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Systemic sustainability effects of contemporary digitalization: A scoping review and research agenda

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ABSTRACT

Digital technology has been understood as a General Purpose Technology (GPT) given its systemic and pervasive nature, and heralded as key to sustainability transitions. We perform a scoping review of 112 contributions to critically appraise research on the sustainability effects of contemporary digitalization. We find that many studies adopt a rather reductionist, deterministic and optimistic lens on the (potential) sustainability effects of digital technologies, mostly neglecting the systemic effects inherent to GPTs. For a better understanding of systemic sustainability effects of contemporary digitalization, we advocate the use of exploratory designs and prospective methods, and a theoretical understanding of technologies as co-evolving with institutions and practices.

1. Introduction

Sustainability and digitalization have become prominent policy objectives over the last decade. Their parallel popularity is exemplified by the European Commission, describing them as '*twin transitions*' (European Commission, 2020) that ought to foster a '*green digital transformation*' (European Commission, 2021). This promissory discourse is echoed in academia, as evidenced by the numerous papers on the sustainability prospects of contemporary digitalization. Scholars have dubbed digitalization as the fifth long wave in economic development (Castellacci, 2006), a new techno-economic paradigm leading to a "*great surge of development*" (Perez, 2010, p. 199), a fourth industrial revolution fostering the "*regeneration and preservation of natural environments*" (Schwab, 2016, p. 2), and as an important step in achieving the sustainable development goals (SDGs) (Popkova et al., 2022) and a circular economy (Chauhan et al., 2022). In short, digitalization is forecasted as a major driver of social, environmental, and economic sustainability.

Underlying these bold optimistic expectations is an implicit understanding of digital technologies as a General Purpose Technology (GPT), a type of technology prone to systemic effects due to its pervasiveness, technological dynamism, and innovation spawning (Cantner & Vannuccini, 2012). We understand systemic effects here in a broad sense, as "(…) *those developments which either happen at large social scales or those that have large-scale effects that go beyond the initial locus of the interaction*" (Nathan et al., 2007, p. 2586). Given the wide diffusion of digital technologies over the past decades and the expected importance of digitalization for sustainability in the

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future, it is of particular interest to probe their systemic effects related to sustainability.

Here, we follow the general paradigm that sustainability comprises the resilience and functioning of complex, co-dependent systems, generally categorized in natural ecosystems, the anthropogenic socioeconomic system, and their relations in socio-ecological systems (Holling, 2001; Ostrom, 2009; Walker et al., 2004). While different concepts focus on different (sub)systems (e.g., sustainable development stimulating socioeconomic resilience) (Glavič & Lukman, 2007; Lee, 2000), we do not take an explicit position here on environmental versus socioeconomic needs since one of our interests is to capture how digitalization literature constructs sustainability. A key question holds how we can reconcile the many ICT-based innovations we have witnessed over the past decades with the rising sustainability concerns including the climate crisis and biodiversity loss (environmental), rising inequality and surveillance (social), and sluggish productivity growth and the rising power of monopolies (economic).

Existing reviews on the sustainability of digitalization are generally limited to single effect categories, disciplines, technologies, or theories (e.g. Beier et al., 2020; Bibri, 2019; Ejsmont et al., 2020; Grybauskas et al., 2022; Piscicelli, 2023; Upadhyay et al., 2021). To our knowledge, no study hitherto has reviewed literature on digitalization and sustainability explicitly focusing on the systemic effects of contemporary digitalization, while the uncertain, complex, and pervasive process of digitalization is best understood from a systemic perspective (Renn et al., 2021). We review 112 peer-reviewed contributions across disciplines, theories, and technologies, explicitly taking a theoretical perspective of General Purpose Technology. Our aim is to understand dominant topics and understandings in research relevant for the 'twin transitions', with a focus on systemic effects and how these have been studied. A scoping review is particularly suitable to review patterns in research on a specific phenomenon (Munn et al., 2018).

By critically appraising research designs in the selected literature, we aim to identify ways forward in our understanding and forecasting of systemic effects. We do so against the background of the paradoxical developments that digitalization has brought about in the recent decades, fostering little productivity growth (productivity paradox), social inequalities (internet paradox) and environmental rebound effects (Jevons paradox). Our critical appraisal of research on contemporary digitalization allows the formulation of a number of research directions for innovation studies and beyond, to stimulate future research on the systemic effects of digitalization. We regard such new directions as timely and pivotal in better understanding the opportunities that digital technologies afford as well as in being critical regarding the unfounded promises voiced by proponents of the 'twin transitions'.

The review is structured as follows. Chapter 2 motivates our theoretical perspective by conceptualizing digital technology as a General Purpose Technology (GPT), and the implications for the study of systemic effects. Chapter 3 discusses the methodology. Chapter 4 describes patterns and critically appraises the selected literature on systemic effects. Chapter 5 discusses research directions and Chapter 6 provides a reflective conclusion.

2. Systemic effects of digitalization

The understanding of digital technology as a systemic and pervasive innovation goes back to the 1980s, when the rise of 'Information Technology' was regarded as a new techno-economic paradigm (Freeman & Perez, 1988). A similar notion introduced later in the 1990s is that of Information Technology as a GPT, "*characterized by the potential for pervasive use in a wide range of sectors and by their technological dynamism*" (Bresnahan & Trajtenberg, 1995, p. 84), with again later some considering Information and Communication Technology (ICT) a 'mega GPT' (Cardona et al., 2013; Lehrer et al., 2016). Historical examples of GPTs include the steam engine and electricity. The semiconductor is regarded as the focal technology underpinning past and contemporary digitalization (Bresnahan & Trajtenberg, 1995). A review concluded that most empirical literature supports the GPT notion for ICT (Cardona et al., 2013). Notwithstanding existing discussions on the determinants and demarcation of a GPT, three aspects are generally regarded to embody a GPT (Cantner & Vannuccini, 2012).

First, a GPT is *pervasive* in the sense that its general applicability makes it widely used in scale and scope, meaning that it spreads fast in a given application domain (scale) while offering promising potential in a rich variety of applications (scope) (Bresnahan & Trajtenberg, 1995). Second, a GPT is characterized by *technological dynamism* as rapid improvement of the technology unfolds, and is required, across application domains after adoption (Bresnahan & Trajtenberg, 1995). Third, a symbiotic interdependency of *innovation complementarities* arises as adoption and advancement of a GPT by user industries improves their respective innovation processes, which incentivizes different sectors to further develop the GPT, creating a continuous feedback loop (Bresnahan & Trajtenberg, 1995).

Conceptualizing contemporary digital technologies as a GPT can help explain the paradoxical contrast between positive expectations and observed effects through a discussion of three exemplary paradoxes on the key infrastructure underlying current digitalization: the internet. The history of the personal computer and the internet, which embody the first wave of digitalization, exemplify the 'pervasiveness', 'complexity' and 'uncertainty' of GPTs: the *pervasive* use of personal computer and the internet creates *complex*, cross-sectoral feedback loops in their actual use, which in turn results in *uncertain* sustainability effects. It is along these three aspects of contemporary digitalization that we later code the articles and proceedings.

2.1. Pervasiveness: the internet paradox

The internet can be regarded as pervasive both in terms of scale and scope. Regarding scale, global internet adoption increased from 10 million users to 2.25 billion users between 1990 and 2011, while the number of websites grew from 1 million to 4 billion between 1990 and 2011 (Warf, 2013). Regarding scope, the internet is used for a variety of applications, including new business models (e.g. digital platforms, e-commerce), new communication channels (e.g. social media), and as a necessary medium for the digitalization of virtually all sectors.

This pervasiveness was generally expected to provide an abundance of societal benefits. For example, the internet was expected to "*solve the long-standing problems of education, make bureaucracies function better, create a global community through increased connectivity, empower the disenfranchised, and forever alter the roles of consumer and producer*" (Sturken et al., 2004, p. 1). While the internet did partially fulfil some of these expectations, such as improved access to educational content (Van Dijck et al., 2018), improved bureaucratic transparency (La Porte et al., 2002), and empowerment of the disenfranchised (Palfrey, 2010), research has also revealed unmet expectations and unintended effects, giving rise to the 'internet paradox' (Kraut et al., 1998, 2003).

For instance, the internet created a 'digital divide' between early adopters and later adopters from disadvantaged groups, as early adopters attracted more users to the internet from the same, advantaged groups (DiMaggio & Garip, 2011; DiMaggio & Hargittai, 2001). The digital divide is still prevalent today, as inequal access to online social networks, information and other resources is "*a product of social inequality as well as a mechanism for perpetuating it*" (Tewathia et al., 2020; Wang et al., 2022, p. 1; Wijers, 2010). Similarly, the 'global digital divide' represents the significant gap in the share of users from high-income countries versus the rest of the world, implying a disproportionate benefit from the internet for high-income countries (Guillén & Suárez, 2005). Furthermore, national restrictions to online access are common and keep intact certain geopolitical borders (Palfrey, 2010). More recent applications of the internet make this paradox even more topical. Digital platforms increasingly shape our communicational, informational, political, and vocational spheres with questionable, self-regulatory institutional capacities (Van Dijck et al., 2018).

2.2. *Complexity: the productivity paradox*

The introduction of the personal computer in office environments was expected to revolutionize work and production, and in particular improve productivity, which is often perceived as "*the fundamental economic measure of a technology's contribution*" (Brynjolfsson, 1993, p. 67). However, from the introduction of the personal computer in 1970 towards the end of the twentieth century, economists observed no positive correlation between productivity and computer diffusion (Dewan & Kraemer, 1998). The unfulfilled expectation of aggregated, positive, economic benefits gave rise to the 'productivity paradox' (e.g., Brynjolfsson, 1993; Brynjolfsson et al., 2019; Cardona et al., 2013; David, 1990; Dewan & Kraemer, 1998) or the 'Solow paradox' (Du & Lin, 2022; Jorgenson et al., 2008; Oliner & Sichel, 2000).

In line with historical examples such as electricity (David, 1990), scholars emphasized that "*a GPT does not deliver productivity gains immediately upon arrival*" (Jovanovic & Rousseau, 2005, p. 1). Similarly, productivity increases have been rather low in the era of digitalization, as the necessary co-evolution of business practices, regulations, and education had to unfold for the personal computer to develop further and become pervasive (David, 1990). A similar paradox has been observed in more recent years. Mature economies observe a decline in productivity growth from shortly after the turn of the millennium up to recent years, despite the ever-increasing adoption and diffusion of ICTs such as online platforms and artificial intelligence (AI). The necessary, dynamic co-evolution of processes and artifacts by users and associated actors (e.g., investors, researchers, policy-makers) is suggested as one requirement for the expected development and applications of AI to materialize (Brynjolfsson et al., 2019).

Large social scales, in which GPTs are uniquely embedded and where their systemic effects materialize, are thus inherently complex for several reasons. First, the high number of system components and their constellation makes it challenging to identify, let alone forecast, the effects of a GPT. Second, this pursuit is further challenged by the rich variety of components, including institutions, technologies, users, and industries. With a GPT representing only a fraction of larger systems, it may not come as a surprise that envisioned effects of digital technologies beyond direct consequences are often overrated or unexpected, and challenging to forecast (Levy et al., 2018).

2.3. *Uncertainty: Jevons paradox*

Many scholars expect a significant decrease in resource use due to ongoing digitalization; for example, digitalization could transform the workplace into a 'paperless office', end commuting traffic congestion due to teleworking, avoid flights via teleconferencing, and reduce consumption through shared use of assets. Empirical studies, however, pointed to the paradox between expected reductions in resource use through efficiency gains on the one hand, and an observed increase in resource consumption on the other hand, also known as the 'Jevons paradox' or rebound effect (Alcott, 2005; Polimeni & Polimeni, 2006; Sorrell, 2009; York, 2006). Efficiency improvements can 'backfire' (Sorrell, 2009) or dampen efficiency advantages because saved resources can be reallocated to other unsustainable production or consumption processes.

The persistent expectation that digital technologies would enable dematerialization has been increasingly scrutinized by observed rebound effects. The 'digital economy' was in its early days described as a 'weightless world' through the substitution of materials by information (Coyle, 1999; Kelly, 1997). The material effects of digitalization received attention only much later. Indeed, the direct material effects of digitalization (e.g., electricity consumption, mining of rare earth metals, electronic waste stream) and indirect material effects (e.g., related to its enabling of more globalized value chains, materialism and consumerism) portray a complex and uncertain picture (Berkhout & Hertin, 2004). Examples of this 'immaterial myth' (Cubitt, 2017) include the rise of paper consumption after the introduction of the personal computer and the internet as many more documents were circulated (Sellen & Harper, 2003), or additional travel activity if traffic is made more efficient through digital technologies (Hilty et al., 2006). A further unexpected trend is that the use of digital technologies itself will take up an ever-increasing share of total energy consumption (Jones, 2018). Summarizing, the immaterial imaginaries of contemporary digital technologies such as online platforms and AI cannot "*function without the minerals and resources that build computing's core components*" (Crawford, 2021, p. 30).

Given various rebound effects, forecasts on the sustainability effects of a GPT are inherently uncertain due to the pervasive and

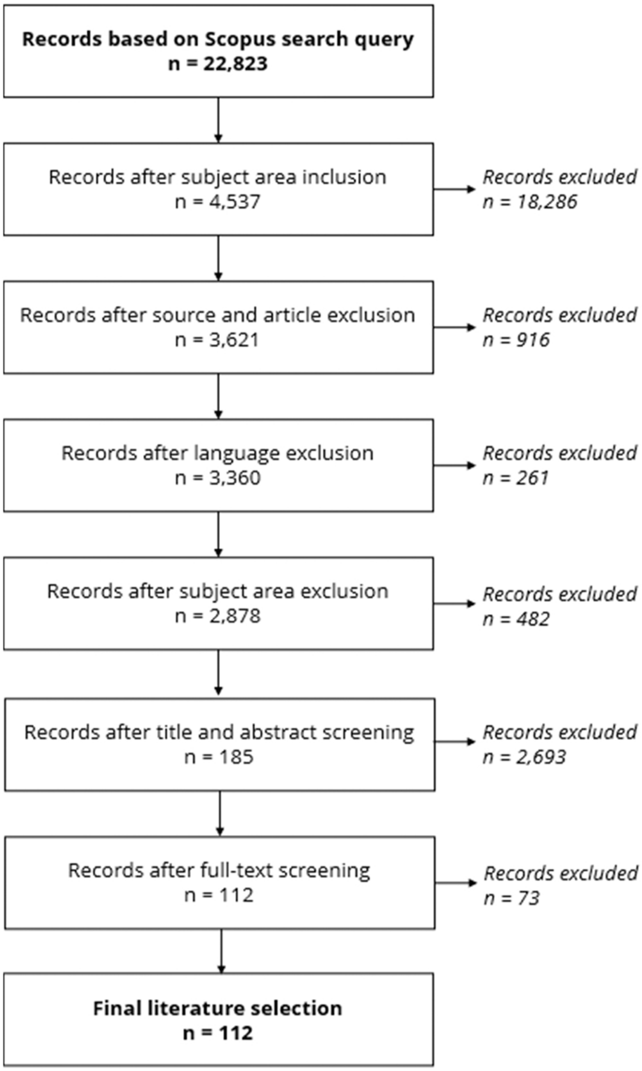


Fig. 1. Search flow.

complex adoption and diffusion patterns. A GPT will, by definition, likely affect most system components either directly or indirectly. However, the direction and the nature of the relationship (positive or negative) remains uncertain *ex-post*. Acknowledging that the promissory discourse of the 'twin transitions' is itself steering what is regarded as a 'desirable' future (Schiølin, 2020), it is all the more important to highlight the ambiguous socioenvironmental effects of digital technologies, rather than assuming that the two transitions go hand in hand. This more nuanced stance on innovation is indeed increasingly echoed in innovation studies to counterbalance the widespread 'pro-innovation bias' (Biggi & Giuliani, 2021; Godin & Vinck, 2017; Martin, 2016), for example, by discussing 'noxious effects' (Biggi & Giuliani, 2021) and the 'dark side of innovation' (Coad et al., 2021).

3. Methodology

Due to its descriptive and explorative character, a scoping review is suitable for reviewing a heterogeneous body of literature examining a central, novel phenomenon, such as contemporary digitalization (Tricco et al., 2018). A scoping review particularly allows the investigation of "(…) *the design and conduct of research on a particular topic"* (Munn et al., 2018, p. 3). Closely following the PRISMA-ScR checklist for the conduct of scoping reviews (Tricco et al., 2018), a flowchart for the literature selection is presented in Fig. 1.

3.1. Data collection

In line with the rationale of a scoping review, we sought to represent the breadth of literature on digitalization in our literature

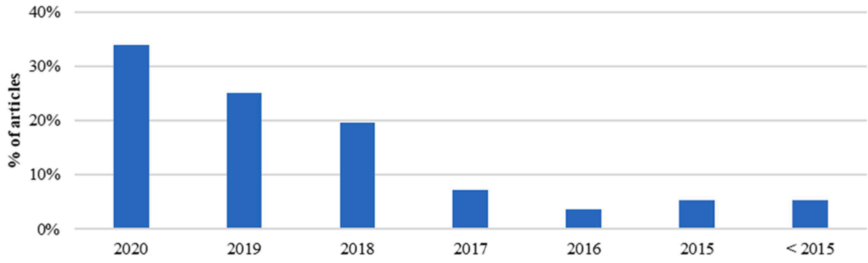


Fig. 2. Distribution of publication year of the literature selection.

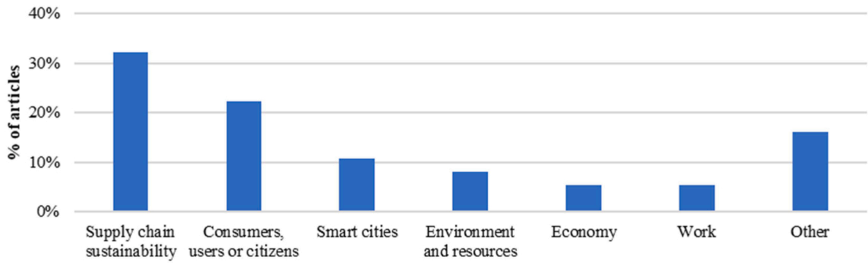


Fig. 3. Dominant application contexts in the literature selection.

selection. We chose keywords that collectively describe the nexus of contemporary digitalization, sustainability, and a systemic, large-scale perspective. The Appendix presents an overview of the keywords. While a systematic review would warrant established, field-specific keywords to distil the best available knowledge, in this scoping review, we aim to capture literature regardless of quality or discipline (Levy & Ellis, 2006). This goal motivated our search strategy to choose common, popular, and exemplary keywords (e.g., Industry 4.0) over established terminology that describes digitalization (e.g., automation, robotization), as this allowed for the collection of literature from a diversity of disciplines where such terms might be scarce or, conversely, implicit.

The keywords were established iteratively among authors and colleagues to refine and expand the search query. For example, in an earlier version of the query, we did not include rebound effects. However, throughout our explorative readings and discussions, the theme emerged as a relevant systemic effect of digital technologies and was therefore included in later versions of the search query. The search query consisted of nine keywords to describe emerging digital technologies or concepts, 39 keywords to describe common environmental, social, or economic effects, and 15 keywords were used to describe common large-scale levels of analysis at which systemic effects materialize, as highlighted by our definition of systemic effects. As the primary analysis took place throughout 2021, we only considered records from 2020 or earlier for this review.

After performing the query search, the first inclusion step was to only include records allocated to journals under the subject areas 'Social sciences', 'Business, management, and accounting', and 'Environmental sciences.' These broad subject areas were included to disregard hits that were solely concerned with the technicalities of ICTs. The second delineation step was to exclude document types other than peer-reviewed articles and conference proceedings, such as book chapters or reviews. By limiting the selection to peer-reviewed contributions we established a consistent quality baseline and manageable selection. Non-English contributions were also excluded.

The remaining literature still included subject areas unlikely to be valuable due to their disciplinary and technical nature. Therefore, as a third delineation step, 13 subject areas most remote from the research topic were excluded to reinforce the logic of the first delineation step. These were 'Earth and Planetary Sciences,' 'Mathematics,' 'Chemical Engineering,' 'Biochemistry, Genetics and Molecular Biology,' 'Physics and Astronomy,' 'Materials Science,' 'Chemistry,' 'Health Professions,' 'Dentistry,' 'Immunology and Microbiology,' 'Pharmacology, Toxicology and Pharmaceutics,' 'Nursing,' and 'Veterinary.' This led to the exclusion of 482 out of 3360 records.

Sequential title, abstract and full-text screening of the resulting 2878 records was performed. The guiding screening criterion was that the record had to study emerging digital technologies as the primary explanation for sustainability effects at a systems level. The final selection consisted of 112 peer-reviewed articles and proceedings, with a rather sudden increase in articles from 2018 onwards (see Fig. 2).

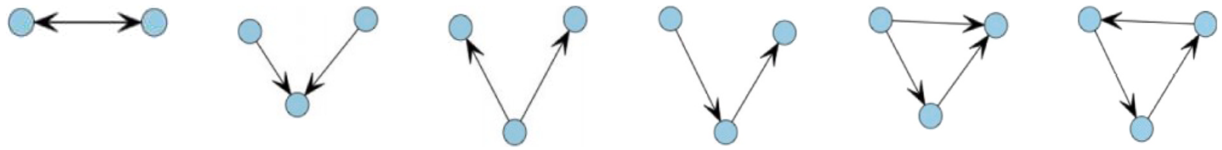
While the selected literature discusses the effects of digitalization in various application contexts, almost a third (32 %) focuses on

Table 1
Overview of the coding categories, concepts, and codes per research aim.

Research aim	Coding category	Concept	Coding
Review the study of systemic effects	Systemic effects	Pervasiveness	Environmental effects, Economic effects, Social effects, Mixed effects
		Complexity	Simple effects, Bidirectionality, Multiple causes, Multiple effects, Indirect effects, Moderated effects, Feedback loop, Other
		Uncertainty	Positive effects, Negative effects, Mixed effects
Critical appraisal	Research design	Research approach	Explorative, Confirmatory, Commentary
		Methodology	Forecasting, Reflexive, Commentary
		Theoretical approach	Economics and management, Environmental sciences, Social sciences, Interdisciplinary approaches, None, Other
		Subject area allocated to respective journal	Environmental sciences, Social sciences, Business, management and accounting, Other

Table 2
A typology of the considered complex effects.

Bidirectionality	Multiple causes	Multiple effects	Indirect effects	Moderated effects	Feedback loop



Source: Adapted from (Levy et al. (2018).

the effects on supply chain sustainability[5] (see Fig. 3). Other notable application contexts are consumers, users, or citizens[6] (22 %), and smart cities[7] (11 %). It is surprising to note that only a small portion of the literature deals with the effects on the environment and resources (8 %), although environmental considerations are often implicitly considered in other application contexts such as smart cities, (inter)national development, or supply chain sustainability.

3.2. Coding

We coded the 112 contributions along two categories inspired by the two research aims stated in the introduction (see Table 1). First, we coded the content using the three aspects of systemic effects described in Section 2. We only considered the primary sustainability effects discussed in a contribution, thereby excluding effects mentioned only exploratively (e.g., in the introduction or conclusion). Regarding the three aspects of systemic effects, the extent to which pervasiveness is acknowledged by existing research was coded by whether the contributions discussed effects in isolation (environmental, economic *or* social effects) or as an interdependent whole (mixed effects of two or all three dimensions).

To better understand how existing research acknowledges complexity, we coded whether contributions discussed effects that can be regarded as simple or complex. An effect was considered simple if the respective ICT (e.g., blockchain) or concept (e.g., Industry 4.0) was treated as the primary responsible for a given effect. An example of a simple effect is reduced resource use due to more efficient, automated machinery. An example of a complex effect is a rebound effect where reduced resource use allows a producer to allocate savings to new economic activities, thereby *increasing* resource use. In these more complex cases, the respective ICT or concept is not directly responsible for a given effect. Contributions were coded on the type of relationship described in the contribution, adopted from the typology by Levy et al. (2018). We coded complex relationships through an analysis of research questions, hypotheses, and frameworks (if provided), or by stipulating evident causal relationships considered in the overall research design. If no dominant relationship could be identified with certainty, we coded the respective record as 'Other.' See Table 2 for a visual overview of the complex relationships considered.

The extent to which records acknowledged the inherent uncertainty of systemic effects was captured by coding whether contributions focused on positive, negative, or mixed effects. As mentioned in the previous chapter, positive and negative (systemic) effects are ideally equally represented in the light of uncertainty and prevailing optimism. Coding was based on the normative stance of the respective record. For example, if a contribution discussed how digital technologies improve economic growth as a desirable effect, we coded it as a positive effect even if one could argue economic growth is not de facto positive. Records that discussed both positive and negative effects were coded as 'mixed effects'.

[5] Understood as environmental, social and/or economic supply chain sustainability.

[6] Understood as the aggregate effects of ICTs on consumers, users or citizens, such as security and privacy risks, human rights, public values and implications for law.

[7] Understood as the effects of ICTs in urban contexts.

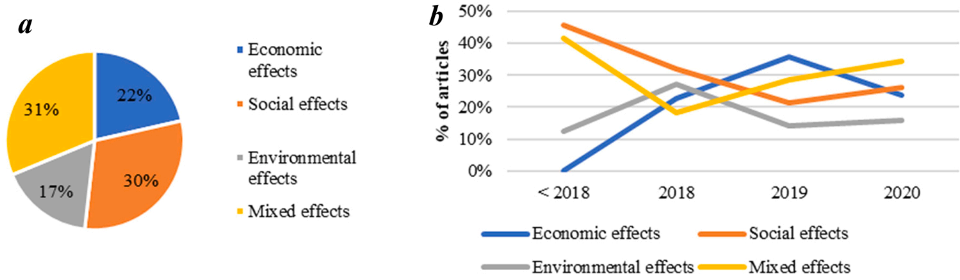


Fig. 4. a (left): Overall distribution of economic, social, environmental or mixed effects. b (right): Annual distribution of economic, social, environmental or mixed effects.

Second, we coded research design characteristics to better understand what differentiated records discussing systemic effects from those that did not. The coding of research designs was thus used as a sense-making tool. More specifically, we coded whether the research design was explorative (*ex-post* identification of effects), confirmatory (*ex-ante* demarcation of effects) or a commentary. Regarding the methodology, we coded whether contributions entailed forecasting (expected effects), a reflexive analysis (observed effects), or a commentary. If the contribution explicitly stated the theoretical approach, it was coded and subsequently grouped into six overarching categories (see Table 1). For each article, the subject area allocated by Scopus to the respective journal was coded. If multiple subject areas were allocated to a journal, or for conference proceedings, the one closest to the content of the contribution was chosen.

Finally, we conducted a critical appraisal of individual records that, to our understanding, best adhered to the aspects of systemic effects this review focusses on. Critical appraisal is common in systematic reviews but less so in scoping reviews, as the latter is "*generally conducted to provide an overview of the existing evidence regardless of methodological quality or risk of bias*" (Tricco et al., 2018, p. 480). The choice for a critical appraisal is motivated by the aim of this scoping review to not only describe if and how current research deals with systemic effects, but also to provide a research agenda to stimulate our knowledge on the subject. A critical appraisal can serve as valuable input to better understand what allows certain contributions to discuss systemic effects and others not.

4. Results

In the sections below, the results of our scoping review are presented based on the analytical dimensions of systemic effects (pervasiveness, complexity and uncertainty). For each dimension, we first describe identified patterns in the literature selection. This is followed by a critical appraisal of studies that (failed to) acknowledge the given analytical dimension.

4.1. Pervasiveness versus reductionism

We reviewed whether the selected literature acknowledges pervasiveness by coding if contributions discuss effects in isolation or, ideally, across multiple domains (economy, society, and the environment). As Fig. 4a shows, 31 % of the selected literature looks at mixed effects while 69 % discusses effects in isolation. Despite the apparent bias towards the study of isolated effects, Fig. 4b suggests that mixed effects are increasingly considered since 2018.

A potential explanatory factor for the strong tendency towards isolated effects could be the choice of theoretical approach. More than a third of the literature addresses digitalization through the lens of economic and managerial approaches. These non-systemic approaches are narrow in their unit of analysis (looking at a firm or its supply chain) and are primarily equipped to forecast and interpret effects within their primary domain leading to the observation of economic and managerial effects.

As a result, micro-level approaches that aim to capture a holistic picture can end up with an exogenous view of otherwise systemic factors. Institutional components are left out in particular from theoretical micro-level approaches. For example, Yadav et al. (2020) acknowledge institutional factors in their policy recommendations on the role of Industry 4.0 towards a circular economy, but treat these factors as exogenous. They posit that "*the government should develop policies favouring the adoption of industry 4.0 and circular economy*" (Yadav et al., 2020, p. 12) and "*sustainability awareness campaigns to educate the organisations as well as their customers*" (p. 12). While selected studies within social sciences emphasize institutional aspects like regulation, policy, and public values, these are rarely part of the research design in contributions from the subject areas of business, management and accounting or environmental sciences. The lack of institutional awareness is further emphasized by the observation that only two contributions explicitly use an institutional approach to capture the effects of digitalization (Giest, 2017; Kshetri, 2017).

Some contributions discuss mixed effects through a similar, narrow theoretical approach. For example, Bag et al. (2020) aim to understand the influence of big data analytics on sustainable supply chain performance from the theoretical viewpoint of supply chain management and dynamic capabilities. They posit that big data can enhance 'shared value,' i.e., simultaneously support economic and environmental performance. In this way, sustainability is regarded as a means for competitive advantage rather than a goal by and of itself. This 'shared value' approach is echoed by Yadav et al. (2020), who similarly draw on supply chain management to discuss the implications of Industry 4.0 for sustainability in supply chains.

Instead of discussing environmental effects from a non-environmental discipline, multidisciplinary approaches (e.g., with fields

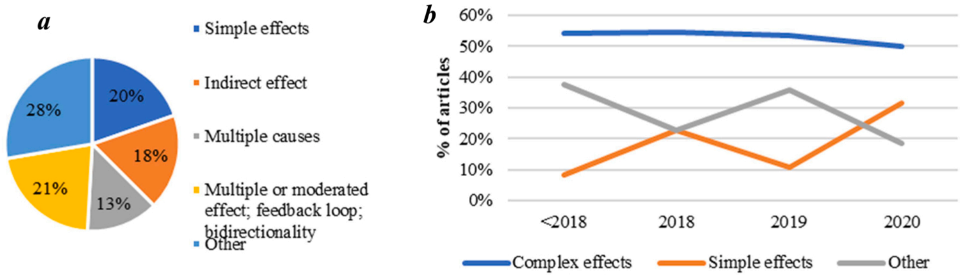


Fig. 5. a (left): Overall distribution of simple and complex effects. b (right): Annual distribution of simple and complex effects.

affiliated to environmental sciences) could provide more nuanced expectations. For example, the benefits that Bag et al. (2020) and Yadav et al. (2020) assume regarding 'green growth' contrast with a rich, critical body of literature from environmental sciences and multidisciplinary approaches. For instance, in the field of political economy, a recent review concluded that green growth lacks empirical support (Hickel & Kallis, 2020). From a socio-economic viewpoint, Bauwens (2021) argues that economic growth and the circular economy face limited compatibility. In addition, environmental scholars have long warned for rebound effects of ICTs (see e.g., Plepys, 2002).

Only 9 % of the literature applies a more multidisciplinary theoretical approach, which could aid a more nuanced identification of pervasive effects. For example, Dauvergne (2020) views AI from the viewpoint of political economy, an approach that considers multiple, competing economic traditions that have been inspired by other disciplines (Stilwell, 2006). This includes traditions that more explicitly acknowledge systemic effects, such as institutional and evolutionary economics (Stilwell, 2006). Similarly, Wiig (2016) uses policy studies, urban geography, and urban politics literature to conclude that the smart city rhetoric in Philadelphia ultimately represented a global economic paradigm rather than a solution for urban inequalities. Most of the literature from business, management, and accounting is based on more reductionist, traditional theoretical approaches, such as the resource-based view and supply chain management.

Two contributions in the selected literature address digitalization effects explicitly from a systemic approach. Kovacs (2018) draws partially on complexity theory to understand the 'dark corners' of Industry 4.0. The effects covered in his contribution are diverse, and the author discusses the implications for security, employment, psychological wellbeing, institutional changes, academic and business practices, and financial markets. Similarly, Ortega-Fernández et al. (2020) apply complexity theory in combination with dynamic capabilities to understand how AI can advance innovation in smart cities.

On a final note, it is rather surprising that we did not encounter contributions from the fields of innovation studies, science and technology studies, or transition studies, despite their interdisciplinarity, systems perspective, and a mutual interest in technology and sustainability. These findings might partially be attributed to techno-centric imaginaries that guide research funding towards natural sciences rather than social sciences, as Genus et al. (2021) find for funding on energy research.

4.2. *Complexity versus determinism*

The extent to which the selected literature considers complexity was coded as complex effects or simple effects, with a sub-typology of six specific complex effect patterns (see Table 2). As Fig. 5a shows, a small part of the sample studies solely 'simple' effects. The remainder, 52 %, considers more complex, non-linear effects. While this indicates that scholarship is aware of complex relationships, a more critical look at the distribution of non-linear effects shows that three complex relationships are strongly underrepresented. These are bidirectionality (2 %), feedback loops (4 %), and moderated effects (7 %). Surprisingly, Fig. 5b suggests that since 2019, simple effects are increasingly considered in contemporary digitalization research.

We turn again to the research designs to better understand why three out of six complex effects are underrepresented. Not including commentaries, around half of the selected literature attempts to forecast the effects of digitalization. Prospective designs are inherent to novel phenomena as limited empirical data is yet available. A Delphi approach is the most frequent forecasting method in the selected literature, used by 15 contributions. The consulted experts are generally a homogeneous group: they are practitioners in 13 out of 15 contributions, sometimes combined with scholars (Kim & Shin, 2019; Pham et al., 2019; Rajput & Singh, 2019) or users (Padyab & Ståhlbröst, 2018). Homogeneous groups create forecasts with low representative judgement (Yousuf, 2007). Furthermore, humans are cognitively limited to forecast complex dynamics (Levy et al., 2018; Stier et al., 2016).

As a result, Delphi studies are likely to leave the complex, non-linear effects unidentified. Additionally, Delphi studies are prone to optimism as humans tend to overestimate the probability of desirable futures compared to less-desired futures, partially enabled by the observation that Delphi experts "*commonly have some stake in the developments that they are to judge within the Delphi*" (Winkler & Moser, 2016, p. 67). This 'desirability bias' is echoed by Beier et al. (2020), who, in a literature review of the sustainability of Industry 4.0, conclude that "*(…) Industry 4.0 is associated with a number of desired outcomes, but hardly any of these mentioned positive sustainability aspects are a necessary result of digitalization*" (p. 11).

However, some contributions use forecasting methods that better acknowledge complexity. Scenario-based analyses can, for example, explicitly accept that the future is open-ended and can unfold in multiple ways. As Hoffmann and Dahlinger (2020) describe, scenario-based studies recognize that the future is characterized by "*volatility, uncertainty, complexity and ambiguity*" (p. 56). Whereas

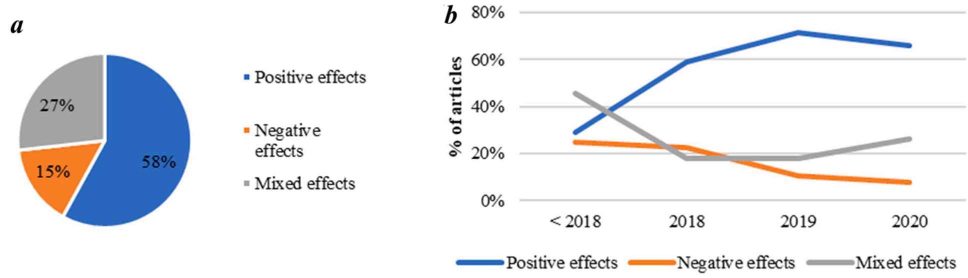


Fig. 6. a (left): Overall distribution of positive, negative and mixed effects. b (right): Annual distribution of positive, negative and mixed effects.

the implications of a Delphi approach are generally understood as "what will happen given our current knowledge", scenario-based analyses are generally more strategy-oriented and "*not meant to be tested against what actually will happen*" (Van der Heijden, 2005, p. 110), thereby explicitly acknowledging that the future is not forecastable with sufficient certainty.

This contrast can be seen in the literature selection when comparing concluding remarks. Rajput and Singh (2019) conclude from a Delphi study that "*It is determined that Artificial Intelligence (E1) and Circular economy (E4) are identified as the common driving enablers*" (p. 109) and that "(…) *sustainable supply chain contributes towards implementing the linkage between circular economy and Industry 4.0*" (p. 109). This factual writing style contrasts with the more nuanced, open-ended forecast of the scenario-based analysis by Hoffmann and Dahlinger (2020) who argue that "*recent advancements in autonomous AI systems, connectivity and decentralized networks, may become key enablers (…) and, therefore, it is important from a societal, political and economic viewpoint to understand, what their impact may be*" (p. 63).

4.3. Uncertainty versus optimism

We coded whether records acknowledged uncertainty by discussing both adverse effects and positive effects. As shown in Fig. 6a, the majority (58 %) of the selected literature focuses exclusively on positive effects. 27 % discusses both risks and benefits of emerging digital technologies, and only 15 % focuses on solely negative effects. As Fig. 6b emphasizes, the selected literature is increasingly leaning towards acknowledging both positive and negative effects (coded as 'mixed effects') since 2018, while a sole focus on negative effects has decreased since then. However, the observation that adverse effects are considered by 42 % of the total sample, while 85 % considers positive effects (of which the majority exclusively focusses on positive effects), signals an optimism bias.

When reviewing the literature, we observed that the study of positive effects was often embedded in a broader, topical narrative of technological optimism. For example, Hoosain et al. (2020) aim to understand the impact of Industry 4.0 and circular thinking on the advancement of sustainable development goals. They posit, in a factual manner, that "*Technologies used in solving real world problems are how we develop measures of success*" (Hoosain et al., 2020, p. 4), referring to Industry 4.0 as a "*ground-breaking strategy*" which "*(…) will increase productivity and growth*" (p. 3). The authors shortly acknowledge the risk of adverse effects but argue that benefits will outweigh these: "*On the one hand, there could be detrimental effects on sustainability, such as electronic waste production. On the other hand, ICT is surely an enabler for more productive use of energy, education, and business processes, which is vital in achieving the SDGs*" (Hoosain et al., 2020, p. 8). When later elaborated upon, Hoosain et al. (2020) forecast that increased electronic waste will be solved through future technological innovations. These expectations do not seem to be grounded in theory, empirics, or diverse expertise.

Another exemplar of this optimistic, technocratic narrative is the contribution by Bibri (2018) who discusses the role of big data and the internet of things in smart sustainable cities. Earlier contributions have already discussed the implicit optimism hidden in terminologies such as 'smart cities'. It provides a normative stance on what is 'smart', implying that a city not employing digital technologies is 'dumb' (Allam, 2018). Starting from an elaborate discussion of all the prospective application areas of digital technologies, Bibri (2018) discusses twelve barriers towards a smart sustainable city. In line with the technocratic narrative, these are called 'challenges', hurdles in the pursuit of a desirable goal. These challenges are "*mostly scientific, computational, and analytical in nature*" (Bibri, 2018, p. 247), and all relate to the design and capabilities of digital technologies. The closest non-technical barrier is privacy and security, which can be solved through technological improvements Bibri (2018) argues. The absence of non-technical barriers is striking given that the concept of smart cities relies on governance for reaping the benefits of "*colossal amounts of urban data*" (Bibri, 2018, p. 230), which in particular requires well-functioning social, political and institutional systems.

Other studies break with the prevailing exogenous view of technologies, and instead put digitalization in a more co-evolutionary perspective. For example, in the context of smart cities, Wiig (2016) discusses Philadelphia's smart city project. Drawing on insights from urban geography, the author puts the socio-political aspect at the forefront and defines smart cities as a governance device that "*encompasses the integration of buildings, neighbourhoods, digital–urban infrastructures, city government, and citizen activities with data analysis to 'solve' a wide variety of urban issue*" (Wiig, 2016, p. 537). Interestingly, the core problems that led to the demise of Philadelphia's smart city project were non-technical forces (Wiig, 2016), absent in many other studies. Giest (2017) similarly acknowledges sociotechnical dynamism by embedding his research on smart cities in institutional complexity theory, which allows him to identify non-technical barriers and limitations, such as that "*policy-makers may not have the 'policy analytical capacity' to analyse and understand*" (Giest, 2017, p. 944) the collected urban data.

Kovacs (2018) echoes a similar observation regarding technological optimism around Industry 4.0 and concludes that "*(…) Industry 4.0 and the Digital Economy evolve in an open, adaptive, complex socio-economic innovation ecosystem characterised by non-linear feedbacks.*

It is therefore rather strange that available studies are merely focusing on the positive effects of Industry 4.0 (…)" (Kovacs, 2018, p. 141). This positivism is particularly related to economic and environmental effects, while social effects are often studied more critically, in line with the review by Grybauskas et al. (2022) on the social implications of Industry 4.0. Dauvergne (2020) emphasizes that "*technology is an instrument of power*" (p. 4). This contribution is the only one in the literature selection that acknowledges (and warns for) rebound effects. Other contributions in the literature selection that break with technological optimism apply a similar constructivist perspective, such as Cheng and Foley (2018) and Van der Zeeuw et al. (2019).

When reviewing the more critical contributions, a recurring theme is the emphasis on historical patterns in technological innovation to put contemporary digitalization in perspective. For example, Kadir and Broberg (2020, p. 2) emphasize that "*how humans use and react to new technologies is not a notion unique to Industry 4.0"*. Dauvergne (2020) draws on past developments in efficiency savings, technological innovation, and resource extraction, allowing the author to place AI in a more nuanced context. He conceptualizes AI as a technological innovation that, similar to previous innovations, induces rebound effects and does not decouple economic growth from resource extraction. The power of historical analogies resonates with historical studies in innovation studies highlighting that past GPTs may differ in their specific effects, but share a contingent nature of development with long-run and large-scale systemic effects.

5. Research directions

Based on our review, we propose three pursuits for future research to stimulate knowledge accumulation on systemic effects. We do so along the three characteristics of GPTs: pervasiveness, complexity and uncertainty.

5.1. Understanding pervasiveness: science and technology studies and transition studies

An important finding of this scoping review is that current studies often lack a systemic theoretical approach. In particular, science and technology studies and transitions studies are largely absent from the selected literature despite their theoretical contributions to a systemic understanding of technology. As Stock and Burton (2011, p. 1091) posit, the *"increasing understanding of system complexity leave traditional scientific disciplines often struggling*" to understand 'wicked' sustainability problems and pervasive phenomena. This is echoed in a review on Industry 4.0 by Beier et al. (2020). Science and technology studies have long emphasized the weaknesses in some of the primary themes that emerged in the findings. For example, they withhold from deterministic technological accounts by carefully balancing the materiality and agency of technologies on the one hand, and the uncertainty, complexity and agency of the social environment in which technologies are embedded, on the other hand (Bijker et al., 1989).

Similarly, the interdisciplinary field of (sustainability) transition studies acknowledges that "*complicated processes (…) cannot be comprehensively addressed by single theories or disciplines*" (Köhler et al., 2019, p. 2). Indeed, sustainability transition scholars listed digitalization as a relevant avenue in a recent research agenda, in particular the opportunities it poses for users and consumers, the power of corporate actors in the digital world, and the increasing permeation of digital technologies in socio-technical systems that are particularly relevant for sustainability, such as energy and transport (Köhler et al., 2019). This is echoed by a recent agenda that outlined more specific digitalization topics (Andersen et al., 2021).

5.2. Understanding complexity: exploratory designs and methodological development

Future research could benefit from two directions to better capture complexity, particularly those patterns of causality that were little acknowledged in the selected literature. First, a significant share of the literature selection utilizes confirmatory research designs, such as Delphi studies. This limits the attempts to identify unintended and unexpected effects as these are, combined with the observed optimism, often not the primary interest (for unintended effects) or that cannot be identified a priori (for unexpected effects). We suggest a shift towards more explorative research designs to address these systemic aspects better. A shift from confirmatory to explorative research designs will require methodological development and novelty, particularly in forecasting studies.

A second route is to get away from forecasting as 'point prediction', knowing that future development will be highly non-linear and unpredictable due to the very systemic nature of digital technologies. Instead, consistent with aiming for sustainability effects of new technologies, one can engage in 'Techniques of Futuring' (Hajer & Pelzer, 2018; Hajer & Versteeg, 2019; Oomen et al., 2021), which focuses on the social construction of imagined futures, thus explicitly moving away from technological determinism. Futuring is particularly suitable for explaining why particular imaginaries of the future tend to dominate and identify novel, alternative futures. These techniques encompass new combinations of forecasting tools such as scenario-based analyses, backcasting, and stakeholder consultation, with the overarching goal to "*bring together a broader set of agents of change*" (Hajer & Pelzer, 2018, p. 225). Similarly, innovations in scenario-based analyses have potential for the forecasting of systemic effects of technologies (Nathan et al., 2007). By engaging in multi-stakeholder processes, alternative imagined futures can emerge, which themselves can have a performative effect on the actions of firms, governments, and cities, thereby affecting the course of technological development pro-actively.

5.3. Understanding uncertainty: past lessons and definitions

To better acknowledge the inherent uncertainty of GPTs and their effects, especially when it concerns forecasts, we propose two avenues. First, greater engagement with the history of technology, including the more recent history of ICTs over the past four decades as we have done, lets one be aware of promissory expectations and pitfalls that befell previous innovations and technological revolutions. As such, a historical context can provide a more nuanced perspective on a phenomenon otherwise clouded by topical, inflated expectations. Historical studies of innovations and technological revolutions have emphasized the consistently complex and uncertain patterns of technological and societal development (see e.g., Geels, 2002; Hughes, 1987; Klein & Kleinman, 2002; Perez, 2004). When acknowledging this, a critical justification is required if one would argue that "this time, it's different".

Second, we argue that a technology-push perspective provides an overly simplistic view on the effects of digitalization, as technologies, user practices, and societal institutions are known to co-evolve (Bijker et al., 1989; Köhler et al., 2019). A definition closer to sociotechnical dynamism emphasizes that technologies are subjects of power and politics, thereby better acknowledging the complex and unintended effects that seemingly impartial technologies can have. For example, Schiølin (2020) traces back how Industry 4.0 was employed by the World Economic Forum as a narrative that convincingly implied Industry 4.0 is an inescapable future to which we can only adapt. Schiølin (2020) describes this as 'future essentialism', where a future socio-technical imaginary dangerously promotes the idea that no other futures exist or can be created. Other popular socio-technical imaginaries such as smart cities, predominantly pushed by corporate narratives, have been criticized as an "*empty rhetorical device*" (Wiig, 2015, p. 271) that promotes reductionistic 'technological salvation' for complex urban challenges (Sadowski & Bendor, 2019; Söderström et al., 2014). The controversial values that these concepts embody arguably contribute to their definitional ambiguity and contestation (Beier et al., 2020). The sociotechnical dynamism and constructivism of digital technologies and technocratic futures could instead be better acknowledged by building on the growing body of literature studying the governance of expectations (Beumer & Edelenbosch, 2019; Konrad & Palavicino, 2017), and the performativity of socio-technical imaginaries (Hajer & Pelzer, 2018).

Systemic effects have the potential to profoundly alter the expected benefits of the digital transition, as these effects help explain why technological hypes during the first digitalization 'wave' have often been followed by disillusionment. This scoping review suggests that systemic effects of contemporary digitalization are poorly understood due to patterns of reductionism, determinism and optimism. This indicates that more research on the topic is needed to avoid the pursuit of an ill-understood transition. Promising deviations in the selected literature provide examples and inspiration for a more nuanced, critical, and, more importantly, systemic perspective on contemporary digitalization. By incorporating an interdisciplinary approach, studying digitalization through exploratory research, applying a constructivist perspective, and avoiding adherence to promising but often empty discourses, we can improve our understanding of the large-scale sustainability effects of digitalization. As the 'digital green transformation' and 'twin transitions' are increasingly prominent in policy discourses, the study of systemic sustainability effects is of significant relevance to better inform us whether this designated future is a probable, feasible, and desirable one.

6. Discussion and conclusion

What unites most research on digitalization and sustainability is the traditional perspective taken on digital technologies as a set of artifacts, while largely ignoring the social and institutional embedding of such artifacts. What thus becomes apparent is that the very conceptualization of digitalization as technology rather than a socio-technical process can negate a systemic perspective. For example, Tokareva et al. (2018) describe the internet of things simultaneously as a "*business and technology area*" (p. 63), a single "*technology*" (p. 64), a collection of "*technologies*" (p. 64) and a "*concept*" (p. 72). Similarly, others (Jeble et al., 2020; Miller & Tolle, 2016; Nuccio & Guerzoni, 2018) define big data differently with varying levels of abstraction. Even more pressing is the ambiguity around broader digital concepts. The obscurity of Industry 4.0 causes Fatimah et al. (2020, p. 3) to describe it as "*digitalization, environmentally conscious, socially aware*", while Kovacs (2018) regards Industry 4.0 more narrowly as a manufacturing philosophy. Bashtannyk et al. (2020) regard Industry 4.0 as a long-standing development, analysing its influence between 2009 and 2019; Cezarino et al. (2019) see Industry 4.0 as an ongoing, emergent development; whereas Grenčíková et al. (2020) conceptualize Industry 4.0 as a future phenomenon that has yet to unfold.

Ambiguity also permeates concepts on the nexus of sustainability and digitalization. Regarding smart cities, Grimaldi and Fernandez (2019, p. 28) describe them as "*cities that use the technology to improve the quality of life for their citizens*". This definition leaves room for normative considerations to what 'quality of life' entails, and most cities already employ (digital) technologies that foster the quality of life (e.g., security cameras, traffic lights, electric charging stations). Bibri (2018) uses the term 'smart sustainable city' to denote a city seemingly similar to the 'smart city' label, that is, a city "*supported by the pervasive presence and massive use of advanced ICT, which (…) enables the city to control available resources safely, sustainably, and efficiently to improve economic and societal outcomes*" (Bibri, 2018, p. 233). These definitional differences challenge efforts to take stock of and build upon research. This ambiguity signals ongoing, collective sense-making of emerging technologies and is inherent to novel research topics (Wang, 2019). To add to this confusion, some contributions in the smart city literature define such cities without any explicit reference to ICT or digital technology more generally (Kusumastuti, Nurmala, Rouli, & Herdiansyah, 2022; Giffinger, Kramar, Fertner, & Meijers, 2007). Efforts to clarify this ambiguity have been pursued in past contributions, but without leading scholars to converge. Definitional ambiguity can cause novel concepts to lose their meaning and credibility (Gonella, 2019; Wiig, 2015), to obstruct forecasts of what technologies will do and ought to do (Bhatnagar et al., 2018), and allow for misguidance and misunderstanding in research and debates (Wang, 2019).

Optimistic, technocratic imaginaries, enabled by the freedom this conceptual ambiguity provides, are common in the broader stock of research on digitalization. The optimism is particularly apparent in the selected management literature, which represents roughly a third of the sample. It often mirrors the aforementioned concept of 'shared value' (Porter & Kramer, 2011). This concept posits that companies can achieve economic success and regain legitimacy by creating "(…) *value for society by addressing its needs and challenges*" (Porter & Kramer, 2011, p. 4). Shared value propagates win-win scenarios across economic, social and/or environmental spheres for organizations. The academic management community eagerly took up the concept, with Crane et al. (2014, p. 133) describing the foundational article as "*a quite dramatic outlier in terms of the rapid scholarly attention*". 'Shared value' is one of many proposals that have suggested that environmental and social issues would be solved through strategic management because sustainability improvements

Table A1
Keywords used in search query.

Category	Keyword
Digitalization	Artificial intelligence; Blockchain; Big data; Cloud computing; Cyber-physical system; Digital platform; Digitalization; Industry 4.0; Internet of Things
Environmental sustainability	Biodiversity; Climate; Circular; CO2; Emission; Energy; Environment; GHG; Hazard; Material; Metal; Mineral; Rebound; Resource; Sustainable; Warming; Waste
Social sustainability	Autonomy; Compliance; Dignity; Discrimination; Equality; Equitable; Inclusive; Justice; Power; Privacy; Regulation; Safety; Security; Skills; Social; Values; Work
Economic sustainability	Economy; Employment; Performance; Productivity; Efficiency
Systems level	Nation; System; Chain; City; Cluster; Complementarity; Country; Field; Industry; Inter; Market; Network; Region; Sector; Socio-technical

are in a company's best interest in the long term (King & Pucker, 2021).

However, history has shown that major sustainability improvements are not easily attained through win-win strategies. The idea lacks empirical grounding (Dembek et al., 2016) and has so far failed to deliver (King & Pucker, 2021). Thus, management research would benefit from a more critical perspective observing systemic effects beyond the level of single organizations. Rebound effects are an exemplary case of this, despite that only one article in the selected literature discussed this (Dauvergne, 2020). This also implies a broader call for empirical research on the 'twin transitions' to contemplate the prevalent narratives of green growth in general and the symbiotic advancement of the three pillars of sustainable development through digitalization in particular (Renn et al., 2021). A recent example of this 'green growth' narrative can be found in a contribution of Wang & Zhou (2022, p. 2), who posit in their study of smart cities that "*the environment needs to be protected while pursuing economic growth and high quality of life*".

These promising macro-discourses are commonplace in much contemporary research, policy, and public debate, and not limited to digitalization. Other popular win-win concepts include servitization, where businesses provide product-service systems rather than only physical products to improve the value and lifetime of products, or reshoring as a strategy to better control supply chain risk and sustainability (Ashby, 2016; Baines et al., 2007; Christopher et al., 2011; Reim et al., 2015). The interdisciplinarity and systems perspective in aforementioned literature fields (e.g., transition studies) can potentially enrich and nuance these expectations. In this regard, Vähäkari et al. (2020) outlined the potential synergies between futures studies and transition studies. Particularly, they argue that transition frameworks can contribute to futures studies through reflexivity to historical developments and dynamics, identification of multiple development paths towards sustainability, and methodological awareness of multi-level thinking between (sub) systems.

We advocate a theoretical turn in all disciplines away from the technology-push perspective. Instead, the co-evolution of technologies, user practices, and societal institutions should be taken as a starting point (Freeman & Perez, 1988; Winner, 1980). Defining emerging digital technologies as an element that both shapes and is shaped by the social and natural environment promotes a systemic perspective with more emphasis on the role institutions and the material nature and impacts of digital technologies have. A definition closer to sociotechnical dynamism is also congruent with the received notion that technologies exert power, thereby better acknowledging the complex and unintended macro-effects that seemingly impartial technologies can have (Winner, 1980).

Systemic effects can profoundly alter the expected benefits of the digital transition for sustainability, as these effects help explain why technological hypes during the first digitalization 'wave' have often been followed by disillusionment. Based on this scoping review, we suggest that systemic effects of contemporary digitalization are poorly understood due to patterns of reductionism, determinism, and optimism. This indicates that more research on the topic is needed to avoid the pursuit of an ill-understood transition. Promising deviations in the selected literature provide examples and inspiration for a more nuanced, critical, and, more importantly, systemic perspective on contemporary digitalization. By incorporating an interdisciplinary approach, studying digitalization through exploratory research, and avoiding adherence to promising but often empty discourses and definitions, we can improve our understanding of systemic sustainability effects of digitalization. As the 'twin transitions' are increasingly prominent in policy discourses, the study of systemic sustainability effects is crucial to better inform us whether this designated future is a probable, feasible, and desirable one.

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The authors report there are no competing interests to declare.

Data availability

Data will be made available on request.

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Appendix A. : Query keywords and search string

See Table A1.

The final search string as shown below incorporated Boolean operators to allow for keyword variations and similarities:

TITLE (("artificial intelligence" OR "big data" OR blockchain OR "cloud computing" OR "cyber-physical system" OR "digital platform" OR digital* OR "industry 4.0" OR "internet of things") AND (biodivers* OR climate OR circular* OR co2 OR emission* OR energ* OR environment* OR ghg OR hazard* OR material OR metal OR mineral OR rebound OR resource* OR sustainab* OR warming OR waste OR autonom* OR compliance OR dignity OR discriminat* OR *equal* OR equit* OR inclusiv* OR justice OR power OR privacy OR regulat* OR safety OR secur* OR skill* OR social OR value* OR work OR econom* OR employ* OR performance OR productiv* OR efficien*) AND (*nation* OR *system* OR chain OR cit* OR cluster OR complementarit* OR countr* OR field OR industr* OR inter* OR market OR network OR region* OR sector* OR socio-technical)).

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