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How Environmentally Sustainable Is the On-Going Industrial Digitalization? Global Trends and a Swedish Perspective

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Abstract. While industrial digitalization presents great opportunities to enhance the efficiency, flexibility, and reliability of production systems, the environmental implications of these improvements are not systematically considered. As digitalization is a relatively new field of research, there are no unified framework to guide its development towards achieving sustainability goals. To support researchers and practitioners towards such a framework, this study aims to formalize the relationship between industrial digitalization and environmental sustainability by reviewing published literature intersection of these two topics. The work was carried out in four steps: (1) Define and scope the problem around environmental considerations when adopting and exploiting digital technologies in manufacturing; (2) Design the literature analysis process to identify publications at the intersection of environmental sustainability and digitalization; (3) Categorise the literature based on established eco-efficiency principles; (4) Visualise and discuss the results about which principles are covered by current research and to what extent. The global trends in the literature collected and analysed are presented along with a more detailed content analysis for Swedish research. While the results confirm that digitalization has the potential to address eco-efficiency principles, relatively few studies explicitly mention the sustainability implications of the research and proposed technological solutions. The paper proposes an eco-efficient smart production model using eco-efficiency as guiding principles. The main argument put forward in this paper is that digital technologies should more systematically contribute to greener industrial systems through energy and material efficiency, pollution prevention, sustainable use of renewable sources, product quality and durability, value retention through remanufacturing, recycling and servitization.

Keywords. Sustainable production, Smart manufacturing, Digitalization, Eco-efficiency, Circular economy.

1. Introduction

Some of the key features of industrial digitalization include efficiency, flexibility, productivity, quality, and reliability through big data analytics and enhanced supply chain interconnectedness [1–3]. While these features could result in sustainability benefits, environmental implications of such improvements are insufficiently considered [3,4]. In response to the pressing needs to address the climate impacts of human activities, natural resource depletion, and the accumulation of waste and pollutants in our ecosystems, many organisations are setting ambitious goals. To translate these goals into

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actionable strategies and practices, a paradigm shift is required to integrate sustainability in industrial system design, development, and operations more systematically [5–7].

As industrial digitalization is still an emerging field, there is no unified framework to guide its development towards achieving sustainability goals, and especially the UN sustainable development goals of responsible consumption and production (SDG 12). To support the development of such a framework, a better understanding of how digital technologies must be implemented to ensure they move us in the right direction, i.e. towards operating within the planetary boundaries [8,9]. Accordingly, this study aims to formalize the relationship between industrial digitalization by reviewing published literature at the intersection of these two broad topics.

2. Methods

This study employed a meta-analysis method [10–12] to explore trends in recent publications at the overlap of the two topics of interests: industrial digitalization and environmental sustainability. The review process followed four steps [11,12]. First, the problem was defined and scoped around the lack of unified framework for green(er) operations when adopting new digital technologies in manufacturing. Second, the research process was designed to selectively collect publications using the keywords identified during the previous step (scoping) and analyse using a specific search strategy aiming to filter highly relevant articles to the specific purpose of this study. Third, the literature was categorised using word-analysis techniques based on terminologies associated with established sustainability principles. Fourth, the analysis results were synthesised and visualised to identify which and to what extent these sustainability principles are covered by current research on industrial digitalization.

2.1. Scoping and search strategy

With the purpose and scope of this study in mind, various keywords were tested in Scopus to identify the main terminology for industrial digitalization. Four keywords emerged as the dominant ones: “digit*”, “smart”, “intelligent” and “industr* 4.0”. Other terms such as “data-driven”, “Big Data”, “data analytics” did not add many results as the dominant keywords already captured the majority of articles also using such terms. The expression “industr* 4.0” on its own yielded the highest number of articles despite emerging the latest (first used in 2012). To increase the likelihood of articles fitting the scope with a strong focus on the manufacturing sector, the digitalization keywords were combined to “production” or “manufactur*” with the proximity operator “W/1”.

The final search strategy filtered the literature restrictively (rather than comprehensively) to capture a high ratio of articles relevant to the study for text mining. This search strategy increased the likelihood that irrelevant articles would not be collected since there was no cleaning process before text mining. This initial search yielded a total of 14392 articles before exclusion criteria were applied. To focus on state-of-the-art engineering research, the results were limited to articles published from 2013 onwards. The results were limited to publications within the field of engineering. Furthermore, conference reviews, editorials, books, errata, and notes were excluded. Only articles in English were retained. This filtering strategy resulted in 5805 publications selected for further analysis, thereafter called the *global sample*. A

subsample of 157 publications was extracted for articles with at least one author affiliated to a Swedish organisation, thereafter called *Swedish sample*.

2.2. Literature analysis

Bibliometric information is briefly presented in section 3.1 to clarify the composition of the literature analysed using SciVal and Bibliometrix [13]. Scopus search engine (for the global sample) and NVivo (for the Swedish sample) were used as a text analysis tool to categorise the articles based on the seven principles for eco-efficiency [14]:

1. Reduce the material intensity of goods and services;
2. Reduce the energy intensity of goods and services;
3. Reduce toxic dispersion;
4. Enhance material recyclability;
5. Maximize sustainable use of renewable resources;
6. Extend product durability;
7. Increase the service intensity of goods and services.

Although the sustainability theme may be theoretical or weak in the publications analysed, if connections to the principles were explicitly made by the authors, the articles were marked as sustainability-related studies. The text mining technique was used on the global sample by searching titles, abstracts and keywords in Scopus, resulting in 389 articles identified as sustainability-related studies. A more detailed content analysis was performed for the Swedish sample when the full-text articles could be accessed. This second, more detailed text analysis was performed using NVivo, resulting in 58 articles from Swedish authors identified as sustainability-related studies. **Figure 1** shows the volume of the literature collected and analysed. The results from the literature analysis is presented for the global sample in section 3.2 and for the Swedish sample section 3.3.

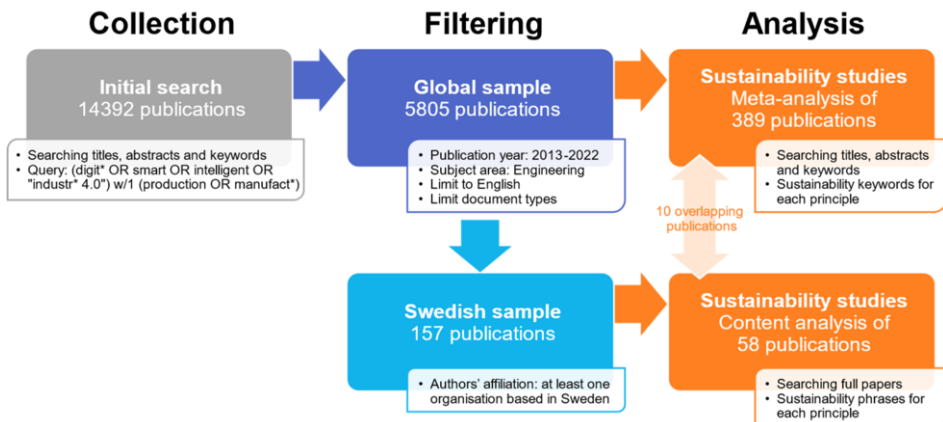


Figure 1. Overview of the research process for literature search, filtering/selection and analysis.

3. Results and Discussion

To provide some context for the literature analysis results, the bibliometric information for the articles collected and analysed are presented (publication year, countries, subject areas, sources and dominant themes for publications addressing the topic of industrial digitalization). Then the trends in sustainability-related studies are presented for the global sample and the Swedish sample.

3.1. Bibliometric information

A descriptive analysis shows the composition of the samples collected and analysed to provide an initial overview of the literature identified as relevant to the study. **Figure 2** shows the number of publications per year for the literature initially collected, filtered for the global and Swedish samples, and the number of publications identified as sustainability-related studies; i.e. mentioning at least one eco-efficiency principle. Disregarding 2021 as all articles are not yet published and indexed, the publication output more than double every two years for the initial, global and Swedish samples (with the exception of 2019 for Sweden). The number of sustainability-related studies, however, grows at a slower rate; i.e. the ratio of studies aligning with eco-efficiency principles is proportionally shrinking which points to a worrying trend. This also reinforces the argument made in the introduction about the need to develop *and use* sustainability framework more systematically in engineering research to ensure that our technological advances and industrial solutions move us towards a more sustainable society.

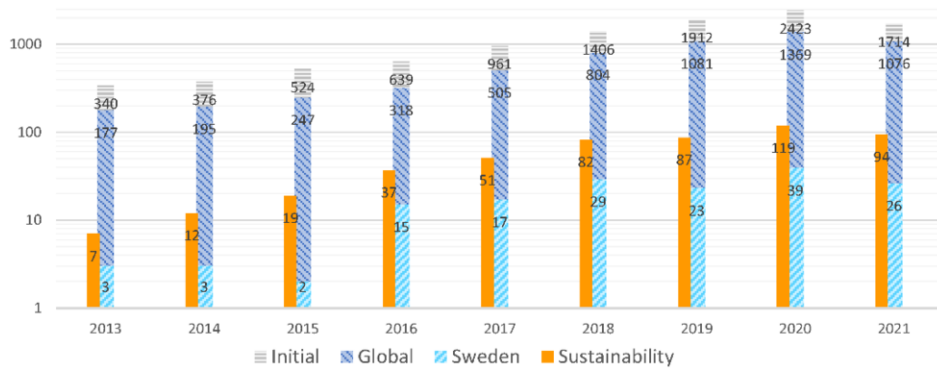


Figure 2. Number of publications per year in the different literature samples (y-axis on a logarithmic scale).

Focusing on the global sample collected, the geographical distribution of articles is shown in **Figure 3** for countries with more than 100 publications. Publications with at least one co-author affiliated to a Swedish organisation (Swedish sample) are highlighted in blue. Focusing on the global sample collected and proportionally to its population, Sweden produced the largest volume of scientific articles (followed by Finland, Norway, Austria, Singapore and Hong Kong).

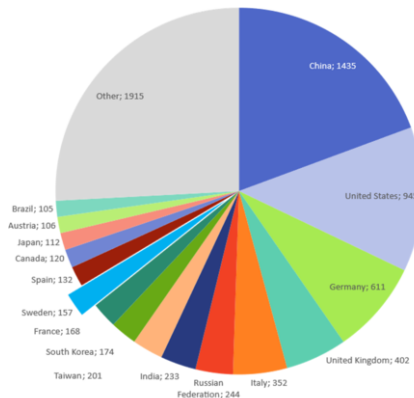


Figure 3. Number of publications per country for the global sample (Swedish sample highlighted in blue).

3.2. Global trends

To categorise publications addressing eco-efficiency principles (EE_x), the keywords and expressions associated with each principle (Table 1) were used to search the articles’ title, abstract and keywords. Some keywords resulted more consistently in articles addressing eco-efficiency principles, thus higher confidence in the categorisation. Variations and synonyms were also tested but resulted in a lower confidence as the context for their use varied broadly with other meaning than intended for this analysis, such as “power reduc*/minimi*” for EE₂, or “service based/oriented” for EE₇.

Table 1. Seven principles of eco-efficiency used for the literature categorization and terminology used for text mining in the global sample (searching title, abstract and keywords).

Eco-efficiency principles	Associated keywords
EE ₁ – Material intensity	Material/resource efficien*/Waste manag*/minimi*/reduc*/eliminat*
EE ₂ – Energy intensity	Energy efficien*/minimi*/reduc*/optimi*/intens*
EE ₃ – Toxicity and pollution	Toxic*/pollut*; Hazardous waste/substances
EE ₄ – Recyclability	Recycl*
EE ₅ – Renewable resources	Renewable; Biodegrad*/bio-based
EE ₆ – Product durability	Remanuf*/refurb*/repair*/durab*/reus* product/component/part
EE ₇ – Service intensity	Product-service system/PSS; Serviti* product

Amongst the 5805 publications of the global sample, 389 articles connected to at least one eco-efficiency principle with medium or high confidence, of which 53 articles categorised with two or more principles. Figure 4 shows the text analysis results.

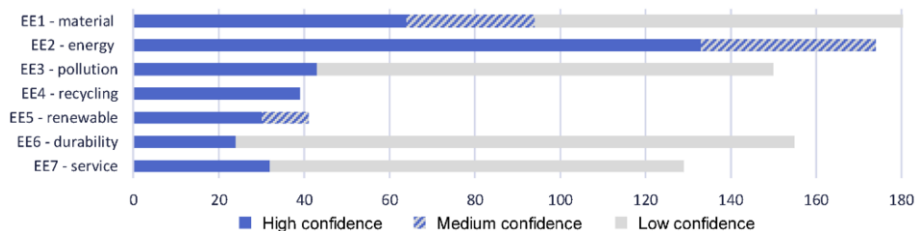


Figure 4. Number of articles in the global sample (N=389) mentioning eco-efficiency principles.

The principle about energy intensity (EE_2) was the most directly and explicitly addressed with 133 articles in this category. Energy efficiency has historically been a strong focus in green manufacturing research, often mentioned in connection to other established topics such as production scheduling [15–20] and real-time optimization [21–23]. Additional expressions such as energy reduction, minimization, and optimization increased the results to 174 articles potentially addressing EE_2 (medium confidence).

Regarding material intensity (EE_1), 64 articles explicitly mentioned resource efficiency or material efficiency [24–28]. Resource efficiency sometimes covers both material and energy [29–31]; 11 articles were marked with high confidence for both principles EE_1 and EE_2 . A wider set of keywords was used to connect to production waste management [32–34], resulting in 94 articles. The 30 additional articles were marked as medium confidence since improved production waste management (e.g. recycling) does not necessarily result in increased efficiency and reduced material intensity of goods and services. Furthermore, the concept of dematerialization also includes other strategies such as lightweight, miniaturization and multifunctionality [35,36]. Servitization is yet another dematerialisation strategy (connected to principle EE_7). Thus the number of articles connecting to EE_1 may be much greater.

For toxic dispersion (EE_3), 43 articles were marked with good confidence. The terms pollution [37–40] was more common than toxicity [41–44]. Broadening the text search to other waste-related expressions (chemical discharge, effluents, hazardous substances, etc.), 150 articles potentially connecting to some extent to this principle, however they would require further content analysis to increase confidence in their connection to EE_3 .

The fourth principle focuses on material recyclability (EE_4) with 39 articles marked with good confidence [45–49]. Other expressions for closed-loop material flows did not increase the results since the *recycl** keyword seemed to cover the topic well.

Regarding the use of renewable resources (EE_5), 30 articles related to renewable sources (mostly energy systems) [50–54]. Adding biodegradable and bio-based materials [55–57], 11 articles were marked with medium confidence.

Similar to material intensity (EE_1), the principle of product durability (EE_6) connects to diverse strategies, with 24 articles addressing the topic of product life extension through remanufacturing, reuse and repair of products, components and parts [58–63]. Broadening the search to remove the condition of proximity between some of the keywords, more articles address circular strategies in relation to product durability [64,65]. An additional search related to product quality resulted in 155 articles [46,66–68], but with a low confidence in the connections to principle EE_6 .

Focusing on the seventh principle about service intensity (EE_7), 32 articles addressed product-service systems and product servitization explicitly [69–72]. Furthermore, a total of 129 articles also mentioned services and servitization (without the proximity to product). These articles seemed more related to equipment maintenance and information systems (e.g. industrial services, cloud services, service architecture, service layer, etc.) [64,73–77] rather than product servitization, thus marked as low confidence.

Although some of the results presented in this section have a high degree of uncertainty, they show some interesting trends in which eco-efficiency principles seem to be better addressed than others. For articles marked as medium and low confidence, further analysis is required to remove false positives (i.e. adding a cleaning step to the text analysis) and achieve higher confidence in the categorisation of articles against the seven eco-efficiency principles.

3.3. Swedish trends

A total of 157 articles were extracted from the global sample based on the country of affiliation. The most productive institutions in the Swedish sample were Chalmers University of Technology with 93 publications and KTH Royal Institute of Technology with 70 publications. Except for 18 articles, the publications were the result of international collaborations; the top six countries in the sample were China (30 publications), United States (21), United Kingdom (13), Germany (12) and Finland (10).

To identify the articles addressing eco-efficiency principles through digitalization within the Swedish sample, the full-text publications were used whenever possible. If the full paper was not accessible, the title, abstract and keywords were used instead. In addition to the terminology used to search the global sample (**Table 1**), other expressions were used less restrictively with the text search query in NVivo (e.g. single words or without proximity operator). A more detailed analysis was performed by reading the surrounding text and manually coding the phrases explicitly mentioning the eco-efficiency principles. The results from this text analysis are shown in **Figure 5**.

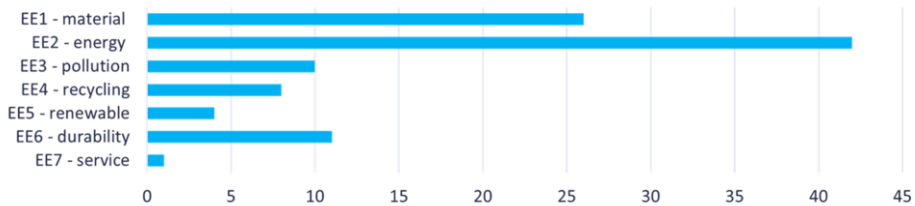


Figure 5. Number of articles in the Swedish sample (N=58) aligning with the eco-efficiency principles.

While the trends in the Swedish sample are mostly consistent with the ones observed in the global sample for the first four principles, there were some noticeable differences for principles EE₅, EE₆ and EE₇. On the one hand, the topic of remanufacturing (associated with principle EE₆ for product durability) is a strong topic in Sweden. Two studies had a strong focus on remanufacturing as the core topic [4,79] and a few more connected digitalization to remanufacturing to some degree [78,80–84]. On the other hand, service intensity (EE₇) and renewable resources (EE₅) seemed less present in Swedish research on industrial digitalization. Although many articles mentioned servitization, only one article addressed product-service systems in line with EE₇ [4]. And four of the studies [4,85–87] mentioned explicitly renewables in line with EE₅.

Turning to material intensity, out of the 26 articles categorised as addressing principle EE₁, half overlapped with energy (EE₂), e.g. [88–91], and most also covered other principles. For example, five articles also addressed energy EE₂, pollution EE₃, recycling EE₄, and durability EE₆ [4,78,80,82,84] and another seven addressed three or more principles [79,81,86,92–94]. These strong overlaps between principles show that the principles are highly synergistic. However, some articles also mention possible trade-offs which digital solutions can help manage; e.g. product performance vs environmental impact [81] or energy consumption vs productivity [95].

3.4. Limitations and further work

The literature was analysed using a text mining technique searching for specific keywords, thus some publications may have been missed due to variations in the terminology used by different researchers. Synonyms and alternative expressions were tested but yielded both relevant and irrelevant studies. The coding of these studies was done manually for the Swedish sample to eliminate irrelevant results, but this could not be done for the global sample due to the high volume of literature to be analysed efficiently with the same manual process. In addition, non-Swedish studies not mentioning environmental implications in the title, abstract or keywords (for example, only stating sustainability benefits in the discussion) were not captured. A different tool supporting full text searches for the global sample would ensure a more comprehensive coverage of the literature tackling eco-efficiency through digitalization.

Focusing on the types of digital solutions, an additional text analysis of the Swedish was performed: automation (37 publications), cyber-physical (production) systems (35), (industrial) Internet of things (30), big data (27), digital twins (25), cloud computing (23) and additive manufacturing (23) are strong topics in Swedish production research. Further work is required to map these technologies against the eco-efficiency principles. Such technology-oriented analysis is planned as part of further work to identify which digital solutions can tackle specific environmental aspects.

4. Conclusion

This paper investigated the relationship between industrial digitalization and environmental sustainability by mapping relevant literature against eco-efficiency principles to identify which principles are addressed by current research and to what extent. Global trends were first presented based on a text analysis performed on titles, keywords and abstracts. A more detailed analysis was performed on full-text articles for publications from Swedish organisations to identify trends in Sweden more specifically. The results were largely consistent between the global and Swedish literature for material and energy intensity, waste recycling and pollution prevention. The Swedish literature addresses product durability better with remanufacturing as a strong research topic.

The results confirm that digitalization can support more environmentally sustainable industrial systems. However, technological development does not systematically lead to greener production. The number of studies considering sustainability is still relatively low. Research addressing environmental challenges explicitly is not keeping up with the growth of digitalization research (i.e. the ratio of studies not considering sustainability is increasing). The results also point to the need for a research model (such as the one proposed in **Figure 6**) that systematically consider the environmental implications of digitalization to ensure that the goals of industrial development and sustainability are aligned, or even reinforce each other.



Figure 6. Proposed eco-efficient smart production model to align the goals of industrial development (digital technologies) and environmental sustainability (eco-efficiency principles).

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