling across all dimensions. According to recent reviews (Moon, 2017; Moallemi, *et al.*, 2021), few simulation models concerning sustainability in information systems overlook ICTs as proactive agents within physical-virtual environments. When considering the potential expansion of modelling, it must also be noted that simulations and scenarios are ultimately the result of different requirements and trade-offs.

7. Concluding remarks

Sustainability has evolved around a notion of socio-economic and environmental development where technology and innovation are instrumental in achieving ever changing goals. This view, however, seems to overlook the profound transformations caused by the proliferation, diffusion and pervasive use of ICTs across sustainable development. Their emissions are significant and growing (Freitag, *et al.*, 2021) and thereby affecting the environment; unresolved digital divides relative to geography, gender, and socio-economic conditions exerts an influence on social sustainability (Hidalgo, *et al.*, 2020; Lythreatis, *et al.*, 2021); and economic sustainability is often disputable (Madudova, *et al.*, 2018). Even if technological progress as enabler of sustainable behaviours corroborates a strong connection between sustainability and innovation (Aricò, 2014), “this relationship is explored by researchers and considered by practitioners almost exclusively in terms of the degree of sustainability of technological solutions” often “lacking an in-depth exploration of how a product or process, in addition to being environmentally and socio-economically sustainable, must or can also be technologically sustainable” [31]. Thus, technology should be recognised as both a solution for sustainability issues and an active part of those same issues.

As such, this paper attempted to address this non-mutual exclusive duality of ICTs, noting that growing attention to digital sustainability has still to be matched by efforts of researchers and practitioners to effectively address socio-economic and environmental issues that are arising from current physical-virtual environments. The limited availability of simulation modelling for digital sustainability demonstrates how ICTs are hardly incorporated as proactive agents influencing and being influenced by current and future socio-ecological ecosystems (Moon, 2017; Moallemi, *et al.*, 2021). The integration of technological and innovation dimensions will undoubtedly increase levels of complexity in simulation modelling, requiring additional efforts to represent existing real world ecosystem complexity. Overlooking, excluding or considering ICTs as merely instrumental, however, can result in models and simulation different from cyber-physical ecosystems being represented, with effects on predictive scenarios and decision-making for targeted sustainability issues.

Digital sustainability research still lacks an over-arching strategic and comparative approach as much as appropriate theoretical underpinnings, with *sustainability* as dominant and separate, “rather than a joint term, when put in relation to *digital*” in literature [32]. As critically described by Seele [33], the current digital sustainability vision builds upon “yet existing technologies, but not yet targeted in a unified way on sustainable development” by following a “normative direction rather than a utopian idea of what could be possible with devices not yet existing.” Cowls, *et al.* (2023) warn of the same risks for smart ICTs, like AI, overlooking “responsive, evidence-based, and effective governance” in their use to combat climate change. By addressing digital transformations through a participatory approach, the *Sustainability in the Digital Age* initiative (https://sustainabilitydigitalage.org) seems to align with this vision. It demonstrates how research communities and institutions are sensitive to sustainability and the potential to further theoretical and practical knowledge within current and future socio-economic and environmental digital-physical ecosystems.

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Notes

1. Digital transformation is a “change process, enabled by the innovative use of digital technologies accompanied by the strategic leverage of key resources and capabilities, aiming to radically improve an entity and redefine its value proposition for its stakeholders.” (Gong and Ribiere, 2021, p. 12).

2. Digital sustainability can be defined as “the convergence of digital and sustainability imperatives that involves a trans-disciplinary approach of deploying digital technologies in tackling sustainability issues” (Pan and Zhang, 2020, p. 4).

3. Chakravorti and Chaturvedi (2017) define smart society as one where digital technology, thoughtfully deployed by governments, can improve on three broad outcomes: the well-being of citizens, strength of the economy and effectiveness of institutions.

4. Zuboff, 2019, p. 8.

5. Anxiety is an emotion characterized by feelings of tension, worried thoughts, and physical changes like increased blood pressure (https://www.apa.org/topics/anxiety).

6. The feeling that you have no connection with the people around you or that you are not part of a group (https://dictionary.cambridge.org/dictionary/english/alienation).

7. Fear of missing out (FOMO) is the feeling of apprehension that one is either not in the know about or missing out on information, events, experiences or life decisions that could make one’s life better (Przybylski, *et al.*, 2013).

8. The concept of ‘Industry 4.0’ emerged in 2011 from an initiative in a high-tech strategy of the German government focusing on the application of cyber-physical systems (*e.g.*, smart ICTs, sensors and algorithms) to manufacturing processes and production (Xu, *et al.*, 2021). The widespread adoption of the notion of ‘Industry 4.0’ should be seen as technology-driven, with a focus on digitization, organizational transformation and productivity enhancement in manufacturing and production systems (Philbeck and Davis, 2019).

9. Dixson-Declève, *et al.*, 2022, p. 5.

10. See Romer (1990), Krugman and Wells (2008) and Stiglitz (2017) for a more complete discussion of economic/technological issues.

11. Rice and Friday, 2020, paragraph 4.

12. Russo, 2018, p. 662.

13. Ellul, 1964; Dafoe, 2015, p. 1,052.

14. Vespignani, 2009, p. 425.

15. Vespignani, 2009, p. 427.

16. See, for example, Paul Miller, 2008. “Writing on the soul: Technology, writing, and the legacy of Plato,” at https://files.eric.ed.gov/fulltext/EJ1081052.pdf, accessed 17 August 2023.

17. Bunge, 1977; Vallor, 2016, p. 48; Wade, 2021.

18. Russo, 2018, p. 659.

19. Galimberti, 2009, p. 9.

20. Floridi, 2015, p. 150.

21. Floridi and Sanders, 2004; Verbeek, 2013, p. 77.

22. Zuboff, 2019, p. 352.

23. Russo, 2018, pp. 664–665.

24. Zuboff, 2019, p. 8.

25. Zuboff, 2019, p. 90.

26. Latour and Venn, 2002, p. 248.

27. Edmonds, 2017, p. 40.

28. Bianchi and Squazzoni, 2019, p. 60.

29. Robinson, 1999, p. 68.

30. Moon, 2017, p. 5.

31. Vacchi, *et al, 2021*, p. 1.

32. Guandalini, 2022, p. 461.

33. Seele, 2016, pp. 852–853.

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