sustainability

MDPI

Review

Digitalisation of Manufacturing Systems: A Literature Review of Approaches to Assess the Sustainability of Digitalisation Technologies in Production Systems

Florian Tomaschko *, Lukas Reichelt and Sandra Krommes

Research Group Sustainable Engineering & Management, Rosenheim Technical University of Applied Sciences, 83024 Rosenheim, Germany

* Correspondence: florian.tomaschko@th-rosenheim.de; Tel.: +49-08031-805-2648

Abstract: The digitalisation of production has a positive impact on manufacturing processes in terms of resource efficiency and environmental impact, particularly in the form of increased efficiency as well as cost and resource savings. However, the use of digitalisation technologies is also associated with efforts such as costs, CO_2 emissions, and raw material consumption. When planning or deciding on the digitalisation of manufacturing systems, it is therefore necessary to assess whether these technologies pay off in terms of sustainability over their life cycle. This literature review (based on the PRISMA guidelines) analyses the relevance of sustainability assessment and its methods for the digitalisation of production in research. The review reveals that research focuses on the benefits of digitalisation technologies in manufacturing, while the assessment of efforts and their benefits is in its infancy. There is a need for further research on holistic assessment methods for digitalisation technologies. In particular, there is a lack of assessment methods that consistently link the economic and environmental dimensions of sustainability, and there is also a lack of guidance for the application of assessment methods in production.

Keywords: digitalisation; sustainability; holistic assessment; cyber–physical system; digital twin; internet of things; industrial internet of things; Industry 4.0; environmental; economic

check for updates

Citation: Tomaschko, F.; Reichelt, L.; Krommes, S. Digitalisation of Manufacturing Systems: A Literature Review of Approaches to Assess the Sustainability of Digitalisation Technologies in Production Systems. *Sustainability* **2024**, *16*, 6275. https://doi.org/10.3390/su16156275

Academic Editor: Barbara Motyl

Received: 22 February 2024
Revised: 1 July 2024
Accepted: 2 July 2024
Published: 23 July 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Digitalisation technologies are becoming increasingly important in the context of sustainable manufacturing. Technologies such as Industry 4.0 (I4.0) are recognised as a key facilitator in the efficiency of industrial processes [1,2]. Due to climate change and the increasing scarcity of resources, sustainable manufacturing and prudent use of raw materials along the product and production life cycle are indispensable. Companies are faced with volatile raw material availability and rising energy and raw material prices that influence their value added and productivity. The extraction and processing of raw materials and the manufacturing of products also result in an environmental footprint. Therefore, cost reduction solutions and effective resource management are needed [3]. Both the research community and the industrial sector attribute great potential to digitalisation for the transformation to greener production. A variety of methods, instruments and tools exist in the context of I4.0 that are intended to make production systems more sustainable and resource-efficient [4–9]. I4.0 technologies offer, as one approach, the possibility of saving costs, energy and raw materials in production through data mining and analytics for dynamic key figures and monitoring [10–13]. However, the described advantages are offset by costs and resources due to hardware and software systems. These systems require energy and raw materials throughout their life cycle and incur investment and operating costs that must be recouped in terms of costs and resource consumption to have an overall positive impact. To be able to assess the benefits of digitalisation technologies holistically, the economic and environmental efforts must also be considered. This paper therefore

analyses the current state of research on sustainability and methods for sustainability assessment in the application of digitalisation technologies such as cyber–physical systems and digital twins in the production environment.

In the following chapters, a literature review (LR) based on research questions is conducted. The LR consists of four steps, during which papers focusing on the environmental and economic assessment of digital twins (DTs) and cyber–physical systems (CPSs) are identified. Subsequently, the approaches and assessment methods used in the identified papers are analysed. This analysis leads to the derivation of assessment criteria for comparing these methods in terms of their environmental and economic sustainability dimensions. As a result, various methods for assessing digitalisation technologies in manufacturing systems are presented, and research gaps in this field are identified.

2. Background and Scope of the Research

2.1. Digitalisation Technology in Manufacturing Systems

Terms such as digital transformation, digitalisation, or I4.0 describe a link between the real, physical world and the digital, virtual world [14]. The term digitalisation encompasses an evolutionary concept, which refers to the transformation of analogue data into digital data and forms the basis for the roof-type concept of I4.0. The basic idea of I4.0 was first mentioned by Kagermann in 2011 and describes the integration of digital technologies into industrial processes and production environments [15]. The terms encompass a variety of technologies, functions and subject areas [16]. On the one hand, the terms cover subject areas such as new business models and smart products, and on the other hand, the use of new digital technologies in the production environment is mentioned [17–20]. I4.0 can essentially be divided into two dimensions: horizontal integration, which includes cross-company and company-internal intelligent cross-linking, and vertical integration, which takes into account intelligent cross-linking of the different hierarchical levels of the production environment [21]. The use of I4.0 technologies in the production environment is expected to increase efficiency and sustainability, for example by improving quality, reducing machine downtime or increasing plant utilisation [22,23]. In this context, I4.0 technologies and methods such as digital twins (DTs), Big Data, cyber–physical (production) systems (CP(P)Ss), (Industrial) Internet of Things ((I)IoT) or artificial intelligence (AI) are used in particular [24] (Table 1).

Table 1. Terms and definitions of I4.0 (own illustration).

Terms	Definitions	Sources
Digitalisation	The term **digitalisation** describes an ongoing evolution of a general process, whereby analogue data are transformed into digital formats. Digitalisation finds application across various sectors including economy, education and healthcare. In an industrial context, it involves capturing, storing and processing information related to machines and equipment, workpieces and products to enhance process efficiency and explore new possibilities.	[12,25]
Industry 4.0	**Industry 4.0** describes the concept of the fourth industrial revolution (Industry 1.0: water and steam power; Industry 2.0: assembly line and electricity; Industry 3.0: automation, computers, and electronics; Industry 4.0: intelligent interconnection of machines and processes; Industry 5.0: interconnection of humans and machines, AI), which entails the integration of digital technologies into industrial processes and production environments and forms the roof over the following mentioned technologies. It encompasses technologies such as the Internet of Things, cyber–physical systems, digital twins, Big Data analytics, and automation to create smart factories and more efficient production processes.	[15–18,26]

Table 1. *Cont.*

Terms	Definitions	Sources
DTs	**DTs** map the physical world as a virtual image (complex digital representation) and can be a part of a CPS. In addition to the function of digitally mapping production machines, DTs are used for the simulation of entire production systems and factories, including their self-description or the mapping of the data basis for machine learning. By using and analysing real-time data from the physical systems, different users are able to view or control the objects as required. The decision-making is facilitated based on the available information from real, simulation and algorithm data.	[27–29]
CPSs/CPPSs	**CPSs** are physical objects equipped with an embedded system as well as sensors and actuators. In addition to the hardware, they also include software components and combine the physical with the virtual world through the use of the IoT. The various components are integrated, controlled and monitored by a computational core and affect production processes. A **CPPS** is a network of several CPSs that together control an entire production system.	[30–32]
IoT	The **IoT** connects things and services (industrial equipment) to an IoT platform, networks it with the entire ecosystem of the company and creates a connection between the systems. It also represents the basis for connecting the CPSs.	[33–35]
Digitalisation-technologies	**Digitalisation technologies** encompass the tools and devices required to digitalise processes or make them Industry 4.0 capable. For instance, these include the necessary hardware and software in the form of smart sensors and actuators, data transmission systems and programmes for data processing and analysis to build CPSs and DTs and combine the two concepts of DTs and CPSs.	[12,36,37]

In a coherent I4.0 value network, DTs form the basis for data generation and build a virtual representation of a physical object or process, continuously updated with real-time data to enable predictive insights. DTs are summarised as many individual elements in CPSs/CPPSs. Integrating CPSs/CPPSs/DTs with physical processes creates complex systems capable of interaction, communication and adaptation. The IoT network serves as an interface to the outside world to expand data availability and to network the CPSs/CPPSs. Based on these data, the desired benefit and an improvement in production conditions can be achieved manually or automatically. Here, sensors and actuators serve as means of communication with the production level [38,39]. Systems that transmit and store data are on a higher level. The systems are intelligently linked and exchange data with each other via the cloud, which is integrated into the IoT [40]. Finally, data are evaluated for decision-making using manual or automated (e.g., machine learning) approaches [21,41]. These technologies require hardware such as sensors, computers and servers and software for data storage, transmission and analysis. The necessary components, in turn, require energy and resources and incur costs to their operation. This must be amortised by the benefits of their use.

2.2. Sustainability as an Assessment Criteria for Digitalisation Technologies in Manufacturing Systems

The assessment of digitalisation technologies in the production environment is similar to the evaluation of investments established in business administration. However, traditional business administration typically only evaluates based on costs and returns [42]. On the other hand, approaches to defining sustainability consider a broader range of evaluation factors. Based on the definition provided by the UN Brundtland Commission, which

characterises sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs", this approach can also be applied to sustainability assessment [9,43]. In 2015, the UN agreed upon 17 Sustainable Development Goals (SDGs). Some of these can also be applied to sustainability assessment in manufacturing systems, namely SDGs 7, 8, 9, 12 and 13 [44]. The mentioned goals encompass various themes and can be attributed to the three pillars of the overarching sustainability concept of the Triple Bottom Line, which includes economic sustainability, environmental sustainability and social sustainability [45,46] (Table 2).

Table 2. Dimensions of sustainability connected to SDGs (own illustration) [44,45].

Terms	Definitions	SDGs
Economic sustainability	Economic sustainability describes the economic activities of a society in a manner that does not result in losses or disadvantages for future generations.	Industry, Innovation and Infrastructure (9), Responsible consumption and production (12)
Environmental sustainability	Environmental sustainability refers to the utilisation of ecosystem structures only to the extent that they can regenerate themselves.	Affordable and clean energy (7), Responsible consumption and production (12), climate action (13)
Social sustainability	Social sustainability describes the enduring social development of a state or society, considering intergenerational equity.	Decent work and economic growth (8)

As mentioned, ecological assessment is a fundamental concept in classical investment appraisal, and there are numerous established methods for this purpose. Therefore, the ecological pillar is considered a crucial decision-making basis in this literature review. For the literature assessment, keywords such as production efficiency, costs and benefits, and investment decision are used. Environmental assessment is gaining increasing importance in times of critical resource and energy situations and is also considered within the framework of the literature analysis. To identify relevant papers, keywords such as environmental consequences, environmental sustainability, life cycle, LCA and energy efficiency are used. The social pillar incorporates human aspects into sustainability assessment. Few or no evaluation methods are available for this new thematic area, and quantifying social impacts is challenging. Therefore, social impacts will not be considered in this literature review.

2.3. Research Questions

Similar to other investment decisions in production, investments in digitalisation technologies and their application need to be considered holistically to ensure sustainability in economic and environmental terms. For this purpose, savings in costs and resources achieved by the technology need to be compared to the expenses and efforts. In the current phase of the increasing digitalisation of production systems, there is a high potential to positively influence the resource efficiency of the new technology [8]. However, this requires methods for holistic assessment that can be implemented in research and practice. In business administration, it is standard practice to calculate the profitability and amortisation of investments over their lifetime. Different methods of profitability and investment calculation are applied [47,48]. In environmental science, Life Cycle Assessment (LCA) is mainly carried out to comparatively analyse the environmental impacts of different product alternatives [49]. Approaches that consider the amortisation of environmental impacts are hardly known or rarely applied. Some of these approaches are defined as environmental payback (period) or environmental break-even. They are applied, for example, to assess new technologies that have a higher environmental impact in one life cycle phase that needs to be amortised in the other life cycles [50,51]. Or they analyse whether the environmental impacts of circular economy systems pay off [52]. The environmental break-even is defined as the point at which the environmental impacts of two systems are equal [53].

A methodology that combines economic and environmental assessment is known as eco-efficiency [54–56]. However, eco-efficiency analyses are used to compare alternatives in terms of their environmental impact and life cycle costs and do not assess the environmental payback or the economic amortisation. Therefore, methods for sustainability assessment of digitalisation in manufacturing systems are necessary to avoid these technologies not paying off. For this purpose, researchers must develop, present and validate methods. Beier et al., 2020, already pointed out that there is little literature in the field of sustainability assessment of digitalisation systems and that further research is needed [57,58]. The aim of this review is to examine the relevance of economic and environmental assessment methods in the digitalisation of manufacturing systems. Another area of interest is which economic and environmental aspects of digitalisation technologies in manufacturing systems are the subject of research and which methods are applied to assess digitalisation technologies in manufacturing systems. The focus here is on technologies such as CPSs, CPPSs and DTs, and the applications of I4.0 in production that contribute to increasing sustainability. In this context, this paper aims to answer the following research questions (RQs):

- RQ 1: What is the importance of "digitalisation technologies (DTs and CPSs) and sustainability" in production environments in research?
- RQ 2: Which subjects are discussed in terms of "digitalisation technologies (DTs and CPSs) and sustainability"?
- RQ 3: How is the sustainability assessment of digitalisation technologies (DTs and CPSs) discussed in research?
- RQ 4: Which approaches exist to assess the economic and environmental benefits of digitalisation technologies (DTs and CPSs) in manufacturing systems?

3. Methods

3.1. Literature Review

This study is based on a literature review (LR), which generally uses a four-step scheme according to Mengist et al., 2020. It is applied particularly in environmental science to identify the relevant literature and evaluate it against the RQs. By doing so, the current state of research is recorded by gathering knowledge quantitively and qualitatively. This will reveal the status of sustainability assessment methods in the subject field and identify research gaps and challenges. Based on defined search terms with keywords, the literature found is analysed in the four successive steps of (1) identification, (2) screening, (3) eligibility and (4) selection. This methodological procedure enables us to review a broad subject field such as digitalisation technologies and sustainability and ensures transparency and replicability. The LR was conducted based on the PRISMA guidelines (Appendix A) [59,60].

The results are divided into quantitative and qualitative results. While the quantitative results analyse and present the literature found regarding publication date, countries and institutions of origin, keywords and topic clusters, the qualitative results characterise the assessment approaches and discuss approaches for the economic and environmental assessment of digitalisation technologies in production in detail.

3.2. Data Collection and Analysis

The LR uses the database Web of Science, and it is extended by a snowball search in the literature that is considered eligible after analysing the identified publications. It includes all kinds of articles such as peer-reviewed, early and open-access articles, proceeding papers and book chapters. In the first step, no period is defined for the publication years, but it turns out that there are no relevant publications before 2017. Therefore, in the second step, the period of publication years from 2016 to 2023 is defined. All publications must be written in English or German and be available online as a full text. Due to the broad subject field and, in particular, the focus on digitalisation technologies in production or manufacturing systems, scientific categories such as physics, chemistry, mathematics and social sciences are excluded (Table 3).

Table 3. Selection criteria for the literature review (own illustration).

Criteria	Included	Excluded
Data base	Web of Science	Scopus, Google Scholar and any other data base
Time period of publication years	<= 2016 to end 2023 *	* the search initially considers studies before 2017, but no relevant publication was found before 2017
Document types	Articles (all, peer-reviewed and open access articles), proceedings and book chapters	--
Science Categories	Engineering Manufacturing, Engineering Industrial, Operations Research Management Science, Computer Science Interdisciplinary Applications, Engineering Electrical Electronic, Materials Science Multidisciplinary, Engineering Multidisciplinary, Automation Control Systems, Computer Science Information Systems, Engineering Mechanical, Green Sustainable Science Technology, Environmental Sciences, Computer Science Artificial Intelligence, Robotics, Multidisciplinary Sciences, Engineering Environmental, Environmental Studies, Management Mechanics	Physics Applied, Telecommunications, Chemistry Multidisciplinary, Chemistry Analytical, Engineering Chemical, Energy Fuels, Mathematics Interdisciplinary Applications, Construction Building Technology, Metallurgy Metallurgical Engineering, Chemistry Physical, Engineering Civil, Physics Condensed Matter, Biotechnology Applied Microbiology, Social Sciences Interdisciplinary and all other specific categories
Publishers and publication titles	all	--
Language	English or German	any other language
Availability	available online as full text	not available online as full text
Countries/ Regions	all	--

To identify the current state of research and analyse it with respect to the RQs, the LR is conducted as follows:

- (1) **Identification:** In the first step, the search terms are defined. Based on the research questions, these terms focus on cyber–physical production systems (CP(P)Ss) and digital twins (DTs) in the production environment. To ensure no relevant literature is missed, no further restrictions were imposed regarding environmental or economic assessment. Therefore, the literature search used the terms “digital twin”, “cyber-physical (production) system” and “manufacturing” and connected them to the search terms (ALL = (manufacturing production “digital twin*”)) and (ALL = (manufacturing production “cyber physical system*” “cyber physical production system*”)) (used queries in “web of Science”: Query 1: manufacturing production “digital twin*”, Query 2: manufacturing production "cyber physical system*" “cyber physical production system*”).
- (2) **Screening:** In the second step, duplicates are removed and the remaining search results are filtered. To identify the articles that are relevant to the research problem, the titles and keywords of the papers are analysed first. All papers that obviously deal with another topic are excluded (no production background). Further, the abstracts of the remaining research results are analysed and assigned to the categories Industry 4.0, digital twins and cyber–physical systems (including CPPSs). Papers with another I4.0 background (Big Data, AI) are excluded. To identify and categorise the literature

that deals with the cost and resource efficiency assessment of digitalisation technologies in production systems, the categories environmental and economical are added. Publications were considered that address environmental or economic issues in the context of CPSs or DTs. From this, papers can be derived that basically deal with the use of digitalisation technology to increase cost or resource efficiency. These categories are necessary to study the importance and dynamics of the research subject related to the search term (RQ 1 and RQ 2). These publications are classified according to the year of publication, the type of publication, the journal category (engineering, environmental, computer and other sciences), the most important journals, the frequency of keywords, the regions (countries) and the most important universities (institutes) of the publications.

- (3) **Eligibility:** In the third step, the existing methods for holistic assessment are filtered out of these results and evaluated in terms of whether they deal with (i) a holistic approach for an economic and/or environmental assessment, (ii) efforts (costs) and benefits associated with digitalisation technologies, (iii) a specific economic assessment and (iv) a specific environmental assessment (RQ 3). In addition, the cross-references of the literature examined are analysed in a snowball search and included in the LR. This is carried out based on the relevant literature, as it is assumed that other relevant literature is mentioned there. As a result, various subject fields are characterised to determine the relevance of the sustainability assessment of digitalisation technologies in research.
- (4) **Selection:** In the fourth step, the papers that meet the criteria are analysed in terms of content in relation to RQ 4 to identify the methods used for a holistic assessment of digitalisation technologies. It is essential to describe the status of the methods presented and to analyse them with regard to the consistency of the approach from problem description to decision-making. Other criteria are whether the assessment includes the entire life cycle from cradle to grave in the assessment methodology and whether it takes into account different impact categories and linear/non-linear cost–benefit functions. It is also of interest whether common assessment methods are applied and whether these consider economic and environmental sustainability dimensions.

4. Results

4.1. Quantitative Results

4.1.1. Identification and Screening Results

Based on a total of 1431 publications found in the first step of the LR, 504 publications were eligible for evaluation after the deletion of duplicates (n = 95) and screening of the titles and abstracts. More than half, namely 832 publications, did not comply with the classification of I4.0, DTs, and CP(P)Ss as well as the economic and/or environmental criteria. Therefore, they were excluded from the screening (Figure 1). The remaining 504 publications were characterised according to year of publication, type of publication, journal categories and journals, authors keywords, regions (countries) and most relevant organisations such as universities or academic institutes. A further analysis classified the remaining 504 publications in terms of content with regard to the subject of economic, environmental and economic–environmental assessment. Based on this, the main aspects of the publications are characterised and used for further classification of the publications.

From the 504 papers, 31 papers were identified and supplemented by 14 publications from cross-references (snowball search) that dealt with economic or environmental assessment. In a full-text screening of these publications, 18 papers were selected for a detailed content analysis with regard to assessment methods [12,61–76].

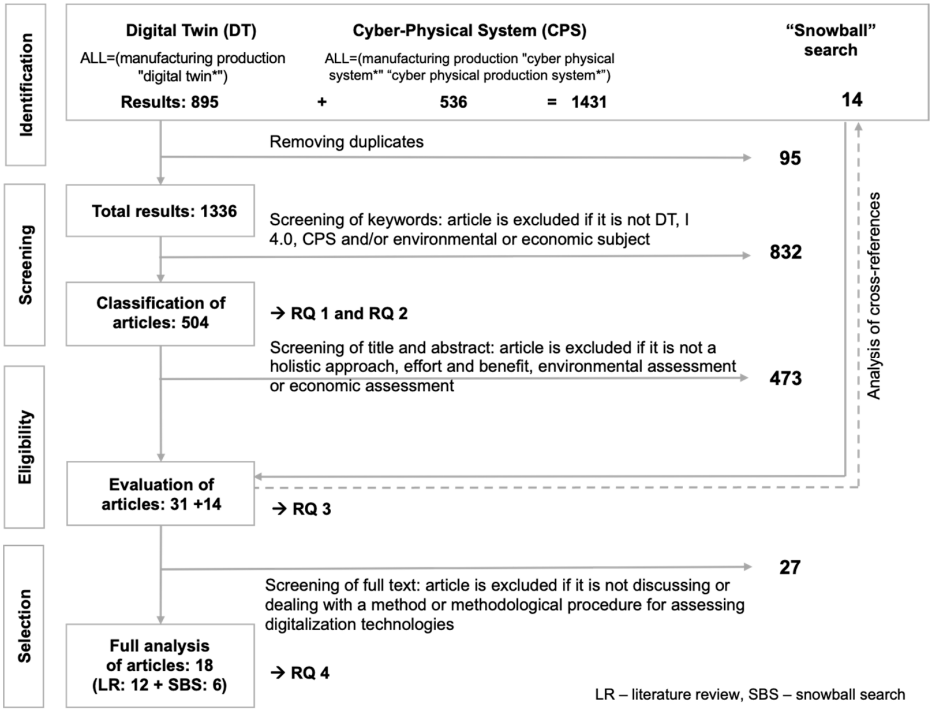


Figure 1. Scheme and results of the LR on the assessment methods for digitalisation technologies in manufacturing systems (own illustration based on Mengist et al., 2020 [59]).

4.1.2. Chronological Development, Type and Journal of Publications

The chronological analysis shows that the first publications on the subject were made in 2017. No relevant publications were found in the LR before 2017. After that, there was an annual increase from 17 in 2017 to 148 in 2022 in publications. From 2020 onwards, this trend was even more prominent. This trend declined in 2023. Only 71 papers were identified in the LR. It is noticeable that many papers from 2023 deal with the new research fields of artificial intelligence [77,78] and Industry 5.0 [79–81], which, however, are not part of this LR (Figure 2).

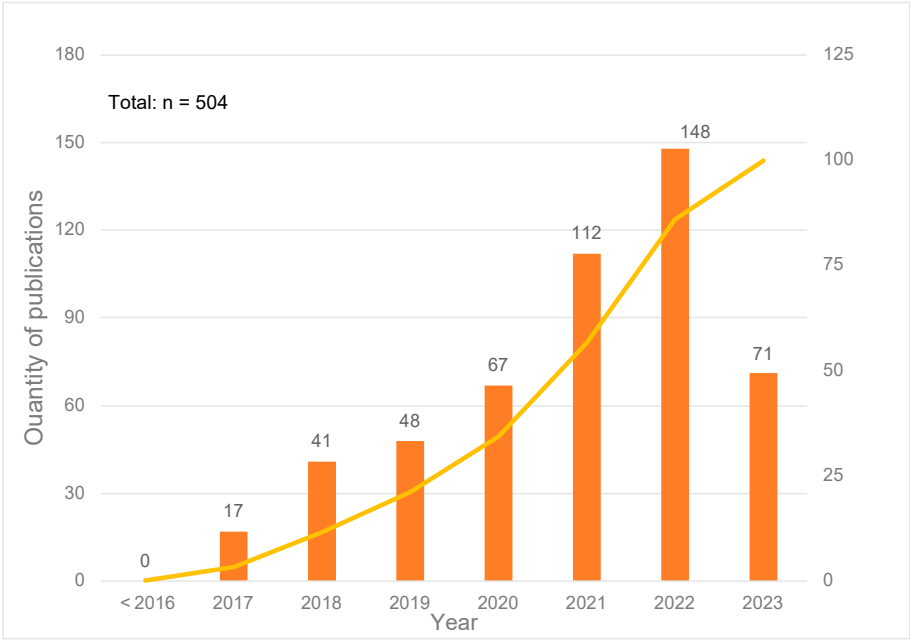


Figure 2. Number and cumulative percentage of publications from ≤2016 to 2023 (own illustration).

Regarding the type of publications, most of them are articles in journals (n = 497). Of these articles, 47 are literature reviews. However, none of the review articles answers the RQs of this LR. Even though they deal with digitalisation and sustainability, they focus on other subjects such as the circular economy, green processes, supply chains or current trends and perspectives in digitalisation and sustainability [82–84]. In contrast, only six are proceeding papers and one is a book chapter (Figure 3).

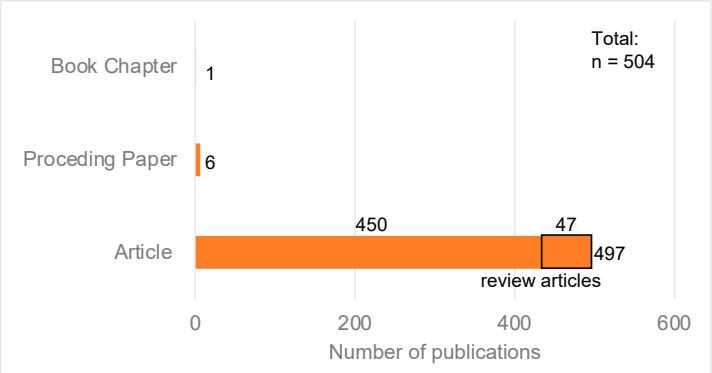


Figure 3. Classification of the publications (n = 504) by publication type (own illustration).

Analysing the publications according to the scientific journal categories, a broader range of science categories are covered, but there is one category that stands out: almost half of the papers are published in engineering journals (48%), followed by computer science (25%), applied sciences (12%), environmental sciences (8%), miscellaneous (3%), management sciences (2%) and natural sciences (1%) (Figure 4).

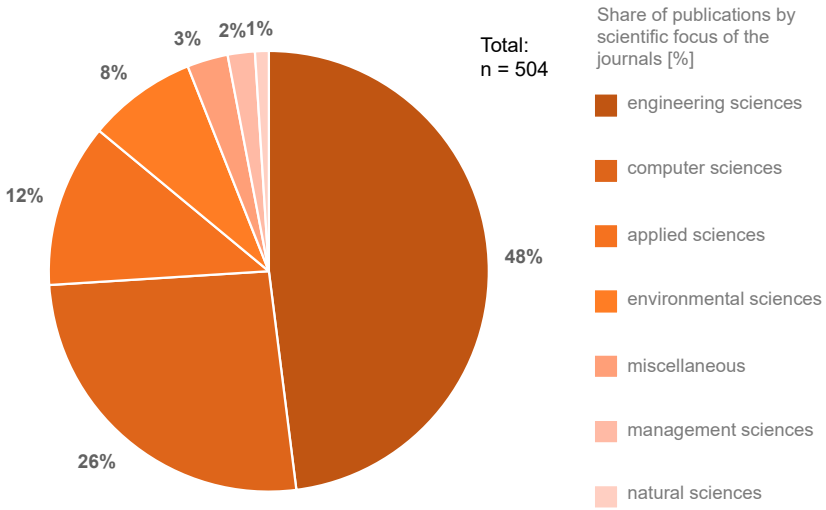


Figure 4. Analysis of publications (n = 504) by journal categories (own illustration).

Looking at the journals in which 10 or more than 10 publications have appeared, these publications are published in journals that deal with production systems, manufacturing, sustainability and clean production. The journals with the most publications are "International Journal of Production Research" (n = 34), "Applied Sciences-Basel" (n = 29), "International Journal of Advanced Manufacturing Technology" (n = 26), and "Journal of Manufacturing Systems" (n = 23). These are strongly related to production and manufacturing topics. This is followed by two journals that belong to the "environmental science" category. Namely, these are the "Journal of Cleaner Production" (n = 22) and "Sustainability" (n = 21). Then, four journals dealing with robotics and manufacturing (Robotics and Computer-Integrated Manufacturing), computers and manufacturing (International Journal of Computer Integrated Manufacturing, Computers in Industry, Journal of

Intelligent Manufacturing)and an open-access platform (IEEE ACCESS) are included in this ranking. In total, these nine journals account for 222 of 504 publications (Figure 5).

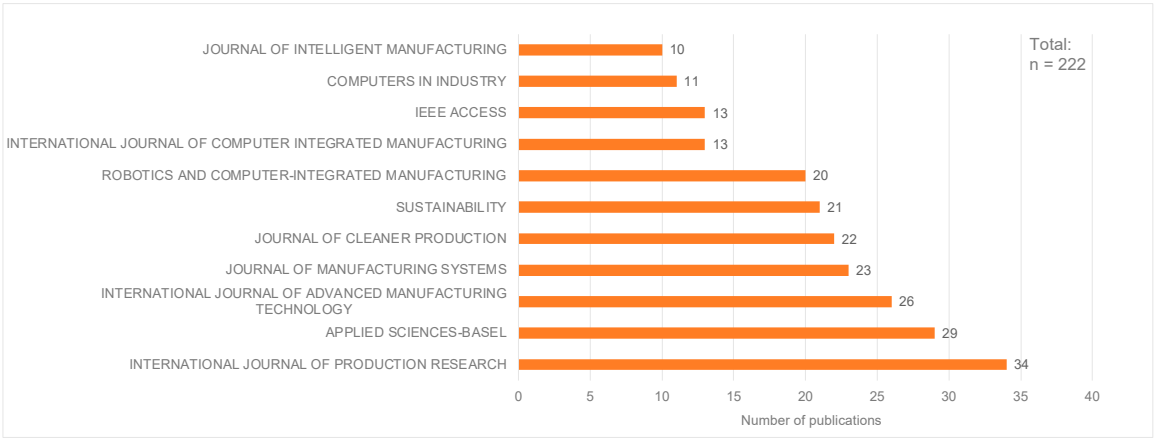


Figure 5. Analysis of publications by journal, with 10 or more publications (own illustration).

4.1.3. Keyword Analysis

Analysing the keywords in the publications shows that most of them are related to the field of engineering, in particular manufacturing and production (Figure 6). The most frequently used keywords focus on digitalisation and manufacturing: Industry 4.0, smart manufacturing, Internet of things, manufacturing systems, production facilities, Big Data, data analytics, artificial intelligence, cloud computing, machine learning and simulation. However, keywords with a lower frequency are also filtered. These keywords are related to economic efficiency in manufacturing, such as optimisation, scheduling and monitoring, or to environmental efficiency, such as energy efficiency and sustainability. Other keywords mentioned in the publications are, for example, collaboration, real-time systems, condition monitoring and reinforcement. From 2023 onwards, the keywords Industry 5.0 and AI appear sporadically.

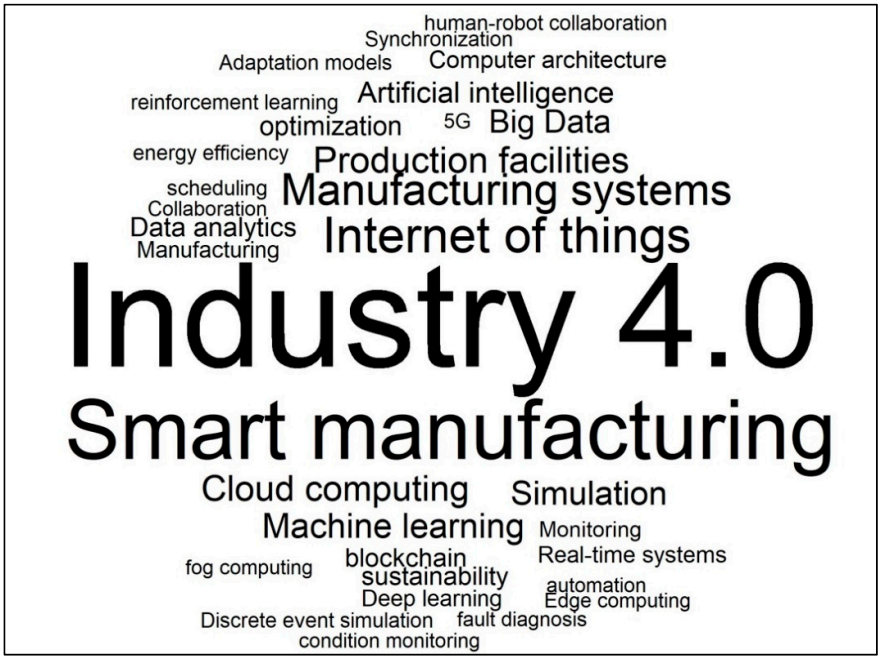


Figure 6. Analysis of keywords in publications (n = 504), sorted by frequency of mention: the larger the words, the more frequently they are mentioned (own illustration).

4.1.4. Publications per Country and Organisations

The countries and universities (institutes) of publications are also of interest. Almost 90% of publications come from European (n = 226) and Asian regions (n = 220), whereby the country of the first author or the country, if only one is named, is assumed (Figure 7). North America counts for 35 and South America for 11 publications, while Australia published eight and Africa four papers. Analysing the publications by the 10 leading countries, China leads the way with 157 publications, followed by Germany (n = 46), Italy (n = 34), the USA (n = 26), Sweden, Spain, Great Britain, South Korea, India and Taiwan. The last six mentioned all have between 12 and 18 publications (Figure 8a). These top ten countries account for more than 70% of the publications (363 of 504 publications). In total, the 504 publications come from 51 countries.

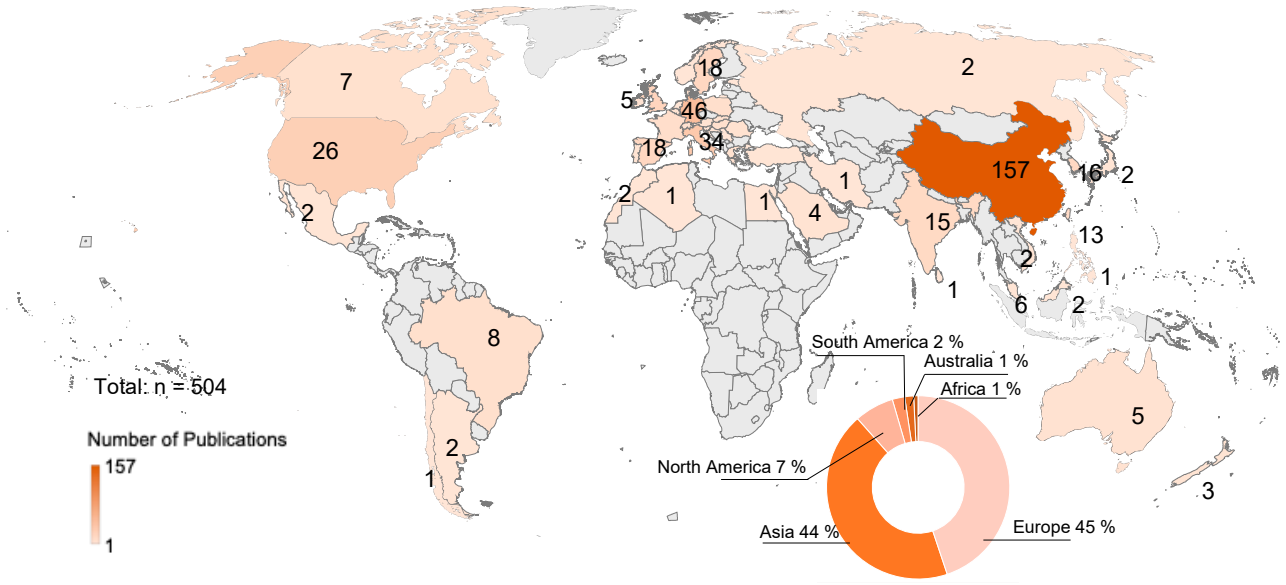


Figure 7. Analysis of publications (n = 504) by countries (own illustration).

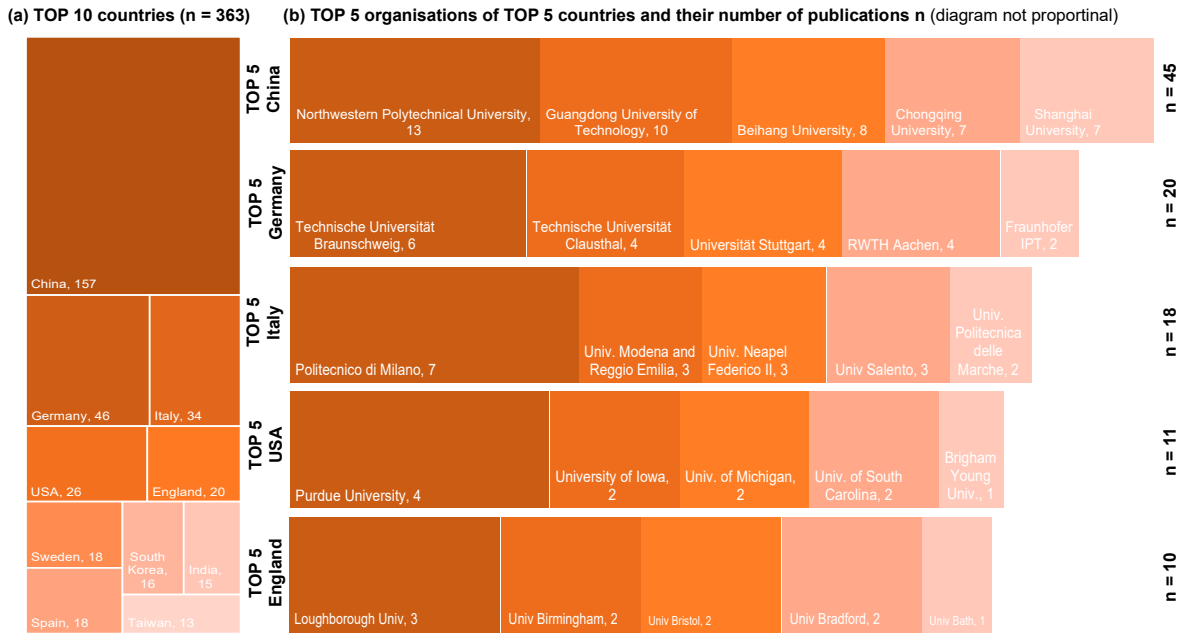


Figure 8. Analysis of (**a**) top ten countries and (**b**) top five countries by top five organisations, based on the number of publications (own illustration).

Counting the top five organisations by the five countries with the most publications (China, Germany, Italy, USA and England), some countries such as China and Italy have organisations that account for more publications in the respective country, while Germany, the USA and England have a more or less balanced involvement of the country's top five publishing organisations (Figure 8).

Analysing the world's leading organisations and ranking them by number of publications, these organisations come from China, Italy and Germany. The leading organisation by number of publications is the Chinese Northwestern Polytechnical University (n = 13), followed by the Guangdong University of Technology (n = 10) and the Politecnico di Milano (n = 7). The other organisations are also from China and have seven or eight publications each, with the exception of Technische Universität Braunschweig, which comes from Germany. The latter also has six publications in this subject field.

4.1.5. Characterisation by Subject Fields

In the next step, the evaluation, the 504 publications are semi-qualitatively analysed by reading the abstract. As a result, the publications are assigned to the two categories "economic issues" and "environmental issues" and their sub-criteria (Figure 9). The category "economic issues" is divided into the sub-criteria support of investment decisions, cost–benefit analysis, efficiency, and optimisation. Meanwhile, the category "environmental issues" is split into environmental consequences, sustainability, LCA, life cycle perspective and energy efficiency.

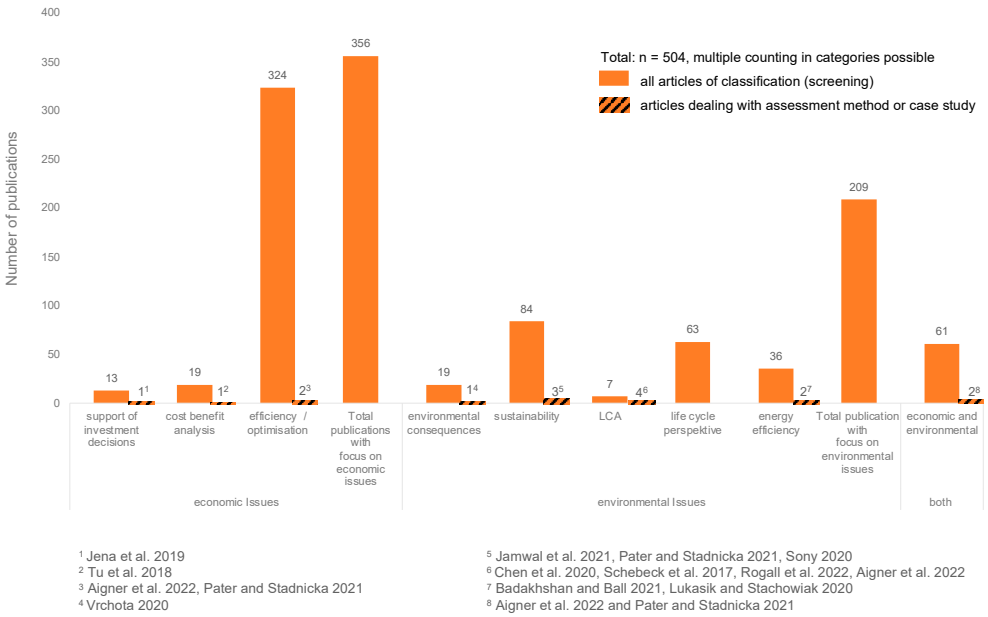


Figure 9. Analysis and results of 504 publications by content (own illustration). [1] [65], [2] [64], [3] [73,76], [4] [70], [5] [69,73,74], [6] [12,66,75,76], [7] [67,71], [8] [73,76].

A total of 356 publications can be assigned to the category "economic issues" and 209 publications deal with "environmental issues". Almost 61 publications can be assigned to both categories. These papers address economic and environmental subjects in their research. However, the economic aspects of digitalisation technologies in manufacturing systems are quantitatively more predominant than the environmental ones. The environmental aspects have a high level of novelty and diversity in the subjects. The aspects vary from overarching topics such as sustainability and environmental consequences of digitalisation technologies to specific topics such as LCA and consideration of life cycle phases. While the LCA topic looks at the methodology, the topic of the life cycle perspective considers environmental aspects of the different life cycle phases of digitalisation technologies. Most of the economic publications within the mentioned sub-criteria deal

with production efficiency, improvements and optimisation of processes or efficiency, and optimisation of production machines. In almost all of these publications, cost reduction is cited as an advantage of digitalisation technologies.

4.2. Qualitative Results

4.2.1. Content Analysis

Based on the quantitative analysis of the 504 publications and an accompanying snowball search of cross-references, 18 publications are identified that are subjected to an economic and/or environmental assessment of digitalisation technologies such as I4.0, DTs or CPSs. A full-text screening of these 18 papers indicates that 6 publications deal with an economic and 14 publications with an environmental assessment [12,61–76,82] (Table 4). Two of these publications are counted twice as they consider both aspects [73,76].

Table 4. Analysis of the literature based on selected assessment criteria (own illustration).

Authors	Subject			Assessment Focus		Link to the Topic of Holistic Assessment of Digitalisation Technologies
	Specific Methodology of Assessment	Literature Research	Case Study	Environmental Assessment	Economic Assessment	
Burggräf et al., 2018 * [62]	X		X		X	Burggräf et al., 2018 present a calculation methodology for the economic assessment of CPS based on established cost accounting models.
Tu et al., 2018 [64]	X		X		X	Tu et al., 2018 assess an IoT/CPS test environment using a classical cost-benefit analysis.
Jena et al., 2019 [65]			X		X	Jena et al., 2019 discuss the need to calculate an ecological return on investment or amortisation period.
Bamunuarachchi et al., 2021 * [72]	X		X		X	Bamunuarachchi et al., 2021 develop a comprehensive cost model for the evaluation of I 4.0 applications in the development phase of digitalisation technologies (cost-efficient development).
Schebeck et al., 2017 [12]	X		X	X		A methodological approach for the environmental assessment of digitalisation technologies is proposed by Schebeck et al., 2017.
Bonilla et al., 2018 * [61]		X		X		Bonilla et al., 2018 recommend the development of a procedure for the quantitative environmental assessment of digitalisation systems.
Thiede 2018 * [63]	X		X	X		Thiede 2018 presents a methodology for the environmental assessment of CPS and demonstrates the need to integrate an economic assessment.
Vrchota 2020 [70]		X		X		Vrchota 2020 indirectly refers to the need for a holistic assessment when using digitalisation systems.

Table 4. *Cont.*

Authors	Subject			Assessment Focus		Link to the Topic of Holistic Assessment of Digitalisation Technologies
	Specific Methodology of Assessment	Literature Research	Case Study	Environmental Assessment	Economic Assessment	
Chen et al., 2020 [66]	X	X		X		Chen et al., 2020 discuss the general effects of digitalisation on environmental sustainability and examine the question of whether these are positive or negative.
da Silva et al., 2020 * [82]		X		X		Da Silva et al., 2020 describe the problem that potential (energy) savings through I 4.0 technology are limited due to the availability of critical raw materials required for its production.
Lukasik and Stachowiak 2020 [67]		X		X		Lukasik and Stachowiak 2020 not only point out the advantages, but also the problem of ecological sustainability.
Oláh et al., 2020 * [68]	X	X		X		Oláh et al., 2020 carry out a Literature review and a scenario-based analysis (qualitative assessment criteria of energy and material consumption).
Sony 2020 [69]		X		X		Sony 2020 indirectly points to the need for an economic assessment (profitability calculation) of digitalisation systems and notes that there is a need for further research into the environmental impact of digitalisation systems.
Badakhshan and Ball 2021 [71]		X		X		Badakhshan and Ball 2021 discuss and recommend analysing not only the advantages of DT but also the problems that arise from its use.
Jamwal et al., 2021 [74]		X		X		Jamwal et al., 2021 refer to the problem of costs and benefits when using digitalisation technology.
Rogall et al., 2022 [75]	X		X	X		Rogall et al., 2022 extend the approach of Thiede 2018 with a method for identifying environmentally relevant influencing parameters of CPS.
Aigner et al., 2022 [76]	X		X	X	X	Aigner et al., 2022 analyses the environmental and economic profitability of retrofitted I 4.0 solutions (retrofit measures, CPPS) by comparing production with/without digitalisation technology of a reference component (or various retrofit scenarios). This deepens the approaches of Thiede 2018 and Rogal et al., 2022.
Pater and Stadnicka 2021 [73]		X		X	X	Pater and Stadnicka 2021 discuss the need for further research to evaluate the use of DT.
	9	**10**	**8**	**14**	**6**	

* identified in a snowball research.

In nine of the papers examined, only the recommendation is made to consider the advantages and disadvantages of digitalisation technologies [61,65,67,69–71,73,74,82]. The

focus here is on recommendations for carrying out an environmental impact assessment. With one exception, the recommendations are exclusively derived from literature reviews on the subject [65]. In addition to this, there are nine papers that discuss the economic and/or environmental assessment methods for digitalisation technologies by applying or presenting methods or carrying out calculations [12,62–64,66,68,72,75,76]. In most of these publications, namely seven out of nine, the methods are evaluated in practice by conducting case studies on environmentally relevant issues [12,62–64,72,75,76]. And only one of these publications, which is a case study, addresses both environmental and economic issues [76]. These nine publications qualify for further analysis as they deal with assessment methods.

4.2.2. Analysis of the Assessment Methods

The nine publications that focus on assessment methods are analysed with regard to defined criteria. These criteria take into account the applied digitalisation technologies such as CP(P)Ss, IoT or DTs, the economic or environmental assessment method, the data sources used in the assessment, the decision criteria and impact categories applied and whether a use case is considered (Table 5). The other nine publications that deal with economic and/or environmental assessment but only provide a literature review without referring to an assessment method or case study were excluded from this analysis [12,62–64,66,68,72,75,76].

In order to illustrate the methodological and chronological development of assessment methods, the publications are analysed in a specific order, irrespective of their alphabetical order in Table 5. Firstly, all publications that deal exclusively with an economic assessment methodology are considered [62,64,72]. Then, the publications that propose an environmental assessment method are taken into account [12,63,66,68,75]. And finally, the publications that discuss both economic and environmental assessment methods are analysed [76]. Within this categorisation, an ascending chronological order is followed.

Burggräf et al., 2018, Tu et al., 2018 and Bamunuarachchi et al., 2021 [62,64,72] applied economic methods for the assessment of digitalisation technologies. Burggräf et al., 2018 propose the development of a return-on-investment model (ROI model). For this purpose, the costs and benefits of digitalisation technologies are considered and a comprehensive catalogue for assessing the costs and benefits is proposed. Not only linear but also non-linear models are taken into account by considering dynamic dependencies [62].

Tu et al., 2018 present an architecture framework for CPSs and IoT as the main purpose of their work. The framework is presented as a concept and mapped in a case study that is validated in the manufacturing industry and in a laboratory demonstrator. To evaluate the framework in the context of the case study, a cost–benefit analysis is conducted. For this, the operating time saved during the use of digitalisation technology is evaluated against the acquisition costs of the technology. The calculated net savings serve as a comparative value in various utilisation scenarios and as a decision-making support as to whether an investment is worthwhile. The data are collected from measurements in the case study. The study concludes that digitalisation technology is already profitable in the specific environment of the case study. In addition to the savings in operating time, it is emphasised that other quantifiable and non-quantifiable factors can also increase the benefits [64].

Bamunuarachchi et al., 2021 developed models for cost calculation, which are primarily from the software sector and focus on the programming cost of the software. They recognised this as a research gap and developed a cost model that includes the costs of identifying and integrating machine data as well as developing and testing the application. For each of these cost types, they developed an equation to cover the relevant cost factors, e.g., required input data, and machine settings. In a case study, they apply their cost model to a milk pick-up process and use the steps of cost identification, degree of adaptability and degree of sustainability. The calculated costs are the basis for decision-making on whether the investment in digitalisation technology makes economic sense [72].

Table 5. Analysis results of the methods based on the defined evaluation criteria (own illustration).

Analysis Criteria	Digitalisation Criteria	Economic Criteria	Environmental Criteria	Used Data Sources	Use Case (Case Study)	Decision Criteria	Impact Category
Description	Which digitalisation technology is considered (CPS/CPPS/IoT/DT/other)?	Which economic assessment takes place and which criteria are evaluated?	Which ecologic assessment takes place and which criteria are evaluated?	Which sources are used to obtain the data for the assessment?	Which use case is applied?	Which criteria are used for evaluation or to support decisions?	Which evaluation basis for the selected methods is used?
Burggräf et al., 2018 [62]	CPS	return on investment (ROI) cost-model	-----	directly from the case study	production environment (focus material flow)	ROI-Model	costs
Tu et al., 2018 [64]	CPS/IoT	cost-benefit-analysis	-----	measured data and data form the case studies	experimental use case (demonstrator)	ratio of benefit to cost	costs
Bamunuarachchi et al., 2021 [72]	I 4.0 applications	cost model	-----	directly from the case study	logistic process	defined cost factors	costs
Schebek et al., 2017 [12]	I 4.0-Technology	-----	LCA method	directly form practice (case studies)	different I 4.0 scenarios (real production scenarios)	ratio of benefit to effort	energy resources, ecosystem services (CO_2), raw materials
Thiede 2018 [63]	CPPS	-----	LCA method	data form different studies to this theme and LCA-Databases (like Eco invent)	different production systems	quotient of output to energy and resource input	global warming potential
Chen et al., 2020 [66]	digitalisation technology (I 4.0-Technology)	-----	LCA approach	literature study	-----	relationship between effort and benefit of the technologies and products	energy, resources (raw materials)
Olah et al., 2020 [68]	I 4.0-Technology (focus CPS)	-----	scenario-based analysis (qualitative assessment)	literature study	-----	resource consumption and environmental impact	material use, energy use, waste, GHG-emissions
Rogall et al., 2022 [75]	CPPS	-----	LCA method	LCA database and from measured data in the case study	prototype process (3D-Prinitng)	energy and material consumption	global warming potential

Table 5. *Cont.*

Analysis Criteria	Digitalisation Criteria	Economic Criteria	Environmental Criteria	Used Data Sources	Use Case (Case Study)	Decision Criteria	Impact Category
Aigner et al., 2022 [76]	CPPS (retrofitting solutions)	calculation based on investment	LCA method	directly from the case study, from databases and other studies	machining process (metal cutting machine)	effort and benefit according to the developed method	global warming potential, cumulative energy expenditure, cumulative raw material expenditure, water consumption, land take, resource criticality

An environmental assessment is proposed by Schebek et al., 2017, who use the principles of the LCA method to calculate the environmental impact through the entire life cycle. They refer to the VDI 4800 standard and use the resource depletion potential impact category. The resource consumption of digitalisation must be amortised through savings. The case studies are based on data from savings and consumptions in the production facilities and literature. The resource consumption (expenses) for digitalisation technology is determined along the entire life cycle, from resource extraction through manufacturing and use to recycling [12]. They propose a step-by-step approach to evaluate different I4.0 scenarios with different technologies. In the first step, they define the current state of the system under consideration. Based on this, they develop a target state, find matches between these two states and calculate the changes. As a last step, they create a decision support. With their methodological framework, they provide a basic concept for a holistic assessment of digitalisation technologies. However, the approach lacks a decision criterion on the meaningfulness of an investment or the derivation of a recommendation for action.

Thiede 2018 specifies Schebek et al., 2017 [12] and develops a methodological approach for assessing the environmental impact in relation to potential savings through CPPSs. For the assessment, an LCA is applied. A production system is considered as a use case in order to carry out a comparative assessment of a manufacturing system with/without a CPPS. The comparison is based on energy or resource efficiency, which is the ratio of input to output. Specifically, it is the ratio of output to input of energy or raw materials. In addition, the environmental impact is calculated for both and serves as the basis for calculating an environmental break-even. The considered impact category includes the Global Warming Potential and considers this along different periods of use with different potential for improvement. This methodology allows the overall environmental impact of the digitalisation technology to be estimated. However, recommendations for implementation and the possibilities to consider different scenarios are missing [63].

In a literature review, Chen et al., 2020 examine the environmental impacts of digitalisation in manufacturing and whether digitalisation technologies can support the reduction in environmental impacts. In total, they identify 93 publications discussing the positive and negative impacts of digitalisation technologies in manufacturing. Their two main findings are that (1) the use of digitalisation technologies in manufacturing processes reduces the environmental impact by increasing resource and information efficiency throughout the product life cycle and that (2) the manufacturing, use and disposal of the digitalisation technology (hardware) cause an environmental burden. However, most of their reviewed literature focuses on the digitalisation of the product life cycle, while less attention is paid to the assessment of digitalisation technology hardware. For decision-making, they outline a combined LCA approach for the environmental assessment of the product and technology life cycle. Notwithstanding this proposal, they note that there is a lack of research on the holistic environmental impacts of digitalisation technologies [66].

In another literature review by Olah et al., 2020, the effects of digitalisation technologies in manufacturing systems on environmental sustainability are analysed in order to determine the positive and negative impacts of I4.0 on the manufacturing sector and its primary technology. In the next step, they describe four scenarios of environmental sustainability and assess the benefits of I4.0 qualitatively based on the results of the literature review and a cross-study. This scenario-based analysis of digitalisation technologies in manufacturing systems is intended to serve companies and other stakeholders as an environmental guide for the introduction of new digitalisation technologies. As the authors noted, there is a lack of quantitative assessment of the environmental impact of digitalisation technologies in manufacturing systems in their research. They therefore recommend methods such as material intensity, LCA and energy calculations to quantitatively assess the impact of digitalisation technologies [68].

Rogall et al., 2022 take the approach of Thiede 2018 [63] and develop it further with regard to a methodology for identifying the environmentally relevant main influencing parameters of CPPSs. Specifically, an approach is presented that serves to enable systematic,

sustainability-oriented development of CPPSs by applying a five-step approach: (1) system definition to identify relevant variables, (2) system understanding to describe relationships between variables, (3) derivation of use case to define specific objectives and stakeholders, (4) CPPS setup to determine necessary data streams and IT elements, and (5) environmental assessment to evaluate potential savings and efforts for setup and operations for digitalisation technologies. In the first and second steps, all variables relevant to the development of a sustainable CPPS that influence sustainability are determined and examined with regard to mutual relationships and interactions. As a result, the identified variables are divided according to their relevance, and a systemic understanding of the CPPS to be developed is formed. In the further steps, they connect the already selected variables with specific technologies of the production environment, create an application scenario for the CPPS and design it with regard to the necessary hardware and software. In the fifth step, the environmental assessment, the potential environmental savings and efforts are calculated for the setup and operation of the CPPS. The setup includes the environmental backpack of digitalisation technologies. The environmental assessment is carried out by using the LCA method and is based on the impact category Global Warming Potential (CO_2 equivalents (kg CO_2_eq)). The environmental footprint of the individual CPPS components (backpack) is then used to derive the necessary savings in energy and material consumption of the operation (payback) to achieve an environmental break-even. Feasibility diagrams that show the environmental footprint versus the environmental savings of CPPS components are proposed to support decision-making in the digitalisation of production. As a result, the minimum environmental benefits of a CPPS component can be read off [75].

Aigner et al., 2022 deepen the approach by Thiede 2018 and Rogall et al., 2022 [75] and apply it to the retrofitting of manufacturing systems with digitalisation technologies. They present a scheme that includes the following steps: (1) definition of the scope of the investigation, followed by (2) the environmental and economic assessment of the retrofitting and (3) a final synthesis of the quantitative results (step 2) into a qualitative assessment to support decision-making. The assessment of the retrofitting is set in reference to the status quo without digitalisation technologies and extended by a sensitivity analysis. As a case study, they use a grinding machine including periphery to evaluate the developed scheme and examine the environmental and economic profitability of retrofitted I4.0 solutions (retrofit measures; CPPS) by comparing production with and without digitalisation technology for a reference component (or different retrofit scenarios). To this end, they define a framework that contains the definition of a system boundary and a functional unit as a basis for comparison [76]. In addition to the actual consideration of the production machines, they also include the peripheral devices required to operate the systems. However, the scope of the production machine and the periphery is limited to the input and output flows of the process. For the environmental assessment of the CPPS, an LCA is carried out that uses the impact categories Global Warming Potential (GWP), Cumulative Energy Demand (CED), Cumulative Raw Material Demand (KRA), water consumption and land use. The economic assessment is based on the investment and the variable costs including the disposal. It is similar to a total cost of ownership calculation [76].

5. Discussion

5.1. Importance of Digitalisation Technologies and Sustainability in Research

When looking at the LR and its quantitative analysis, it is noticeable that digitalisation technologies in manufacturing systems in connection with sustainability have arrived in research (RQ 1). With 504 publications, this is not a marginal subject of research, especially when one considers that the keywords were used to limit the scope to digitalisation technologies in manufacturing and that individual technologies such as additive manufacturing were excluded. However, it is a subject that emerged in the last six years and received increased research attention in 2021 and 2022 in particular (Figure 2). More than half of the publications were published in this period. The importance of the subject can also be derived from the number of reviews: 10% of these (n = 47) are review articles that deal

with the current state of research and the research gaps in this subject field. The subject is particularly relevant in Europe and Asia, as most of the publications originate from these regions (Figure 7). China, in particular, dominates the number of publications, followed by European countries such as Germany, Italy and Sweden, but also the USA (Figure 8). In these countries, technical universities and institutes are publishing on this topic. This is also reflected in the publication journals. Most journals are dedicated to production technology or manufacturing (48%), computer technology (25%), applied sciences (12%) and environmental sciences (8%) (Figure 4). Among the top journals are two that deal with environment and sustainability, which emphasise the link between the subjects of manufacturing and sustainability as a current research area (Figure 5). The keyword analysis confirms this further and shows a connection between the highlighted digitalisation technologies and various optimisation methods such as data analytics, machine learning, reinforcement learning, simulation and blockchain on one hand and efficiency such as (energy) efficiency, (condition) monitoring, and fault diagnosis on the other hand (Figure 6).

5.2. Research Subjects in the Field of Digitalisation Technologies and Sustainability

The analysis has shown that the focus in the field of digitalisation and sustainability is on economic topics. The topics of efficiency and optimisation are dealt with here. In contrast, environmental topics are discussed to a lesser extent in the context of digitalisation. In terms of environmental topics, the focus is on the keywords sustainability and life cycle perspective (Figure 9). These subject fields share a common focus on sustainability and digitalisation from a quantitative perspective. Qualitative methods for evaluating technologies or their application scenarios are less commonly used, for example, to support investment decisions, cost–benefit analysis or LCA. In general, the benefits of digitalisation technology, such as efficiency, sustainability and energy efficiency, are often emphasised, while the disadvantages (environmental impact) are not taken into account. It is noteworthy that the disadvantages are mainly mentioned in the economic area. A closer look at the selected publications that specifically address the sustainability assessment of digitalisation technologies shows that they use quantitative assessment methods. The papers focus on the LCA method for environmental publications and cost–benefit analysis, including ROI models, for economic publications [12,64–66,75,76]. The papers analysed deal more with specific content such as energy efficiency, support of investment decisions or environmental impact than with general subject areas such as efficiency and optimisation or sustainability. Compared to general publications, this trend is noticeable.

This is confirmed when looking at literature analyses carried out by other authors. For example, Chen et al., 2020 found that there are only a few papers that objectively consider the advantages and disadvantages of the digitalisation of manufacturing. In most cases, the advantages outweigh the disadvantages. When negative effects are considered, they are often very generalised or focus on specific technologies. There is no overarching view [66]. Olah et al., 2020 come to a similar conclusion in their literature review and state that there is no clear consensus on the long-term impact of digitalisation technologies on the environment. They see a need for research [68]. Bonilla et al., 2018 confirm the assessment by Chen et al., 2020 [66] that the effects are predominantly positive [61]. Badakhshan and Ball (2021) carry out research specifically on a digital twin and also conclude that there is a lack of studies that deal with sustainability challenges [71]. Sony (2020) confirms this with his research, and notes that although there is a lot of literature on the subject, there are only a few studies that summarise the advantages and disadvantages of digitalisation technology in terms of sustainability. He cites the advantages in terms of increased efficiency in production and in environmental issues. This is consistent with the results of this review [69].

5.3. Sustainability Assessment of Digitalisation Technologies in Research

From a sustainability perspective, it is essential that the advantages of digitalisation technologies outweigh the disadvantages. Or, to put it another way, the efforts made

in favour of these technologies in the manufacturing systems must pay off in terms of economic, environmental and social requirements. In this context, Schebek et al., 2017 [12] point out that although the use of digitalisation technologies in production can be expected to result in potential reductions, the technologies themselves also consume resources. According to that, consumption occurs during the production of digitalisation components and their operation. Additionally, da Silva et al., 2020 [82] describe the problem that potential (energy) savings through I4.0 technology are limited due to the availability of critical raw materials required for its production. Olah et al., 2020 [68] argue in the same direction: I4.0 in manufacturing systems stands for efficiency increase and operational optimisation, but other dimensions such as the resource consumption or environmental impact of these technologies are not considered. Or they can even lead to negative effects. From an economic perspective, Jamwal et al., 2021 [74] emphasise the cost–benefit balance when applying digitalisation technologies. With regard to that, Burggräf et al., 2018 [62] address the socio-economic dimension of sustainability. They raise the fact that digitalisation technology poses challenges for small- and medium-sized enterprises in terms of costs and expertise. Badakhshan and Ball 2021 [71] argue along the same lines and recommend analysing not only the benefits of digitalisation technologies but also the problems that arise from them.

On this basis, it is assumed that there is a need for further research into the sustainability assessment of digitalisation technologies in manufacturing systems. The focus of this assessment should be on the economic and environmental assessment, while the socio-economic aspects addressed by Burggräf et al., 2018 [62] and Badakhshan and Ball 2021 [71] ask for a maturity model to assess the readiness for the adoption of digitalisation technologies in manufacturing systems. Maturity models for digitalisation technologies are attracting widespread attention in research. For example, Hein-Pensel et al., 2023 found 24 maturity models for the adoption of I4.0 [83]. Referring back to the sustainability assessment, Pater and Stadnicka 2021 [73], Sony 2020 [69] and Vrchota 2020 [70] also conclude from their literature reviews that digitalisation technologies in manufacturing require a holistic sustainability assessment. The latter must focus on an economic and environmental assessment (RQ 3). This LR has identified nine assessment methods, of which three deal with an economic, five with an environmental and one with an economic and environmental assessment method (Table 4). Using the research agenda of Machado et al., 2020, which classifies research efforts on sustainability requirements for I4.0 into the areas of business model, production, supply chain, product and policy development, the research subject of economic and environmental assessments of digitalisation technologies in manufacturing systems must be added in the area of production [84].

5.4. Approaches for the Economic and Environmental Assessment of Digitalisation Technologies

In terms of economic and environmental sustainability, the LR identifies three dimensions of assessment methods for digitalisation technologies in manufacturing systems: nine publications deal with an economic (n = 3), environmental (n = 5) or both economic and environmental assessment methods (n = 1). These assessment methods can be further characterised as to whether they are qualitative or quantitative methods or whether they apply more general considerations (Figure 10).

The economic assessment methods all deal with quantitative methods that are familiar with cost accounting or business case calculations [62,64,72]. The method of cost–benefit-analysis applied by Tu et al., 2018 [64] and Bamunuarachchi et al., 2021 [72] compare the investment costs with the potential cost savings of the digitalisation technologies in manufacturing systems, but the authors do not take into account operating or disposal costs. Instead of cost–benefit analysis, Burggräf et al., 2018 [62] calculate the return on investment (ROI) that also excludes the costs of operating and disposing of digitalisation technologies. In both the cost–benefit analysis and the ROI, the authors do not take into account the timing of costs and savings. Therefore, the application of the familiar quantitative economic

method lacks a life cycle approach and a dynamic calculation method to make a holistic assessment of digitalisation technologies in manufacturing systems.

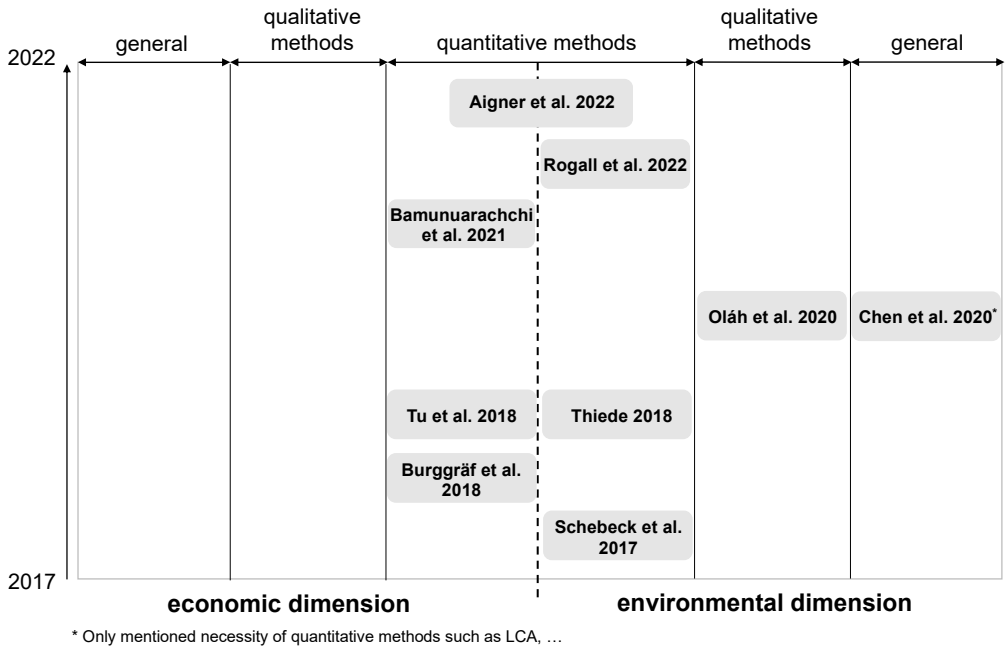


Figure 10. Classification of economic and environmental assessment methods for digitalisation technologies in manufacturing systems (own illustration) [12,62–64,66,68,72,75,76].

In addition to the economic methods, the environmental assessment methods are divided into qualitative and quantitative ones [12,63,75,76]. Based on different scenarios, Olah et al., 2020 [68] assess the contribution of digitalisation qualitatively and provide guidance for the adoption of these technologies. This is comparable to the literature review by Bonilla et al., 2018 [61], which assesses digitalisation technologies qualitatively based on the results of the review. However, this qualitative method cannot be used to assess specific digitalisation technologies in manufacturing systems. Consequently, they recommend quantitatively assessing digitalisation technologies and propose methods such as material intensity, LCA and Cumulative Energy Demand. In contrast to that, Schebek et al., 2017 [12], Thiede 2018 [63] and Rogall et al., 2022 [75] apply a quantitative method. They all refer to LCA and its principles. They all propose a comparative assessment based on the LCA method and use the calculation of an environmental break-even point (eBEP). The eBEP was first introduced by Fleischer 1993 [53]. Schebek et al., 2017 [12], Thiede 2018 [63] and Rogall et al., 2022 [75] use different impact categories in life cycle impact assessments and consider different life cycles for their assessments. Additionally, the methodological procedure of the assessment differs between them. Further, Schebek et al., 2017 [12] introduce the raw material criticality assessment as a supplement to LCA. The LCA method is also proposed by Chen et al., 2020 [66]. They propose an LCA of the technology and product life cycle. Aigner et al., 2022 [75] extend these methods and include an economic assessment. Thus, they form a first approach that holistically assesses digitalisation technologies in manufacturing systems. Instead of a cost–benefit analysis or an ROI assessment, Aigner et al., 2022 [75] came up with a method that refers to the method of total cost of ownership (TCO). The LCA method seems to be crystallising as an environmental method, while the methodological procedure lacks a consistent methodological procedure, which is essential for transferring it into practice (RQ 4).

The reflection of the assessment methods with regard to holistic assessment criteria makes it possible to reflect the current state of research (Figure 11). It can be seen that only a small proportion of the publications analysed (n = 9) meet these criteria. A criterion is a consistent methodological procedure that is presented as a step-by-step guide by three

authors [12,72,76]. However, these procedures only describe the implementation of the studies in the publications. In practice, these can be used to a limited extent as the boundary conditions for investment decisions and manufacturing facilities are not taken into account in the methodological procedure. Further research is needed to define the parameters and conditions of manufacturing systems that are relevant for the assessment, particularly with regard to a temporal system boundary. This is necessary, for example, to assess economic and environmental savings, especially when digitalisation technologies are retrofitted.

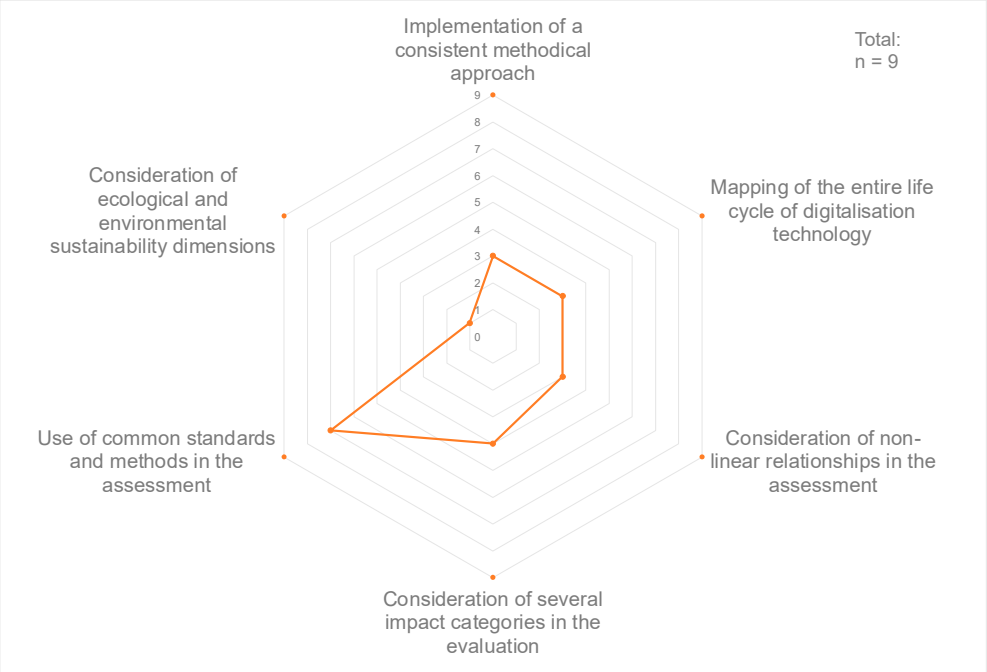


Figure 11. Cumulative fulfilment of the holistic assessment criteria of the assessment methods by publications (n = 9) (own illustration).

In terms of a holistic assessment, all phases of the life cycle of digitalisation technologies must be taken into account. This means that, in addition to the efforts and benefits of the operation, the raw material extraction and manufacturing as well as recycling must be considered. Only Schebek et al., 2017 [12], Chen et al., 2020 [66] and Aigner et al., 2022 [75] take into account the entire life cycle of digitalisation technologies. All others consider other physical system boundaries for the assessment. This often neglects the upstream or downstream chain or limits the assessment to the use phase of digitalisation technologies. The necessity of geographical, technical or temporal boundaries, as required in LCA, is not discussed and requires further research in addition to the physical system boundary.

Additionally, the physical and temporal behaviour of efforts and benefits during operation (use phase) can also have an influence. In theory, linear gradients are often assumed for the use phase, whereas in practice, non-linear gradients or changes due to initial states often exist. Thiede 2018 [63] and Rogall et al., 2022 [75] use feasibility diagrams to compare the environmental impacts of CPPSs and achieve improvements. Their non-linear gradients classify the profitability of different digitalisation technologies for decision-making. Burggräf et al., 2018 [62] present a dynamic cost assessment with non-linear curves in addition to a static one with linear cost gradients. They note that costs must be calculated dynamically, as technological progress leads to non-linear cost curves.

The economic and environmental impacts of digitalisation technologies are crucial to ensure a holistic assessment. Sustainable manufacturing must take both the economic and environmental dimensions into account [76]. As far as the assessment is concerned, the methods used must be scientifically recognised. LCA is the method of choice for environmental assessment and is well known. However, the chosen impact categories of the

LCA vary in different publications [12,66,76]. GWP and CED are often used, supplemented by raw material demand, land use or another method for assessing the criticality of raw materials. The methods for economic assessment rely on methodologies taken from cost accounting or business case calculation, but often do not take into account the entire life cycle's costs [62,64,76].

6. Conclusions

This LR aims to characterise the relevance of digitalisation technologies in manufacturing systems and sustainability in research. The focus here is on the questions of assessment and the methods for assessing the sustainability of digitalisation technologies in manufacturing, whereby only the economic and environmental dimensions of sustainability are considered. The LR provides evidence that the subject is receiving attention in research, whereby it is narrowed down from the description and assessment of the economic and environmental sustainability benefits to the assessment methods (RQ 1). From 2017 to 2023, there was an increase in publications on the topic. Even though the number of publications has recently decreased to 71, there is still research interest.

Many publications discuss the benefits of digitalisation technologies in manufacturing without addressing the efforts of producing and operating them or using an assessment method to quantify them (RQ 2). However, a few methods for assessing the sustainability of digitalisation technologies in manufacturing systems are discussed. They are becoming increasingly important. Starting in 2017, individual research focused on assessment or assessment methods to quantify the effects of digitalisation technologies in manufacturing systems. This is followed by methodological developments that elaborate on physical system boundaries, applying different impact categories and additional methods of economic and environmental assessment.

However, nine potentially relevant papers are identified that address the assessment of CPSs and DTs. The focus is on environmental aspects (n = 5). Three papers address economic aspects, and only one case considers a holistic assessment in terms of both environmental and economic aspects (RQ 3). The analysed assessment methods can be distinguished into qualitative and quantitative approaches (RQ 4). For economic assessment, exclusively quantitative methods are employed, covering a broad range from cost–benefit analysis to KPIs and investment appraisal. However, all approaches lack a holistic consideration that also incorporates the end of life of the technologies. For environmental assessment, qualitative methods such as scenario development and evaluations based on literature reviews predominate, but no specific assessment approaches can be identified. This highlights the lack of concrete assessment approaches for CPSs or DTs in industrial practice. Among the few identified quantitative approaches, a form of LCA is predominantly used. However, there is still a need for further research regarding a holistic analysis until the end of the life cycle, a specific methodological approach for industrial practice, and the inclusion of multiple impact categories. Overall, most of the analysed evaluation methods lack the integrated representation of environmental and economic criteria and the depiction of non-linear relationships. Additionally, an evaluation of the approaches in industrial practice is necessary.

Therefore, further research is identified in the field of a holistic assessment method to support sustainability in decision-making in the field of digitalisation technologies in manufacturing systems. This is to be supplemented by a standardised methodological approach that considers physical, technical, temporal and, in some cases, geographical system boundaries as well as relevant assessment parameters for the retrofitting or investments of manufacturing systems. However, this is a young research field that is still being developed further, and its sustainability assessment needs cooperation between different specialist disciplines.

As with any literature review, the LR at hand may be limited due to the keywords defined and the search engine used. Other keywords and additional search engines such as Scopus and Google Scholar can lead to different literature results. The period was set

until 2023. Furthermore, in this young field of technology and research, limitations arise due to non-uniform definitions of topics, even more so as digitalisation technologies in manufacturing systems are a multidisciplinary field of research in production and manufacturing technology, computer technology and science, as well as environmental sciences. The social aspects of sustainability and their assessment methods are not considered. This would complement a holistic sustainability assessment. However, the impact categories and assessment methods are still under development.

Author Contributions: All of the authors were involved in the development of the results and the creation of the article as follows: conceptualization: F.T. and S.K.; methodology: F.T. and S.K.; analysis: F.T., S.K. and L.R.; software: L.R.; writing: F.T. and S.K.; review and editing: F.T. and S.K. All authors have read and agreed to the published version of the manuscript.

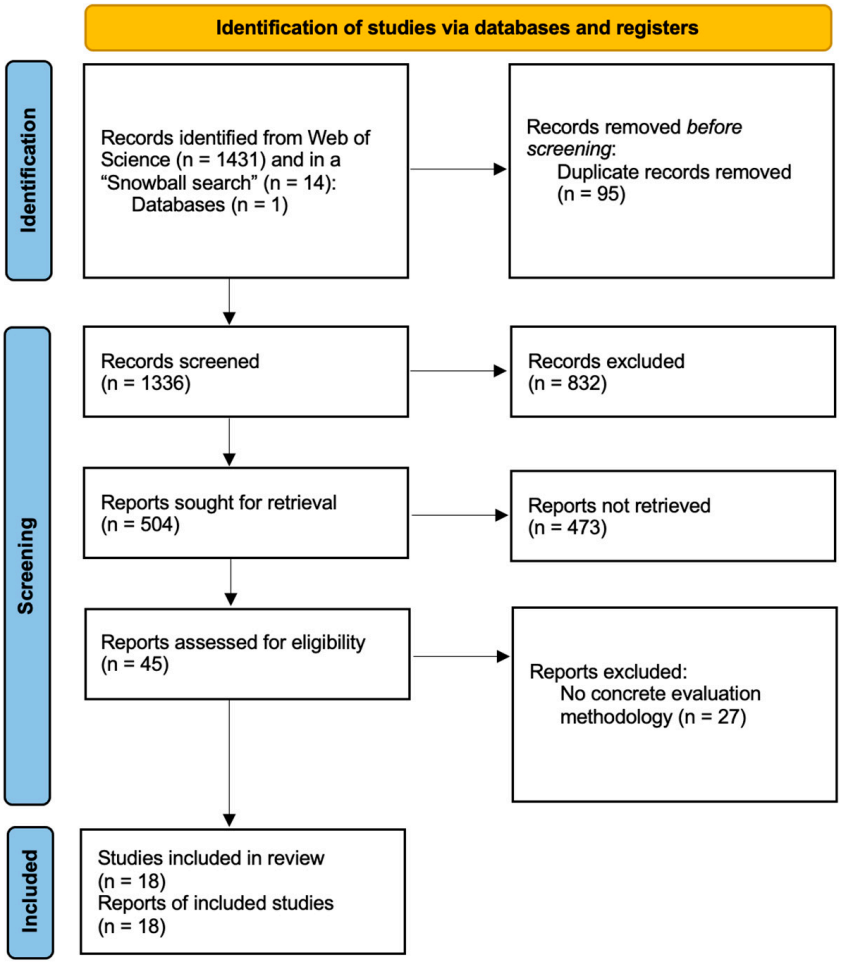
Funding: This LR was supported by funding from the Bavarian Academic Forum (BayWISS).

Data Availability Statement: The raw data for the LR were taken from the Web of Science database. The evaluation of the raw data can be accessed under the "Publikationsserver OPUS der Technischen Hochschule Rosenheim" (https://opus4.kobv.de/opus4-rosenheim/home, accessed on 1 August 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The methodology of the literature search is based on the PRISMA method. Therefore, for the sake of completeness, the PRISMA flow diagram is attached.



References

1. Sartal, A.; Bellas, R.; Mejías, A.M.; García-Collado, A. The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. *Adv. Mech. Eng.* **2020**, *12*, 1687814020925232. [CrossRef]
2. Kumar, R.; Singh, R.K.; Dwivedi, Y.K. Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges. *J. Clean. Prod.* **2020**, *275*, 124063. [CrossRef] [PubMed]
3. Biedermann, H.; Topic, M. Digitalisierung im Kontext von Nachhaltigkeit und Klimawandel—Chancen und Herausforderungen für produzierende Unternehmen. In *CSR und Klimawandel*; Sihn-Weber, A., Fischler, F., Eds.; Springer GmbH: Berlin/Heidelberg, Germany, 2019; pp. 41–62.
4. Dillinger, F.; Bernhard, O.; Kagerer, M.; Reinhart, G. Industry 4.0 implementation sequence for manufacturing companies. *Prod. Eng.* **2022**, *16*, 705–718. [CrossRef]
5. Klimant, P.; Koriath, H.-J.; Schumann, M.; Winkler, S. Investigations on digitalization for sustainable machine tools and forming technologies. *Int. J. Adv. Manuf. Technol.* **2021**, *117*, 2269–2277. [CrossRef]
6. Leiden, A.; Herrmann, C.; Thiede, S. Cyber-physical production system approach for energy and resource efficient planning and operation of plating process chains. *J. Clean. Prod.* **2020**, *280*, 125160. [CrossRef]
7. Rojek, I.; Mikołajewski, D.; Dostatni, E. Digital Twins in Product Lifecycle for Sustainability in Manufacturing and Maintenance. *Appl. Sci.* **2020**, *11*, 31. [CrossRef]
8. Tschiggerl, K.; Topic, M. Potenziale durch Industrie 4.0 zur Steigerung der Ressourceneffizienz. *WINGbusiness* **2018**, *51*, 25–28.
9. Krommes, S.; Tomaschko, F. Conceptual Framework of a Digital Twin Fostering Sustainable Manufacturing in a Brownfield Approach of Small Volume Production for SMEs. In *Manufacturing Driving Circular Economy, Proceedings of the 18th Global Conference on Sustainable Manufacturing, Berlin, Germany, 5–7 October 2022*; Kohl, H., Seliger, G., Dietrich, F., Eds.; Springer Nature: Berlin/Heidelberg, Germany, 2023.
10. Krommes, S.; Tomaschko, F. Chance für mehr Ressourceneffizienz. *Z. Wirtsch. Fabr.* **2021**, *116*, 58–63. [CrossRef]
11. Ma, S.; Zhang, Y.; Lv, J.; Yang, H.; Wu, J. Energy-cyber-physical system enabled management for energy-intensive manufacturing industries. *J. Clean. Prod.* **2019**, *226*, 892–903. [CrossRef]
12. Schebek, L.; Kannengießer, J.; Campitelli, A.; Fischer, J.; Abele, E.; Bauerdick, C.; Anderl, R.; Haag, S.; Sauer, A.; Mandel, J.; et al. Ressourceneffizienz Durch Industrie 4.0: Potenziale für KMU des Verarbeitenden Gewerbes. 2017. Available online: https://www.ipa.fraunhofer.de/de/Publikationen/studien/studie-ressourceneffizienz.html (accessed on 21 February 2024).
13. Neumeier, A.; Wolf, T.; Oesterle, S. The Manifold Fruits of Digitalization—Determining the Literal Value Behind. In Proceedings of the 13th International Conference on Wirtschaftsinformatik, St. Gallen, Switzerland, 12–15 February 2017; pp. 484–498.
14. Javaid, M.; Haleem, A.; Singh, R.P.; Sinha, A.K. Digital economy to improve the culture of industry 4.0: A study on features, implementation and challenges. *Green Technol. Sustain.* **2024**, *2*, 100083. [CrossRef]
15. Kagermann, H.; Lukas, W.; Wahlster, W. Industrie 4.0—Mit dem Internet der Dinge auf dem Weg zur 4. Industriellen Revolution. VDI Nachrichten No. 13. 2011. Available online: https://www.ingenieur.de/technik/fachbereiche/produktion/industrie-40-mit-internet-dinge-weg-4-industriellen-revolution (accessed on 21 February 2024).
16. Kagermann, H.; Anderl, R.; Gausemeier, J.; Schuh, G.; Wahlster, W. *Industrie 4.0 im Globalen Kontext*; Herbert Utz Verlag: München, Germany, 2016.
17. Hankel, M. Entwicklung von smarten Produkten. In *Industrie 4.0 Potentiale Erkennen und Umsetzen*; Schulz, T., Ed.; Vogel Business Media GmbH & Co.: Würzburg, Germany, 2017.
18. Scheer, A.-W. *Unternehmung 4.0: Vom Disruptiven Geschäftsmodell zur Automatisierung der Geschäftsprozesse*; Springer Fachmedien Wiesbaden GmbH: Wiesbaden, Germany, 2020.
19. Brecher, C.; Herfs, W.; Özdemir, D.; Obdenbusch, M.; Nittinger, J.; Wellmann, F.; Königs, M.; Krella, C.; Sittig, S. Die vernetze Werkzeugmaschine. In *Handbuch Industrie 4.0*; Reinhart, G., Ed.; Carl Hanser Verlag GmbH & Co.: Munich, Germany, 2017.
20. Niebauer, J.; Riemath, A. Wandel des klassischen Büroarbeitsplatzes. In *Industrie 4.0 Wie Cyber-Physische Systeme die Arbeitswelt Verändern*; Andelfinger, V.P., Hänisch, T., Eds.; Springer Fachmedien Wiesbaden GmbH: Wiesbaden, Germany, 2017.
21. Stock, T.; Seliger, G. Opportunities of Sustainable Manufacturing in Industry 4.0. In Proceedings of the 13th Global Conference on Sustainable Manufacturing—Decoupling Growth from Resource Use, Bihn Duong, Vietnam, 16–18 September 2015; pp. 536–541. [CrossRef]
22. Kunju, F.F.K.; Naveed, N.; Anwar, M.N.; Haq, M.I.U. Production and maintenance in industries: Impact of industry 4.0. *Ind. Robot Int. J. Robot. Res. Appl.* **2022**, *49*, 461–475. [CrossRef]
23. Suleiman, Z.; Shaikholla, S.; Dikhanbayeva, D.; Shehab, E.; Turkyilmaz, A. Industry 4.0: Clustering of concepts and characteristics. *Cogent Eng.* **2022**, *9*, 2034264. [CrossRef]
24. Ching, N.T.; Ghobakhloo, M.; Iranmanesh, M.; Maroufkhani, P.; Asadi, S. Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *J. Clean. Prod.* **2022**, *334*, 130133. [CrossRef]
25. Bauernhansl, T. Die Entwicklungsstufen der Digitalen Transformation. In *Handbuch Industrie 4.0: Band 1: Produktion*; Bauernhansl, T., Ed.; Springer: Berlin/Heidelberg, Germany, 2023; pp. 3–12.
26. Babel, W. IoT und Industrie 4.0—Zusammenhänge. In *Internet of Things und Industrie 4.0*; Babel, W., Ed.; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2023; pp. 15–20.
27. Drath, R. The digital Twin: The Evolution of a key concept of industry 4.0. *visIT* **2018**, *19*, 6–7.
28. Sauer, O. The digital twin—A key technology for Industrie 4.0. *visIT* **2018**, *19*, 8–9.

29. Ovtcharova, J.; Grethler, M. Beyond the digital twin—Making analytics come alive. *visIT* **2018**, *19*, 4–5.
30. Siepmann, D. Industrie 4.0—Struktur und Historie. In *Einführung und Umsetzung von Industrie 4.0*; Roth, A., Ed.; Springer: Berlin/Heidelberg, Germany, 2016; pp. 17–34.
31. Gill, H. From Vision to Reality: Cyber-Physical Systems. In Proceedings of the HCSS National Workshop on New Research Directions for High Confidence Transportation CPS: Automotive, Aviation, and Rail, Vienna, Australia, 18–20 November 2008.
32. Lee, E.A.; Seshia, S.A. Introduction to Embedded Systems—A Cyber-Physical Systems Approach. 2011. Available online: https://ptolemy.berkeley.edu/books/leeseshia/ (accessed on 21 February 2024).
33. Schlick, J.; Stephan, P.; Loskyll, M.; Lappe, D. Industrie 4.0 in der praktischen Anwendung. In *Industrie 4.0 in Produktion, Automatisierung und Logistik*; Bauernhansl, T., ten Hompel, M., Vogel-Heuser, B., Eds.; Springer Vieweg: Wiesbaden, Germany, 2014; pp. 57–84.
34. Sinsel, A. *Das Internet der Dinge in der Produktion*; Springer: Weingarten, Germany, 2020.
35. Atzori, L.; Iera, A.; Morabito, G. The Internet of Things: A survey. *Comput. Netw.* **2010**, *54*, 2787–2805. [CrossRef]
36. Obukhova, A.; Merzlyakova, E.; Ershova, I.; Karakulina, K. Introduction of digital technologies in the enterprise. *E3S Web Conf.* **2020**, *159*, 04004. [CrossRef]
37. Demartini, M.; Evans, S.; Tonelli, F. Digitalization Technologies for Industrial Sustainability. *Procedia Manuf.* **2019**, *33*, 264–271. [CrossRef]
38. VDI 2206. *VDI 2206 Entwicklungsmethodik für Mechatronische Systeme*; Beuth Verlag GmbH: Berlin, Germany, 2004.
39. Gausemeier, J.; Czaja, A.; Dülme, C. *Innovationspotentiale auf dem Weg zu Industrie 4.0*; Universität Paderborn, Heinz Nixdorf Institut: Paderborn, Germany, 2015.
40. Acatech. *Umsetzungsstrategie Industrie 4.0 Ergebnisbericht der Plattform Industrie 4.0*; Acatech: Munich, Germany, 2015.
41. Lu, Y. The Current Status and Developing Trends of Industry 4.0: A Review. *Inf. Syst. Front.* **2021**. [CrossRef]
42. Voegele, A.A.; Sommer, L. *Kosten—Und Wirtschaftlichkeitsrechnung für Ingenieure*; Carl Hanser Verlag: München, Germany, 2012.
43. World Commission on Environment and Development. *Our Common Future, Report of the World Commission on Environment and Development*; Oxford University Press: New York, NY, USA, 1987.
44. The United Nations. Sustainable Development: The 17 Goals. Available online: https://sdgs.un.org/goals (accessed on 18 April 2022).
45. Henriques, A.; Richardson, J. *The Triple Bottom Line: Does It All Add up?* Earthscan: London, UK, 2004.
46. Vereinte Nationen. Transformation unserer Welt: Die Agenda 2030 für nachhaltige Entwicklung. In *UN Generalversammlung Siebzigste Tagung*; Vereinte Nationen: New York, NY, USA, 2015.
47. Sendroiu, C.; Roman, A.G.; Roman, C. Increasing the practical value of accounting information in the machine building industry applying the standard—Cost method. *Metal. Int.* **2007**, *12*, 35–39.
48. Chacko, G. *Valuation: Methods and Models in Applied Corporate Finance*; Pearson Education: New York, NY, USA, 2014.
49. European Commission. Joint Research Centre Institute for Environment and Sustainability, International Reference Life Cycle Data System (ILCD). In *Handbook: General Guide for Life Cycle Assessment*; Publications Office of the European Union: Luxembourg, 2010.
50. Dillman, K.J.; Árnadóttir, Á.; Heinonen, J.; Czepkiewicz, M.; Davíðsdóttir, B. Review and Meta-Analysis of EVs: Embodied Emissions and Environmental Breakeven. *Sustainability* **2020**, *12*, 9390. [CrossRef]
51. Hesser, F.; Wohner, B.; Meints, T.; Stern, T.; Windsperger, A. Integration of LCA in R&D by applying the concept of payback period: Case study of a modified multilayer wood parquet. *Int. J. Life Cycle Assess.* **2017**, *22*, 307–316. [CrossRef]
52. Fetner, H.; Miller, S.A. Environmental payback periods of reusable alternatives to single-use plastic kitchenware products. *Int. J. Life Cycle Assess.* **2021**, *26*, 1521–1537. [CrossRef]
53. Fleischer, G. Der ökologische break-even-point für das Recycling. *Abfallwirtsch. J.* **1993**, *3*, 209–215.
54. Caiado, R.G.G.; De Freitas Dias, R.; Mattos, L.V.; Quelhas, O.L.G.; Filho, W.L. Towards sustainable development through the perspective of eco-efficiency—A systematic literature review. *J. Clean. Prod.* **2017**, *165*, 890–904. [CrossRef]
55. Kicherer, A.; Schaltegger, S.; Tschochohei, H.; Pozo, B.F. Eco-efficiency. *Int. J. Life Cycle Assess.* **2006**, *12*, 537–543. [CrossRef]
56. Lueddeckens, S. A review on the handling of discounting in eco-efficiency analysis. *Clean Technol. Environ. Policy* **2022**, *25*, 3–20. [CrossRef]
57. Deutscher Bundestag. *Abschlussbericht der Enquete-Kommission „Schutz des Menschen und der Umwelt—Ziele und Rahmenbedingungen einer Nachhaltig Zukunftsverträglichen Entwicklung" (No. Sachgebiet 1101)*; Deutscher Bundestag 13. Wahlperiode: Berlin, Germany, 1998.
58. Beier, G.; Ullrich, A.; Niehoff, S.; Reißig, M.; Habich, M. Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes—A literature review. *J. Clean. Prod.* **2020**, *259*, 120856. [CrossRef]
59. Mengist, W.; Soromessa, T.; Legese, G. Method for conducting systematic literature review and meta-analysis for environmental science research. *MethodsX* **2020**, *7*, 100777. [CrossRef]
60. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Int. J. Surg.* **2021**, *88*, 105906. [CrossRef]
61. Bonilla, S.H.; Silva, H.R.O.; Terra da Silva, M.; Gonçalves, R.F.; Sacomano, J.B. Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges. *Sustainability* **2018**, *10*, 3740. [CrossRef]

62. Burggräf, P.; Dannapfel, M.; Bertling, M.; Xu, T. Return on CPS (RoCPS): An Evaluation Model to Assess the Cost Effectiveness of Cyber-Physical Systems for Small and Medium-Sized Enterprises. In Proceedings of the PICMET '18: Technology Management for Interconnected World, Honolulu, HI, USA, 19–23 August 2018.
63. Thiede, S. Environmental Sustainability of Cyber Physical Production Systems. In Proceedings of the 25th CIRP Life Cycle Engineering (LCE) Conference, Copenhagen, Denmark, 30 April–2 May 2018.
64. Tu, M.; Lim, M.K.; Yang, M.-F. IoT-based production logistics and supply chain system—Part 2 IoT-based cyber-physical system: A framework and evaluation. *Ind. Manag. Data Syst.* **2018**, *118*, 96–125. [CrossRef]
65. Jena, C.M.; Mishra, K.S.; Moharana, S.H. Application of Industry 4.0 to enhance sustainable manufacturing. *Environ. Prog. Sustain. Energy* **2020**, *39*, 13360. [CrossRef]
66. Chen, X.; Despeisse, M.; Johansson, B. Environmental Sustainability of Digitalization in Manufacturing: A Review. *Sustainability* **2020**, *12*, 10298. [CrossRef]
67. Lukasik, K.; Stachowiak, T. Intelligent Management In The Age Of Industry 4.0—An Example of A Polymer Processing Company. *Manag. Prod. Eng. Rev.* **2020**, *11*, 38–49. [CrossRef]
68. Oláh, J.; Aburumman, N.; Popp, J.; Kahn, M.A.; Haddad, H.; Kitukutha, N. Impact of Industry 4.0 on Environmental Sustainability. *Sustainability* **2020**, *12*, 4674. [CrossRef]
69. Sony, M. Pros and cons of implementing Industry 4.0 for the organizations: A review and synthesis of evidence. *Prod. Manuf. Res.* **2020**, *8*, 244–272. [CrossRef]
70. Vrchota, J.; Pech, M.; Rolínek, L.; Bednár, J. Sustainability Outcomes of Green Processes in Relation to Industry 4.0 in Manufacturing: Systematic Review. *Sustainability* **2020**, *12*, 5968. [CrossRef]
71. Badakhshan, E.; Ball, P. Reviewing the Application of Data Driven Digital Twins in Manufacturing Systems: A Business and Management Perspective. In Proceedings of the IFIP WG 5.7 International Conference, APMS, Nantes, France, 5–9 September 2021; Rannenberg, K., Dolgui, A., Lemoine, D., Romero, D., Bernard, A., von Cieminski, G., Eds.; Springer Nature: Berlin/Heidelberg, Germany, 2021; pp. 256–265.
72. Bamunuarachchi, D.; Georgakopoulos, D.; Banerjee, A.; Jayaraman, P.P. Digital Twins Supporting Efficient Digital Industrial Transformation. *Sensors* **2021**, *21*, 6829. [CrossRef]
73. Pater, J.; Stadnicka, D. Towards Digital Twins Development and Implementation to Support Sustainability—Systematic Literature Review. *Manag. Prod. Eng. Rev.* **2021**, *12*, 63–73. [CrossRef]
74. Jamwal, A.; Agrawal, R.; Sharma, M.; Giallanza, A. Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions. *Appl. Sci.* **2021**, *11*, 5725. [CrossRef]
75. Rogall, C.; Mennenga, M.; Herrmann, C.; Thiede, S. Systematic Development of Sustainability-Oriented Cyber-Physical Production Systems. *Sustainability* **2022**, *14*, 2080. [CrossRef]
76. Aigner, F.J.; Kühnl, M.; Castellani, F.; Greßmann, A.; Aigner, J.; Gyenge, P.; Herrmann, C.; Abraham, T.; Rogall, C.; Arafat, R. *Ökologische und Ökonomische Bewertung des Ressourcenaufwandes: Industrie-4.0-Retrofit-Maßnahmen an Werkzeugmaschinen*; VDI Zentrum Ressourceneffizienz GmbH (VDI ZRE): Berlin, Germany, 2022.
77. Jia, Z.; Wang, M.; Zhao, S. A review of deep learning-based approaches for defect detection in smart manufacturing. *J. Opt.* **2023**, *53*, 1345–1351. [CrossRef]
78. Sommer, M.; Stjepandić, J.; Stobrawa, S.; von Soden, M. Automated generation of digital twin for a built environment using scan and object detection as input for production planning. *J. Ind. Inf. Integr.* **2023**, *33*, 100462. [CrossRef]
79. Ivanov, D. Design and deployment of sustainable recovery strategies in the supply chain. *Comput. Ind. Eng.* **2023**, *183*, 109444. [CrossRef]
80. Kazemi, Z.; Rask, J.K.; Gomes, C.; Yildiz, E.; Larsen, P.G. Movable factory—A systematic literature review of concepts, requirements, applications, and gaps. *J. Manuf. Syst.* **2023**, *69*, 189–207. [CrossRef]
81. Zizic, M.C.; Mladineo, M.; Gjeldum, N.; Celent, L. From Industry 4.0 towards Industry 5.0: A Review and Analysis of Paradigm Shift for the People, Organization and Technology. *Energies* **2022**, *15*, 5221. [CrossRef]
82. da Silva, F.S.T.; da Costa, C.A.; Crovato, C.D.P.; Righi, R.d.R. Looking at energy through the lens of Industry 4.0: A systematic literature review of concerns and challenges. *Comput. Ind. Eng.* **2020**, *143*, 106426. [CrossRef]
83. Hein-Pensel, F.; Winkler, H.; Brückner, A.; Wölke, M.; Jabs, I.; Mayan, I.J.; Kirschenbaum, A.; Friedrich, J.; Zinke-Wehlmann, C. Maturity assessment for Industry 5.0: A review of existing maturity models. *J. Manuf. Syst.* **2023**, *66*, 200–210. [CrossRef]
84. Machado, C.G.; Winroth, M.P.; Ribeiro Da Silva, E.H.D. Sustainable manufacturing in Industry 4.0: An emerging research agenda. *Int. J. Prod. Res.* **2020**, *58*, 1462–1484. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.