A systematic review of empirical studies on green manufacturing: eight propositions and a research framework for digitalized sustainable manufacturing

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ABSTRACT

Manufacturers are facing increasing pressures to adapt their operations to meet sustainability goals. Research and developments on industrial digitalization (aka Industry 4.0) present new opportunities to create and capture value in ever-more complex and connected industrial systems. However, digitalization does not always align with sustainability, and case studies combining these two topics are still scarce. To address these gaps, we adopted a bottom-up approach to (1) identify existing environmental solutions and their implement challenges by reviewing 208 empirical studies, and (2) formulate eight propositions to guide further work so that digitalization supports environmental improvements more systematically. Finally, a framework for Digitalized Sustainable Manufacturing consisting of four research themes is proposed, pointing to future research needed to align industrial development with sustainable development goals. The propositions and framework aim to structure and focus future research by targeting specifically the challenges encountered when implementing environmental solutions in manufacturing.

1. Introduction

With the recognition of the environmental imperative, many manufacturers are adapting their operations to meet sustainability goals (Kiel et al., 2017; Lubin & Esty, 2010; Sarkis & Rasheed, 1995). This is evident with the uptake of the UN Sustainable Development Goals (United Nations 2015) in many companies’ strategies and annual reporting. Despite the growing body of scientific knowledge, there is an enduring consensus that the manufacturing industry is still operating in a largely linear and unsustainable manner (Frosch & Gallopoulos, 1989; Kazancoglu et al., 2021; Stahel, 2013; Verma et al., 2022). External incentives are still required to drive environmental actions in industry. For example, the Paris Agreement (UNFCCC – United Nations Framework Convention on
Climate Change, 2015) and the European Green Deal (European Commission, 2019) stimulated national and international programmes, providing ambitious targets and action plans to transition towards a clean, carbon-neutral and circular economy. The European Climate Law sets the binding target of 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels (European Commission, 2021). Other initiatives include the Factories of the Future Roadmap at a European level (EFFRA – European Factories of the Future Research Association, 2013), the Foresight report about the future of manufacturing in the UK (Foresight, 2013), and the Smart industry strategy in Sweden (Ministry of Enterprise and Innovation, 2016).

Accordingly, a broad range of solutions were developed, from new design tools and innovative business models, to cleaner technologies and sustainability assessment methods. Comprehensive review studies have mapped current research efforts (Esmaeilian et al., 2016; Haapala et al., 2013) as well as developed classifications, taxonomies and terminologies (Glavić & Lukman, 2007; Moldavska & Welo, 2017) to establish the theoretical foundations for sustainable manufacturing. At a meso and micro level, numerous approaches can support manufacturers in shifting to more ethical and responsible practices (Baumann & Cowell, 1999; Bhatt et al., 2020; Finnveden & Moberg, 2005; Kristensen & Mosgaard, 2020). On the one hand, digital technologies create new opportunities for companies to capture value in ever-more complex and connected systems (Lee, Bagheri & Kao, 2015; Monostori et al., 2016) and sustainable manufacturing increasingly relies on these technological advances (Ren et al., 2019; Stock et al., 2018). On the other hand, researchers have recognised that digitalization does not always align with sustainability (Machado et al., 2020; Verma et al., 2022).

This study aims to identify how digitalization can support green manufacturing systematically. However, there are too few empirical studies demonstrating how digitalization can be used to enhance the environmental performance of manufacturing systems. Since such direct evidence is missing, the work was carried out in two steps:

1. Examining empirical studies through a systematic literature review to identify implementation challenges for practices, measures, tools and methods – thereafter called ‘environmental solutions’ – to assess, manage and improve environmental performance in manufacturing;

2. Adopt a bottom-up approach to describe ways in which digitalization can help overcome the challenges identified and support the implementation of environmental solutions in manufacturing (propositions and research framework).

Accordingly, the research questions (RQ) are:

RQ1. What are the implementation challenges encountered when implementing environmental solutions in manufacturing?

RQ2. How can digitalization help overcome these challenges to support the systematic implementation of environmental solutions?

This section introduces the background and study aim. Section 2 details the research methods employed to collect, analyse, and synthesise the empirical studies on
environmentally sustainable manufacturing. Section 3 presents the results from the systematic literature review to address RQ1 and synthesises the findings with eight propositions to tackle RQ2. Section 4 discusses the findings in the context of ongoing research and proposes a research framework for Digitalized Sustainable Manufacturing. Finally, Section 5 summarises the study and its key messages.

2. Methods

This section details the methods employed to collect and analyse published empirical studies demonstrating environmental solutions applied in manufacturing companies. The systematic literature review (Baumeister & Leary, 1997; Davis et al., 2014; Snyder, 2019) and framework development followed the steps shown in Figure 1.

2.1. Literature search

This systematic review focused on empirical studies presenting environmental solutions applied to manufacturing. Therefore, conceptual or theoretical papers – albeit highly interesting – were not targeted. The search terms were selected by testing various synonyms and combinations to minimise irrelevant results, searching title, abstract and keywords using Scopus.

Since this study aimed to understand how digitalization can support sustainable manufacturing in practice, a test search was performed with an additional set of keywords (digital* OR smart OR ‘industr* 4.0’ OR ‘cyber physical’ OR 'big data'). This search yielded few results showing that empirical studies at the intersection of sustainability and digitalization are still scarce. The final keywords and search query are shown in Table 1.

The irrelevant subject areas were excluded, such as medicine, biochemistry and psychology. Only articles, conference papers, reviews and book chapters in English were retained. The initial sample contained 656 publications as described in section 3.1.

2.2. Screening and detailed analysis

The initial sample was screened independently by two researchers using a web application for systematic reviews (Ouzzani et al., 2016) to filter relevant articles based on the title,
abstract and keywords. The screening also supported the development of the categories and labels (Table 2) to be used for the subsequent detailed analysis. Documents were excluded if they did not explicitly contain case studies or environmental solutions applied to manufacturing, thus not relevant to address RQ1. Complementary search and screening were performed to capture articles recently added in the Scopus database as of July 2022. The post-screening sample contained 420 articles as described in section 3.1.

The final labels were applied based on detailed analysis of the full paper to characterise the type of environmental solutions presented in each paper. Documents were excluded when insufficient information was found to apply to the labels with good confidence. The analysis prioritised highly cited articles (considered as influential), articles in reputable journals (considered as high-quality and containing more information than short

| Category and questions | Labels and their description |
|------------------------|-----------------------------|
| 1. Type of study       | CS: case study, single or multiple in-depth case studies |
| What type of study design was used by the authors? | CC: cross-case analysis or meta-analysis |
| 2. Research area       | TD: tool or method development |
| What is the authors’ field of research? What field of research do they contribute to? | LC: life cycle studies |
| 3. Type of method      | RE: resource efficiency, eco-efficiency |
| What type of assessment or improvement methods were used? How was the environmental impact/sustainability performance managed? | CSR: corporate social responsibility |
| 4. Type of measure     | LEAN*: lean (repeated in cat. 3) |
| What type of measures, practices or improvements are proposed and implemented in manufacturing? | SCM: supply chain management |
| 5. Unit of analysis    | DES*: design (repeated in cat. 4) |
| What is the focus of the assessment? What is the ‘system’ being assessed? | SERV: servitization |
| 6. Scope               | CE: circular economy |
| What is the scope of the assessment? | DIG: digitalization |
| 7. Sustainability dimensions | IND: indicators and indexes related to environmental performance |
| Which dimensions of sustainability are directly impacted by the solution(s)? | LCCX: life cycle methods, e.g. life cycle assessment, life cycle inventory, life cycle costing, sustainability life cycle assessment, etc. |
|                        | M&S: modelling and simulation |
|                        | MCDA: multi-criteria methods, e.g. multi-criteria decision analysis, analytic hierarchy process, fuzzy logic, etc. |
|                        | LEAN: lean and Six Sigma tools (linked to cat. 2); e.g. value stream mapping, just-in-time, 5S, total productive maintenance, Six Sigma, etc. |
|                        | TEC: engineering, operational or technical measures |
|                        | BUS: business, strategic or managerial measures |
|                        | DES: sustainable design (linked to cat. 2); e.g. eco-design, DE, DFX, etc. |
|                        | INST: institutional measures and policy instruments, e.g. governance, regulations, standards, etc. |
|                        | PROD: product or service |
|                        | PROC: process or manufacturing technology |
|                        | MAT: material, energy, water, waste |
|                        | SC: supply chains |
|                        | CORP: company |
|                        | C2Gv: cradle-to-grave |
|                        | C2Gt: cradle-to-gate |
|                        | G2G: gate-to-gate |
|                        | ENV: environmental |
|                        | ECO: economic |
|                        | SOC: social |
2.3. Framework development

Based on the findings and eight propositions, practical implications are discussed in section 4.1 and a research framework for Digitalized Sustainable Manufacturing is presented in section 4.2 to align sustainability and digitalization more systematically. The framework was developed using a bottom-up approach to provide recommendations for further research around four themes and address the practical challenges identified in the systematic review.

2.4. Limitations and research quality

The literature on sustainable manufacturing is expansive and still growing. Thus, this study employed a search strategy designed to deliver a high ratio of relevant and high-quality articles in line with the specific purpose of the present study. To ensure broad coverage of environmental solutions captured in the post-screening sample, articles were selected to cover all labels applied during the screening, prioritising the analysis according to the criteria described in section 2.2.

Researcher bias in qualitative analysis, such as the one presented in this paper, is unavoidable. However, the methods employed for the literature search, screening and detailed analysis were designed to minimise their impact and increase objectivity using the labels described in Table 2 as a data-extraction tool (Tranfield et al., 2003). Since researcher bias cannot be eliminated completely, the researchers’ prior knowledge was used as a positive driver to increase the quality of the analysis by extracting value from the articles closest to their area of expertise. The detailed analysis was coordinated to minimise repeated work while ensuring an overlap of at least two articles between researchers to validate internally the analysis process and consolidate the labels.

In some instances, the labels proved challenging to apply confidently as there could be a degree of uncertainty: the interpretation of the case studies relied purely on the information documented in the papers. For example, if the authors claimed that their proposed environmental solution had economic benefits but reported no supporting evidence in the article, the label ECO (economic dimension) was not applied. Similarly, the label CE (Circular Economy) was only applied if the case study demonstrated explicitly how the proposed solution supported closed-loop material flows (as opposed to ‘potential’ for more circular flows but was not implemented in the case study). The labels for the ‘research area’ and ‘scope’ were the most difficult to ascertain, thus considered less reliable than the other sets of labels to draw conclusions. However, all labels were still useful to analyse the literature collected. For good transparency, all labels applied to the 208 papers included in the detailed analysis are provided in Appendix.
3. Results

This section presents the findings from the systematic literature review. Section 3.1 presents the initial and final samples through descriptive bibliometric information. Section 3.2 further details the final sample composition and categorisation of empirical studies. Section 3.3 reports on the challenges and opportunities identified with eight propositions to form the foundations for the framework development presented in section 4 (Discussion).

3.1. Bibliometric information of literature collected and reviewed

The initial sample contained 656 articles and the final sample reviewed 208 articles. The number of publications per year is shown in Figure 2. Ten articles in the initial sample were published before 1997 but omitted from Figure 2 to increase readability. Most of the papers reviewed were recent: over 80% were published in the last ten years and over 50% in the last five years (since 2018).

Figure 3 shows the geographical distribution of the authors’ affiliations by continent. The United States was the most represented country in the initial sample, with 148 publications, of which 53 were reviewed. The next most represented countries were China, the United Kingdom, India and Italy, with 71, 69, 60 and 56 publications in the initial sample, of which 20, 18, 20 and 19 were reviewed, respectively.

Given the interdisciplinary nature of the topic, the articles collected and analysed came from a broad range of disciplines. The three dominant subject areas were Engineering, Environmental Science, and Business & Management, as shown in Figure 4. Most of the publications were journal articles (478 documents in the initial sample, 174 reviewed) and conference papers (132 in the initial sample, 28 reviewed). The samples further included review articles (25 in the initial sample, 2 reviewed) and book chapters (21 in the initial sample, 5 reviewed). The top 12 sources and document types are shown in Figure 5.

3.2. Descriptive results from the categorisation

This section presents the categorisation of the 208 publications from the final sample based on full-text analysis. The full list of articles reviewed and labels applied to categorise each article can be found in Appendix. This systematic review primarily

![Figure 2. Publication year of the articles in the initial sample collected and final sample reviewed.](image-url)
targeted case studies to analyse environmental solutions implemented in manufacturing. Out of the 208 publications analysed, 162 presented in-depth case studies (labelled CS) and 31 presented a cross-case analysis (labelled CC). Over half of the sample (98 articles) presented a new tool, method or framework, of which 14 articles did not include in-depth case studies (labelled TD only). They were still used in the analysis as they reported insights on the benefits and challenges related to the tool implementation.

Conversely, nine articles presented in-depth case studies without using a specific tool or method (CS but no label for the type of method). They were still included as they presented environmental solutions applied at a strategic level for corporate social responsibility and green supply chain management (BUS, CSR and SCM). Similarly, 16 industry-wide surveys and cross-case studies did not use a specific environmental tool or
method (CC but with no label for the type of method). They were also included as they provided insights into trends for business and institutional solutions in the manufacturing industry (BUS and INST).

Figure 6 provides an overview of the number of articles applying different methods and their distribution across type of measure, unit of analysis, scope and sustainability dimensions. There was a dominance of quantitative methods with the use of sustainability indicators (IND, 94 articles) and life cycle methods (LCX, 83 articles) to assess and manage manufacturing performance with direct environmental benefits (ENV, 192 articles), often focusing on the impacts generated within the manufacturing systems, thus gate-to-gate in scope (G2G, 89 articles). When life cycle methods were applied, a wider scope was adopted to consider the impact of upstream life cycle stages (material sourcing and supply chain strategies), i.e. cradle-to-gate in scope (LCX and C2Gt, 28 articles) and downstream life cycle stages (product delivery, customer satisfaction and end-of-life management), i.e. cradle-to-grave in scope (LCX and C2Gv, 38).

Figure 5. Sources of articles in the initial sample collected and final sample reviewed.

Almost a third of the final sample combined with more than one method (62 articles) to evaluate the sustainability impacts of products or processes. Multi-criteria decision
analysis (MCDA, 30 articles) was often combined with other methods to present a new tool, method or framework (MCDA and TD, 24 articles). For example, a life cycle perspective can help identify and develop more holistic environmental indicators (IND and LCX, 19 articles) and develop decision-support tools (IND and MCDA, 18 articles; LCX and MCDA, 4 articles) when employed with process modelling and dynamic simulations (IND and M&S, 12 articles; MCDA and M&S, 6 articles).

Most of the studies presented engineering, operational or technical measures (TEC, 141 articles) to improve processes and products, which were the most common units of analysis (PROC and PROD, 89 and 64 articles respectively) followed by manufacturing organizations as a whole (CORP, 55 articles). Except for three studies about a design methodology (Belucio et al., 2021; Desing et al., 2021; Kishita et al., 2010), design solutions (DES, 11 articles) overlapped completely with engineering solutions (TEC). Articles proposing business solutions (BUS, 73 articles) had particularly diverse units of analysis: manufacturing organisations (BUS and CORP, 45 articles), manufacturing processes (BUS and PROC, 20 articles), supply chains (BUS and SC, 21 articles) and products (BUS and PROD, 9 articles). Institutional solutions (INST, 15 articles) focused on organizations (INST and CORP, 14 articles), except for one article focusing on a specific energy technology (INST and PROD, Ratner & Lychev, 2019). The unit of analysis material was associated with technical measures (MAT and TEC, 17 articles), except for one article purely about business measures (Sangwan et al., 2019). Material-oriented studies largely overlapped with process-oriented studies (MAT and PROC, 12 articles). Supply chain studies proposed either business (SC and BUS, 21 articles) or technical measures (SC and TEC, 10 articles), and two articles covered both technical and business measures (Chithambaranathan et al., 2015; A. A. Choudhary et al., 2021; Geffen & Rothenberg, 2000; Kerdlap et al., 2020).

### 3.3. Environmental solutions and implementation challenges

This section describes the environmental solutions presented and implemented in the empirical studies reviewed. Then, eight propositions (P1-P8) are made about ways in which digitalization can support these environmental solutions and how it can help overcome the implementation challenges identified. Each subsection is organised so it can be read independently.

#### 3.3.1. Sustainable and smart manufacturing for resource efficiency

While the literature on Industry 4.0 (I4.0) is growing fast, the sustainability implications are still not well understood. Amongst the 208 articles reviewed, 15 studies used digital solutions (labelled DIG) to evaluate and generate environmental benefits (Ali & Johl, 2022; Barni et al., 2018; Epping & Zhang, 2018; Gupta et al., 2021; Jena et al., 2020; Z. Z. Jiang et al., 2012; S. S. Kamble & Gunasekaran, 2021; H. S. H. S. Lee & Choi, 2019; Lin et al., 2021; Pelegrino et al., 2019; Rodriguez et al., 2022; Sadiq et al., 2021; Santos et al., 2019; Turan et al., 2022; W. Zhang et al., 2019).

Recently proposed frameworks and conceptual models for sustainable I4.0 are promising, but real-world applications are needed to demonstrate their usability and effectiveness. For example, Rodriguez et al. (2022) proposed a framework and indicators to optimize quality and sustainability performance in additive manufacturing processes. Lin et al. (2021) proposed a blockchain-based LCA framework to transfer inventory data
securely between suppliers and manufacturers. The smart factory framework by Jena et al. (2020) aims to support autonomous maintenance scheduling by predicting failures and assist decision-making to optimise resource use and minimise waste. The Digital Twins framework proposed by Barni et al. (2018) aims to optimise a product’s life cycle across the whole value chain.

Academic research is increasingly using testbeds to develop and transfer new technologies from experimental to industrial scale. This is essential to provide concrete evidence of how digitalization can enhance industrial practice. These empirical studies should also consider sustainability implications, such as the testbed presented by Lee, Shin, et al. (2015) to demonstrate data-driven solutions for smart and sustainable manufacturing.

Although new technologies can support manufacturing operations’ efficiency and overall sustainability, integration challenges could arise due to costs involved, calibration knowledge required, and broadened application scope, as discussed in the study by Epping and Zhang (2018) about process automation. The vertical integration of various components of the industrial network, cloud computing, and supervisory control terminals is central to the success of digital manufacturing solutions (Jena et al., 2020). Challenges regarding the collection of relevant and accurate environmental data, as well as avoiding environmental information overload still need to be addressed (Santos et al., 2019). Some researchers suggested to integrate product and process information onto a single dashboard to cover performance variables across different functions within the production system and beyond the factory gate (Jena et al., 2020; Turan et al., 2022).

P1: Digitalization should support resource efficiency and environmental impact reduction.

3.3.2. Sustainability as a driver of performance
Despite good awareness of the global impacts caused by current production and consumption patterns, environmental regulations are sometimes loosely enforced (Shojaeipour, 2015) and investments in environmental technologies (Klassen & Whybark, 1999) and pollution prevention strategies are still considered as unproductive capital costs (Carmichael et al., 2003; Greschner Farkavcova et al., 2018). On the one hand, in the absence of strong external pressures to incentivize these investments, proactive approaches to environmental sustainability are needed but challenging to motivate (Pakdeechoho & Sukhott, 2018; Taghipour et al., 2022). On the other hand, more stringent environmental regulations and stronger market pressures (e.g. increased environmental awareness among consumers and adoption of environmental certification as criteria for supplier selection) are likely to arise in the near future (Alamroshan et al., 2022; J. J. Yang et al., 2022).

Some researchers argued that current sustainability assessment tools at managerial level (labelled BUS) are typically oriented towards external reporting and are not suited to support planning and business decisions (Ahmad et al., 2017). In addition, LCA, the most common method used, often focuses solely on environmental impact and does not account for social and economic implications, limiting its impact on decision-making and leading to missed opportunities. A potential solution is to combine LCA with other methods, such as data envelopment analysis (Ahmad et al., 2017) and LCC (Pergola et al., 2018). Resta et al. (2016) proposed an organisational LCA to overcome the three main
difficulties encountered by decision makers: 1) they lack the right information, 2) they struggle to define the business case for value creation, and 3) the execution of their sustainability strategies is often flawed.

**P2: Digitalization should support the proactive integration of sustainability as a driver of performance.**

### 3.3.3. Holistic view of manufacturing systems to identify potential trade-offs

Traditional performance indicators used in manufacturing are recognised as insufficient to support sustainability improvements (Santos et al., 2019; Shokri et al., 2022; Tan et al., 2011). Many researchers advocate for a more holistic definition of manufacturing performance to capture the interactions within and across the three dimensions of sustainability (Badurdeen et al., 2015; Pask et al., 2017; Resta et al., 2016). Considering each dimension in isolation could result in suboptimal solutions or unintended consequences (Badurdeen et al., 2015; Kluczek, 2016; Qi et al., 2006; Skornowicz et al., 2017).

Various methods were proposed to use composite indicators encompassing all dimensions of sustainability (Cagno et al., 2019; A. A. Choudhary et al., 2021; Errigo et al., 2022; Jasiulewicz-Kaczmarek et al., 2021; Z. Z. Jiang et al., 2012; Sangwan et al., 2019). For instance, Peças et al. (2018) proposed a methodology to apply eco-efficiency at product level considering an environmental profile (based on key performance indicators, KPIs) and a value profile (based on value indicators). Social and environmental sustainability goals are usually compatible (Echeverria et al., 2021; Hegab et al., 2018; Pinto, 2020; Sari et al., 2021; Zhou & Schoenung, 2009); e.g. reduce toxicity for both humans and the environment. However, social aspects are often considered difficult to quantify but indicators exist to support more socially sustainable manufacturing; e.g. as employee retention, organisational health and safety (accidents, injuries, fatalities, etc.), environmental and safety training programmes, work satisfaction, growth and opportunity (Ahmad et al., 2019; Cagno et al., 2019; Raj & Srivastava, 2018).

While many studies report synergistic environmental and economic gains, these synergies need to be intentionally and carefully designed to be realised. To identify these synergies and lower the barriers to sustainable practice adoption, companies need multi-disciplinary tools which are easy to use and deliver reliable results at the nano, micro and macro levels (Kluczek, 2016). Quantifying explicitly and more objectively environmental benefits, impacts and risks of alternative solutions or scenarios allow the identification of potential trade-offs and synergies between the different dimensions of sustainability (Badurdeen et al., 2015; Krystofik et al., 2014; Resta et al., 2016; Wilhelm et al., 2015).

**P3: Digitalization should support a holistic view of manufacturing systems to identify potential trade-offs.**

### 3.3.4. Life cycle thinking to avoid rebound effects

Life cycle assessment (LCA) is the most common method used to assess environmental impacts at the production level (G. B. Gamage & Boyle, 2006; Joachimiak-Lechman et al., 2019) and supply chain level (Kara & Ibbotson, 2011; Wong et al., 2020). Manufacturing studies integrating both upstream and downstream impacts (covering processes from raw material extraction to end-of-life products) are still uncommon (Lin et al., 2021). The
system boundaries, functional unit and temporal scale for a corporate LCA can be ambiguous and thus difficult to define (Ewing et al., 2011). This ambiguity creates a gap between what companies measure and improve, and what ‘should’ be done to achieve sustainability at a system level (Favi et al., 2019; Garbie, 2014).

Amongst the life cycle studies reviewed, less than half had a cradle-to-grave scope. Many studies focused on gate-to-gate (G2G) or cradle-to-gate (C2Gt) to evaluate manufacturing alternatives using a life cycle inventory analysis (C. K. C. K. Lee et al., 2016; Shanbag & Manjare, 2020; Zendoia et al., 2014). Examples of upstream integration include cradle-to-gate assessment of material sourcing and transport strategies (Greschner Farkavcova et al., 2018; Lin et al., 2021), life cycle inventory to assess the impact of process consumables and utilities (Z. Z. Jiang et al., 2012; Narita et al., 2007), and energy accounting to compare process technologies (Almeida et al., 2018). Examples of downstream considerations in manufacturers’ decision-making include quantitative indicators for customer satisfaction (R. Ben Ruben et al., 2017) and customers’ environmental requirements (Altmann, 2015). In these studies, direct access to primary data from upstream and downstream stakeholders increased the results’ accuracy and reliability. Such analysis can highlight trade-offs to avoid rebound effects from a manufacturer perspective (unintended consequences outside the factory gates).

Various life cycle methods can be combined to account for the environmental, economic (e.g. Schwab Castella et al., 2009; D. Yang et al., 2017), and/or social impacts (e.g. Lenzo et al., 2018; Wilhelm et al., 2015) of products and materials’ life cycle stages, highlighting different opportunities and priorities from different perspectives. When multiple impact categories are considered (midpoint approach), results’ interpretation can be complex since alternatives may improve performance in one category but worsen in another (Holt & Berge, 2018; Mirabella et al., 2014). To support decisions, an LCA endpoint approach can narrow down to fewer impact categories or a single score or index (e.g. J. R. Gamage et al., 2016; D. Yang et al., 2017). However, this aggregation decreases transparency and increases uncertainty.

The complexity of the method itself and the data required to obtain reliable results present significant challenges for manufacturing companies to use LCA (Zendoia et al., 2014). For example, Linkosalmi et al. (2016) reported difficulties due to impact allocation for each product type since production data are usually aggregated at plant level, or due to high uncertainty in estimating the product service life and maintenance requirements. In addition, life cycle methods tend to focus on environmental issues and ignore time, local conditions and subjective judgements for different contexts (H. Zhang & Haapala, 2015).

P4: Digitalization should support a life cycle perspective of manufacturing systems to avoid rebound effects.

3.3.5. Reliable and transparent sustainability assessments for business decision

Some business research studies (labelled BUS) recognised that decision-making processes are often subjective and proposed methods to integrate qualitative and quantitative indicators in business decisions, such as weighting and stakeholder involvement (Cagno et al., 2019; Dey & Cheffi, 2013; Rajak & Vinodh, 2015). Evaluating the broader implications of social and environmental initiatives could highlight indirect economic benefits, such as improved brand reputation and new revenues in the long run (Krystofik et al., 2014; Wilhelm et al., 2015). An additional challenge lies in selecting the right number of
KPIS, as a too-large selection of indicators can be counterproductive (Cagno et al., 2019; Rajak & Vinodh, 2015). Other important factors to consider are as follows: companies’ definition of sustainability targets and priorities; uncertainty in the occurrence of sustainability problems (risks management); and time delays from unexpected changes in other parts of the system.

Managers may have limited motivation or place low priority in undertaking sustainability initiatives as they are considered costly, time-consuming, and effort-demanding without directly contributing to profitability and business success (Skornowicz et al., 2017). In addition, smaller manufacturers typically have access to fewer resources and low influence over supply chains compared to major players (Lenzo et al., 2018). Finally, some manufacturers lack the capacity to collect environmental information and are limited to internal process data that are insufficient to perform sustainability assessments (Sangwan et al., 2019). Therefore, quantitative methods allowing quick and reliable analysis of different scenarios are needed to corroborate business decisions (Almeida et al., 2018; Carmichael et al., 2003; Q. Q. Jiang et al., 2018).

Studies attempting to include impacts beyond the factory gates reported concerns regarding data quality and availability. Sustainability assessment methods often require extensive data collection, normalization and aggregation (Badurdeen et al., 2015). Assessments’ usefulness relies on primary data accuracy from both internal sources and external stakeholders (Q. Q. Jiang et al., 2018) which are often unavailable (e.g. Feng et al., 2014; Zapolloni et al., 2019). Furthermore, there are issues regarding impact allocation (Plehn et al., 2012), systematic truncation (Dong et al., 2013), and uncertainty in later stages of the product life cycle (Cooper & Gutowski, 2020; R. B. Ruben et al., 2017; Santolaya et al., 2019), potentially leading to inaccurate or unreliable results and limiting the assessment usefulness for decision-making.

**P5: Digitalization should support sustainability assessments for data-informed and fact-based business decisions.**

3.3.6. **Hybrid methods for optimisation towards sustainable manufacturing systems**

All the influencing factors in manufacturing systems are difficult to capture with a single method. Combining multiple methods can help to overcome the shortcomings of individual methods (Alamroshan et al., 2022; Ghosh et al., 2022; Raj & Srivastava, 2018; Rajak & Vinodh, 2015; R. B. Ruben et al., 2017). For example, Raj and Srivastava (2018) combined fuzzy logic with the Best Worse Method (BWM), R. B. Ruben et al. (2017) developed an adaptive neuro fuzzy inference system for Lean sustainable systems, and Rajak and Vinodh (2015) and Ghosh et al. (2022) applied fuzzy logic to evaluate multiple dimensions of sustainability. LCA can also be combined with life cycle costing and social life cycle assessment (Epping & Zhang, 2018), simulation modelling (Adhitya et al., 2011) and multi-criteria decision analysis (MCDA) (Pineda-Henson & Culaba, 2004). When used along with an MCDA technique, LCA provided the MCDA method with the impact categories, indicators or measures to build the hybrid decision-making methodology.

MCDA methods, such as analytical hierarchy process (AHP) (Dey & Cheffi, 2013; Garbie, 2014; Z. Z. Jiang et al., 2012; Kluczek, 2016; Qi et al., 2006; Shojaeipour, 2015; Wen & Shonnard, 2003) and fuzzy logic (A. A. Choudhary et al., 2021; Ghosh et al., 2022; Hui et al., 2002; Rajak & Vinodh, 2015; R. B. Ruben et al., 2017), are used to evaluate...
environmental impacts while accounting for the subjective preferences of decision makers and the vagueness of normative sustainability concepts.

System behaviour was also considered in sustainability assessments using system dynamic modelling to assess social and environmental aspects in manufacturing (H. Zhang, 2019). Furthermore, modelling techniques such as data envelopment analysis (Belucio et al., 2021; Karimi et al., 2020) were integrated with MCDA techniques such as AHP to manage sustainability performance across value chains. Hybrid approaches that incorporate new technologies such as digital twins and sensor monitoring strategies could help overcome the issues that arise by using these life cycle methods in isolation, by monitoring and collecting real-time data, allowing for appropriate indices to be used in the calculations (Barni et al., 2018; Jena et al., 2020; Turan et al., 2022). For example, Barni et al. (2018) showcased the potential of using the Digital Twins concept to optimise manufacturing processes and support decision-making. The relatively quick assessment and comparison of the sustainability performance of existing value chains and planned production was demonstrated using a data-driven LCA-based framework. This helped provide accurate descriptions of system performance as various phases of the product life cycle were monitored and optimised using simulated and real-world data.

**P6: Digitalization should support hybrid sustainability methods for manufacturing system optimisation.**

### 3.3.7. Integration of sustainability into established operations management systems

Multiple studies present Lean and Six Sigma as imperatives to guarantee and sustain reduced environmental impact in manufacturing (R. Ben Ruben et al., 2017; Cheung et al., 2017; Gholami et al., 2021; Santos et al., 2019; Shokri et al., 2022). For example, Cheung et al. (2017) presented a new methodological approach combining a cradle-to-gate LCA and Value Stream Mapping (VSM) to evaluate the environmental impact of Lean improvements in production (reduced non-added value, lead time, labour and energy consumption). Similarly, R. Ben Ruben et al. (2017) proposed the Lean Six Sigma framework and Santos et al. (2019) proposed the Plug&Glean approach to diagnose and improve manufacturing companies’ productivity and environmental performance. These studies show that Lean and green are highly synergistic.

However, other studies highlighted potential misalignments between Lean and green (Baumer-Cardoso et al., 2020; S. S. Choudhary et al., 2019; Skornowicz et al., 2017). Although they still report environmental benefits alongside cost savings and quality improvements, they caution against assuming that Lean always leads to greener operations. When dedicated metrics are not in place, Skornowicz et al. (2017) reported that environmental improvements might be overlooked. Other researchers reported increased environmental impacts resulting from specific Lean solutions (Baumer-Cardoso et al., 2020; S. S. Choudhary et al., 2019); e.g. just-in-time manufacturing can lead to increased impacts due to more frequent transport, additional packing and smaller batches, and flexibility may also require additional resources when switching between production setups.

To remedy the shortcomings of Lean and Six Sigma productivity tools, variants of well-established tools have been developed to combine operational and environmental metrics incorporating safety, toxicity, pollution and other sustainability aspects (Antomarioni et al., 2018; Brown et al., 2014; Chiarini, 2014; S. S. Choudhary et al.,
3.3.8. For example, Green Integrated Value Stream Mapping (GIVSM) proposed by S. Choudhary et al. (2019) and Sustainable Value Stream Mapping (Sus-VSM) developed by Faulkner and Badurdeen (2014) add sustainability metrics to the standard VSM visualisation and assessment method. These methods complement traditional productivity tools by making the trade-offs between Lean, green and other factors (such as health and safety) visible. They also provide a more complete view of value-adding, non-value-adding or value-negative processes accounting for all sustainability dimensions.

P7: Digitalization should support the integration of sustainability into established operations management systems.

3.3.8. Manufacturing in a circular, service-based economy

While many studies focused on more efficient ‘forward value chains’, fewer studies investigated how manufacturing companies directly enabled closed-loop material flows (labelled CE). For example, Bacenetti et al. (2015) and Rieckhoff and Guenther (2018) used a cradle-to-gate LCA (LCX and C2Gt) to evaluate different circular scenarios. Other studies included end-of-life considerations for more circular manufacturing systems using life cycle methods adopting a cradle-to-grave scope (LCX and C2Gv) (Albizzati et al., 2021; Biganzoli et al., 2019; G. B. Gamage & Boyle, 2006; Gao & Wan, 2022; Schwab Castella et al., 2009; Zanghelini et al., 2014; W. Zhang et al., 2019) (Biganzoli et al., 2019; G. B. Gamage & Boyle, 2006; Schwab Castella et al., 2009; Zanghelini et al., 2014; W. Zhang et al., 2019). Bacenetti et al. (2015) and Biganzoli et al. (2019) looked at potential waste valorisation and reuse of by-products (after reconditioning) in production processes. Rieckhoff and Guenther (2018) and Schwab Castella et al. (2009) assessed the impact of different material composition and different recycling rates on the economic and environmental performance of the manufacturing system. By measuring the interactions between socio-technological systems and the natural environment, such methods could support organisations and their supply chains in improving their performance through increased resource productivity and circular strategies.

Finally, some studies have considered product-service systems to develop circular scenarios through maintenance, remanufacturing and product life extension (Chun & Lee, 2017; Luglietti et al., 2014; Zanghelini et al., 2014). Surprisingly, few papers discussed how manufacturing fits with service-based business models or only did so to a limited extent (Chithambaranathan et al., 2015; Dong et al., 2013; Geffen & Rothenberg, 2000; Krystofik et al., 2014; Luglietti et al., 2014; Resta et al., 2016; Shetty et al., 2015; Wong et al., 2020).

P8: Digitalization should support manufacturers in a more circular, service-based economy.

3.4. Synthesis of the literature findings and propositions

Based on the trends observed in empirical studies for sustainable manufacturing, challenges in implementing environmental solutions in manufacturing are identified and are summarised in this section.
While the studies reviewed are positive about the potential of I4.0 to manage the environmental performance of manufacturing systems, there are few published empirical studies. Real-world applications are needed to demonstrate digital tools’ usability and effectiveness for smart and sustainable manufacturing. Digital tools can support data sharing and collaboration across the value chain, which in turn can support more circular production systems. Further work is needed to define robust frameworks to systematically align the goals of digitalization and sustainability in manufacturing.

Quantitative methods (and LCA in particular) are the most common approach to assess the environmental impacts at the process, product and company levels. Most of the life cycle studies reviewed focused on direct, on-site environmental impacts and excluded either material extraction and processing, or use and end-of-life phases. Many researchers advocate for a more holistic analysis of industrial systems’ performance. Attempts to include impacts beyond the factory gate have hindered data availability, data quality issues and other methodological issues. The development of transparent, open-source databases, standardised metrics and standardised assessment methods can help overcome these hurdles.

Some of the environmental solutions proposed can reduce subjectivity in decision-making through the use of quantitative indicators. These methods include weighting and stakeholders’ involvement to account for qualitative aspects. Some studies reported low motivation to invest time, efforts and resources in using environmental solutions due to the absence of direct financial gains. Easy-to-use and reliable decision-making tools are needed to evaluate the broader impacts of sustainability initiatives and highlight indirect and long-term economic and social benefits.

Different methods are often combined to overcome their respective shortcomings. These hybrid methods can identify different opportunities from different perspectives, highlighting trade-offs and potential rebound effects. While multi-methods can yield more holistic results – especially those including full LCA – the data, skills and efforts requirements act as implementation barriers. More advanced data analytics can automate (or at least ease) sustainability assessments to integrate social and environmental considerations more consistently and systematically. In addition, sustainability education, life cycle literacy and digital literacy are needed to increase the uptake of such complex assessment methods.

Efficiency and productivity tools such as Lean and Six Sigma are imperatives to guarantee and sustain reduced environmental impact in manufacturing. They are largely synergistic with green manufacturing but do not always align automatically. Dedicated metrics are necessary to avoid unintended consequences and ensure that productivity improvements also generate benefits along the other dimensions of sustainability. Digital technologies can support further productivity and efficiency improvements, but they must be explicitly designed to do so as they do not replace Lean and environmental management principles.

Some studies in the final sample investigated closed-loop material flows through production waste recovery and products’ end-of-life management. LCA can help identify new opportunities and evaluate different circular scenarios. Common circular strategies for manufacturing companies include remanufacturing and product life extension, which can be realised through product-service systems. Our sample suggests that sustainable manufacturing research efforts largely focus on forward value chains to improve the resource efficiency of linear production systems. Circular principles for manufacturing and tools supporting collaboration across the value chain need to be further developed.
To address the aforementioned challenges, this section made eight propositions about ways in which digitalization can support the implementation of environmental solutions to assist researchers and decision makers in advancing the sustainability performance of manufacturing systems.

4. Discussion

This section discusses the implications of the review results by placing them in the context of ongoing research and by presenting a framework for Digitalized Sustainable Manufacturing.

4.1. Implementation challenges and practical implications

There is a plethora of sustainability tools, methods, frameworks and models in the literature, some of which were reviewed in this study. However, there is still a lack of formal, structured and globally accepted methods to measure the sustainability impacts of manufacturing processes (Mesa et al., 2019). Companies need clearer guidance to implement sustainability methods efficiently (J. Y. J. Lee & Lee, 2014) and allocate responsibilities for carrying out the assessment, especially when several actors are involved (Greschner Farkavcova et al., 2018). Barriers to the adoption of sustainable manufacturing tools and methods have been identified. For example, sustainability methods in manufacturing . . .

- have generally not been holistic and can be subjective (Cagno et al., 2019; Dey & Cheffi, 2013; Garbie, 2014; Raj & Srivastava, 2018);
- require large amounts of data, time and effort to implement (Kluczek, 2016; Sangwan et al., 2019; Skornowicz et al., 2017; Trianni et al., 2019);
- require choosing appropriate indicators and metrics (Cagno et al., 2019; Lenzo et al., 2018; Mesa et al., 2019; Rajak & Vinodh, 2015);
- may not be sufficiently applicable to a company’s specific needs (Geffen & Rothenberg, 2000; Lenzo et al., 2018; Trianni et al., 2019);
- lack accuracy and have highly uncertain results (Linkosalmi et al., 2016; Shojaeipour, 2015; Trianni et al., 2019).

The review by Neri et al. (2018) identified similar challenges (categorised as external drivers, internal enablers and barriers), and defined mechanisms through which these drivers and barriers interact. The tools and methods reviewed in our study can be used to facilitate the mechanisms proposed by Neri et al. (2018) to foster the adoption of sustainability measures.

Synergies between reduced costs and reduced environmental impacts through resource efficiency and technology innovation can create a win-win situation, known as the Porter hypothesis (Porter & van der Linde, 1995). The scope or system boundaries for the assessment will ultimately affect the magnitude of the environmental impacts accounted for. We need a clearer scope definition for sustainability targets, standardised sustainability metrics and evaluation methods integrated with established approaches such EMS standards and Lean Six Sigma. This integration can ease the systematic implementation of environmental solutions as part of continuous
improvement activities (rather than viewing sustainability as isolated ‘green activities’ or ‘add-ons’ on top of business-as-usual). For example, at an operational level, explicit environmental measures and indicators can be used in Sus-VSM (Brown et al., 2014; S. S. Choudhary et al., 2019).

A large portion of the studies in our final sample used life cycle approaches and various indicators for sustainable manufacturing. Life cycle methods (LCX) could be further categorised by specifying the context and purpose of the assessment to guide the selection of the appropriate life cycle method (Finnveden et al., 2009). Similarly, the empirical studies labelled IND could be further analysed using the standardised categorisation proposed by Joung et al. (2013) or the sustainability indicator constructs proposed by Rahdari and Anvary Rostam (2015). The diversity and large number of indicators can make it difficult to identify the most relevant KPIs for the industrial system considered. To address this challenge, Issa et al. (2015) and Kibira et al. (2018) proposed a procedure for selecting KPIs for sustainable manufacturing.

Despite the increased ubiquity and availability of data (e.g. Kellens et al., 2012; Shin et al., 2017), many studies report difficulties in accessing ‘real data’ from upstream and downstream stakeholders (e.g. actual data collected directly from suppliers as opposed to generic data from life cycle databases). There are also difficulties in forecasting how the products will be distributed, used, serviced and handled when they reach their end of life; this is especially the case for global manufacturers. Approximate life cycle data and assumptions on impact allocation are often necessary to complete life cycle assessments, leading to a high level of uncertainty in the estimated environmental performance (and potentially unreliable or inaccurate results). Better transparency across the supply chain – for instance, with widespread use of Product Environmental Footprint (PEF), Environmental Product Declarations (EPDs) and the related standard ISO 14025 (Gelowitz & McArthur, 2017) – and further development of life cycle databases – such as the International Reference Life Cycle Data System and the European Reference Life Cycle Database (Allacker et al., 2017) – are often highlighted as remedies to these data challenges.

Finally, there are differences between environmental approaches more suitable for small and medium enterprises (SMEs) than for multinational corporations (MNCs) or the other way round (Abdulaziz-al-Humaidan et al., 2021; Ali & Johl, 2022; Bos-Brouwers, 2010; Epping & Zhang, 2018; Errigo et al., 2022; Kikuchi & Hirao, 2010; Trianni et al., 2019; Yu et al., 2011). SMEs seem to encounter additional challenges due to the lack of resources and long-term perspective needed to apply sustainability tools and methods. A dedicated in-depth analysis of methods applied in SMEs is required to draw conclusions regarding SME-specific challenges and opportunities.

4.2. Research framework for digitalized sustainable manufacturing

Based on the eight propositions made, this subsection proposes a framework to guide future research and address the second research question: How can digitalization support the systematic implementation of these solutions?

With the fast-growing interest in digitalization since 2015, many review articles exploring sustainability and I4.0 have been published and are largely exploratory (Gobbo et al., 2018; Kiel et al., 2017; Müller et al., 2018; Stock & Seliger, 2016). Most notably, S. S. S. Kamble et al., (2018) propose a framework for Sustainable Industry 4.0
based on six principles: interoperability, decentralization, virtualization, real-time capability, modularity, and service orientation. Research agendas have also been proposed for I4.0 and sustainable manufacturing (Machado et al., 2020), I4.0 and circular economy (de Sousa Jabbour et al., 2018), and I4.0 and sustainable business models (Man & Strandhagen, 2017) amongst others. To reach a higher level of research maturity, the field needs more normative research considering positive and negative impacts of digital technologies to improve sustainability in manufacturing processes (Chen et al., 2020; Machado et al., 2020). Therefore, the research framework in Figure 7 is based on a bottom-up approach to target practical issues identified in published empirical studies.

In addition, case studies using digitalization for sustainable manufacturing are still scarce but growing rapidly as we enter the ‘take off’ phase of the diffusion of innovation (Rogers, 2003). To boost this take off, the proposed research framework contains four themes to guide future studies on digitalized manufacturing systems: (R1) Digital Environmental Impact Analysis, (R2) Sustainable Cyber-Physical Systems, (R3) Digital Knowledge Platforms and Communication Solutions, and (R4) Ethical Data Management and Cybersecurity.

The first theme is Digital Environmental Impact Analysis to overcome problems related to data availability, transparency, access, and analysis. Digital twins can capture crucial information about products and processes addressing the issue of data availability, especially when including impacts beyond the factory gates (Barni et al., 2018). The digital thread can be used to address the issue of transparency by pushing information along the value chain to simulate and analyse the effects of improvement scenarios at different points in the product life cycle, thereby identifying potential trade-offs or rebound effects.

Despite advances in open-source software and public life cycle databases, the knowledge, skills, time and efforts required to carry out LCA calculations transparently and accurately for everyday industrial activities is still challenging. Life cycle studies’ quality and usefulness heavily depend on detailed inputs and outputs associated with each product life cycle stage and critical methodological choices. Thus, life cycle literacy in industry needs to be developed to increase LCA uptake (linking to the third theme, Digital Knowledge Platforms and Communication Solutions).

Many factors of influence are beyond the control of manufacturers. Digitalization and big data analytics may enable new data models to support sensitivity and uncertainty analysis for prospective LCA studies. Accounting for the dynamic and uncertain environment businesses operate in, more mature metrics are needed to increase confidence in decision-making and incentivize investments for long-term sustainability (Donnellan et al., 2011). For example, accounting for uncertainty during products’ use and end-of-life management (Krystofik et al., 2014) and risk management using supply chain analytic tools (Zhu et al., 2018).

Reverse supply chain analytic tools are especially needed to support product end-of-life management and analyse different closed-loop routes for different materials. Considering uncertainty and variability is critical as circular flows (waste and end-of-life products) are inherently unpredictable in terms of quantity and quality compared to the forward supply of virgin materials. An additional step towards real-time analysis can be enabled by automated environmental impact assessment to support continuous improvements accounting for variations in supply and demand, and other external factors. In turn, it allows better and faster response to risks and sudden changes (i.e. resilience).
The second theme, Sustainable Cyber-Physical Systems, deals with the challenges of implementing the proper digital infrastructure to support factory automation and coordinate efforts between people and machines at all levels towards self-configuring, self-adjusting, and self-optimising environment. While the productivity gains are well recognised, increased digital maturity does not replace Lean management principles. Thus, the
Digital technologies must be integrated with established good practices. For example, cyber-physical systems built on discrete event simulations of factory models (Li et al., 2016) can be used to optimise controls over operations and scheduling for minimal energy-related CO₂ emissions and minimal total job tardiness.

However, deciding which aspects of the production systems would benefit from physical and/or cognitive automation requires careful considerations for socio-ecological sustainability. The growing demand for materials to produce information and communications technologies (ICT) and issues related to waste electrical and electronic equipment management (WEEE) (Ongondo et al., 2011) as well as the energy-related climate impact resulting from their intense use (Nguyen et al., 2013) also needs to be accounted for in the environmental performance assessment of digitalized production systems. In many cases, the environmental benefits of their use largely exceed the impact of their production. From a social perspective, automation ‘can either replace workers or sustain them by making their tasks more flexible, safer, and socially more inclusive’, provided that workers’ psychosocial stress and automated tools’ occupational risks are managed well (Leso et al., 2018).

The third theme is Digital Knowledge Platforms and Communication Solutions focusing on the use of technology to facilitate communication and knowledge transfer, thereby supporting both internal and external collaboration between people. There are three aspects to this research theme: (1) the need to develop life cycle literacy and adequate knowledge for the correct use of sustainability assessment methods; (2) the need to develop digital literacy and know-how in manufacturing for the productive exploitation of 4.0 technologies (J. Lee et al., 2015); and (3) the need to communicate environmental information in a timely and transparent manner. For example, internal communication platforms for employees’ engagement include mobile devices with apps providing personalised information about complex work tasks (e.g. remanufacturing), or virtual boards with sustainability KPIs tracking processes in real-time (Pêças et al., 2018). Such tools can be used to train the current workforce on environmental issues (reskilling and upskilling) and ensure skills continuity by retaining and transferring knowledge from experienced workers to new recruits, who are often a young workforce more familiar with digital technologies (Colbert et al., 2016). External collaborative platforms with suppliers and other relevant partners could be used in a similar manner to share knowledge and upgrade the skills of all actors across the value chain. By making the right information available to the right users at the right time and in the right format, efforts can be harmonised to achieve sustainability goals, such as the UN Sustainable Development Goals.

Finally, the fourth theme, Ethical Data Management and Cybersecurity, is a key enabler for the other three themes. This could help overcome the barriers related to trust and data sharing both within companies and across value chains (Cash et al., 2003; Nair et al., 2021). When transitioning to Industry 4.0-enabled processes, several factors need to be considered for sustainability decision-making (other than the triple bottom line), including information handling and cybersecurity issues that could affect products’ performance and the holistic decision-making (Adhitya et al., 2011). The lack of systems integration, ethical issues with artificial intelligence, data quality issues, inadequate data visualisation, lack of data mining skills, lack of trust when sharing data, and many other aspects (Broo & Schooling, 2021; Despeisse & Turanoglu Bekar, 2020) need to be considered in further research.
5. Conclusion

The interdisciplinary research area at the intersection of sustainability and digitalization trends is growing fast but still in its infancy. Despite the positive outlook for digitalization in manufacturing, it does not systematically lead to more sustainable operations (Machado et al., 2020). Digitalization also presents the risk of accelerating our linear economy with faster and more efficient production of goods and services, thereby further trespassing planetary boundaries already exceeded during the previous industrial revolutions (Desing et al., 2020). It is critical to align the goals of sustainable development and industrial development, so they reinforce each other (rather than compete or conflict with one another). In other words, the adoption of digital technologies should enable more sustainable industrial performance, and sustainability challenges should act as a driver for innovation and technological advances.

This study analysed published empirical studies in the field of green manufacturing. Based on the trends observed in the literature, challenges in implementing environmental solutions were identified. Some key recommendations for future research include the development of hybrid methods to enable more holistic analysis of industrial systems’ performance beyond the factory gate, highlighting trade-offs and potential rebound effects across life cycle stages and across sustainability dimensions (environmental, economic and social). Further development of standardised assessment methods, science-based metrics and life cycle databases can help overcome hurdles related to data availability, data quality, subjectivity in decision-making and other methodological issues.

To address the challenges identified, eight propositions were made about ways in which digitalization can support environmental solutions more systematically. In turn, the propositions aim to guide researchers and decision makers in advancing the sustainability performance of manufacturing systems. Digitalization should support . . .

P1: resource efficiency and environmental impact reduction
P2: the proactive integration of sustainability as a driver of performance
P3: a holistic view of manufacturing systems to identify potential trade-offs
P4: a life cycle perspective of manufacturing systems to avoid rebound effects
P5: sustainability assessments for data-informed and fact-based business decisions
P6: hybrid sustainability methods for manufacturing system optimisation
P7: the integration of sustainability into established operations management systems
P8: manufacturers in a more circular, service-based economy

Practical implications for sustainable manufacturing were then discussed in connection to ongoing research efforts, and a framework for Digitalized Sustainable Manufacturing was proposed. The framework adopts a bottom-up approach to tackle the challenges identified in the review of empirical studies. It contains four research themes with recommendations to contribute to the growing Industry 4.0 research agenda with a strong focus on environmental sustainability in manufacturing. The first theme, Digital Environmental Impact Analysis, addresses the need for more research to support the twin transition of ‘digital and green’ by building on recent developments in the field of environmental studies, data science, and digital technologies. The second theme, Sustainable Cyber-Physical Systems, advocates the need for better coordination between people and machines to exploit digital technologies and industrial data more productively, leading to safer and greener manufacturing operations. The third
theme, *Digital Knowledge Platforms and Communication Solutions*, aims to promote the development and use of 4.0 technology to facilitate skills development (e.g. life cycle literacy and digital literacy) to lower the barrier for sustainability assessment methods, as well as facilitate collaboration (e.g. timely and transparent communication of environmental information) to harmonise efforts to achieve sustainability goals. Finally, the fourth theme, *Ethical Data Management and Cybersecurity*, highlights underlying challenges requiring further research related to trust, data sharing, systems integration, and other security issues.

To summarise, digitalization can unlock new ways of exploiting data and technologies to ease and scale up the adoption of environmental solutions. But green manufacturing opportunities need to be considered explicitly in both research and industrial developments to be realised. We therefore urge researchers and industry leaders to address sustainability issues more systematically to avoid accelerating the linear economy and further trespassing the planetary boundaries.

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