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Citation for the original published paper (version of record):
Despeisse, M. (2022). How Environmentally Sustainable Is the On-Going Industrial Digitalization?
Global Trends and a
Swedish Perspective. Advances in Transdisciplinary Engineering, 21: 316-328.
http://dx.doi.org/10.3233/ATDE220150

SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220150

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.

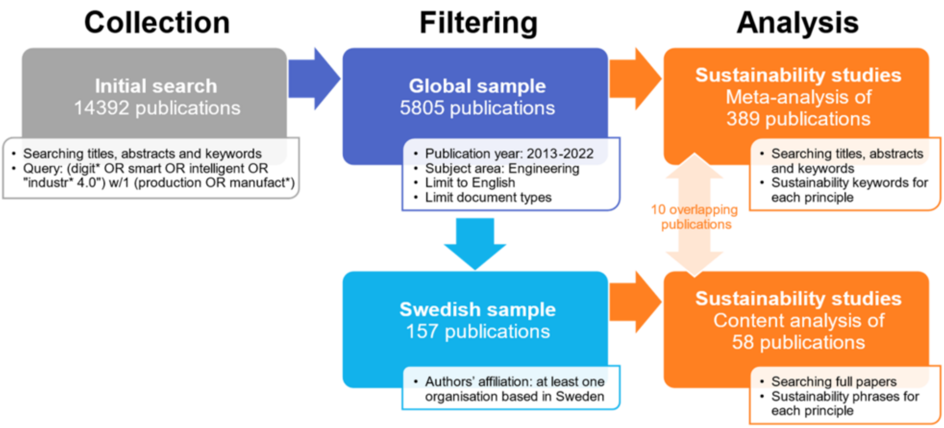

Figure 1. Overview of the research process for literature search, filtering/selection and analysis.

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.

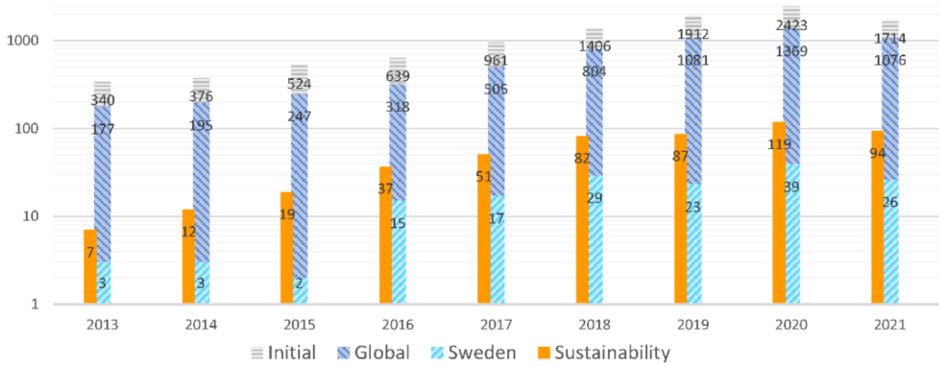

Figure 2. Number of publications per year in the different literature samples (y-axis on a logarithmic scale).

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).

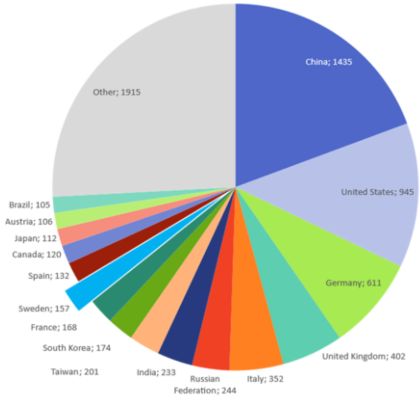

Figure 3. Number of publications per country for the global sample (Swedish sample highlighted in blue).

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 EE_2, or "service based/oriented" for EE_7.

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.

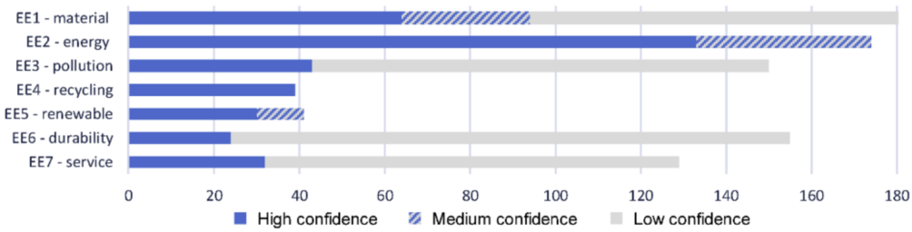

Figure 4. Number of articles in the global sample (N=389) mentioning eco-efficiency principles.

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 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**.

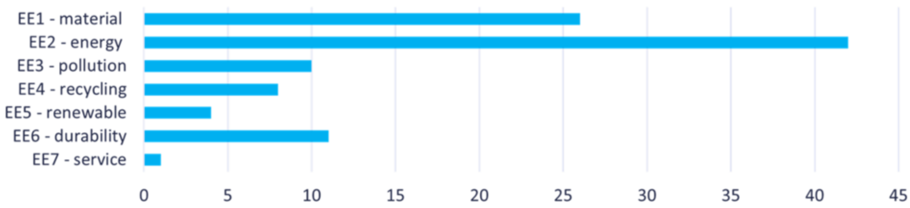

Figure 5. Number of articles in the Swedish sample (N=58) aligning with the eco-efficiency principles.

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 EE_5, EE_6 and EE_7. On the one hand, the topic of remanufacturing (associated with principle EE_6 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 (EE_7) and renewable resources (EE_5) seemed less present in Swedish research on industrial digitalization. Although many articles mentioned servitization, only one article addressed product-service systems in line with EE_7 [4]. And four of the studies [4,85–87] mentioned explicitly renewables in line with EE_5.

Turning to material intensity, out of the 26 articles categorised as addressing principle EE_1, half overlapped with energy (EE_2), e.g. [88–91], and most also covered other principles. For example, five articles also addressed energy EE_2, pollution EE_3, recycling EE_4, and durability EE_6 [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 too 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).

Acknowledgements

This work was supported by the Swedish innovation agency Vinnova under grant no. 2019-00787 (REWIND project) and the strategic vehicle research and innovation programme (FFI) under grant no. 2020-05180 (FREED project).

References

[1] Liao Y, Deschamps F, Loures EFR, Ramos LFP. Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. Int J Prod Res; 2017;55:3609–29.
[2] Tao F, Qi Q, Liu A, Kusiak A. Data-driven smart manufacturing. J Manuf Syst; 2018;48:157–69.
[3] Dubey R, Gunasekaran A, Childe SJ, Papadopoulos T, Luo Z, Wamba SF, et al. Can big data and predictive analytics improve social and environmental sustainability? Technol Forecast Soc Change; 2019;144:534–45.
[4] Ren S, Zhang Y, Liu Y, Sakao T, Huisingh D, Almeida CMVB. A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions. J Clean Prod; 2019;210:1343–65.
[5] Garetti M, Taisch M. Sustainable manufacturing: Trends and research challenges. Prod Plan Control; 2012;23:83–104.

[6] Stock T, Obenaus M, Kunz S, Kohl H. Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential. Process Saf Environ Prot; 2018;118:254–67.
[7] Kraus S, Rehman SU, García FJS. Corporate social responsibility and environmental performance: The mediating role of environmental strategy and green innovation. Technol Forecast Soc Change; 2020;160.
[8] Rockström J, Steffen W, Noone K, Persson A, Chapin III FS, Lambin E, et al. Planetary boundaries: Exploring the safe operating space for humanity. Ecol Soc; 2009;14.
[9] Clift R, Sim S, King H, Chenoweth JL, Christie I, Clavreul J, et al. The challenges of applying planetary boundaries as a basis for strategic decision-making in companies with global supply chains. Sustain; 2017;9.
[10] Tranfield D, Denyer D, Smart P. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br J Manag; 2003;14:207–22.
[11] Snyder H. Literature review as a research methodology: An overview and guidelines. J Bus Res; 2019;104:333–9.
[12] Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: An overview and guidelines. J Bus Res; 2021;133:285–96.
[13] Aria M, Cuccurullo C. bibliometrix: An R-tool for comprehensive science mapping analysis. J Informetr; 2017;11:959–75.
[14] World Business Council for Sustainable Development. Eco-efficient leadership for improved economic and environmental performance. 1996.
[15] Mariano E, Nucci F, Prete AD, Grieco A. Minimization of energy consumptions by means of an intelligent production scheduling. Key Eng Mater; 2015;639:525–32.
[16] Lin C-C, Deng D-J, Chen Z-Y, Chen K-C. Key design of driving industry 4.0: Joint energy-efficient deployment and scheduling in group-based industrial wireless sensor networks. IEEE Commun Mag; 2016;54:46–52.
[17] Otis PT, Hampson D. Improve production scheduling to increase energy efficiency. Chem Eng Prog; 2017;113.
[18] Wang Y, Li K, Gan S, Cameron C. Analysis of energy saving potentials in intelligent manufacturing: A case study of bakery plants. Energy; 2019;172:477–86.
[19] Wang J, Liu Y, Ren S, Wang C, Wang W. Evolutionary game based real-time scheduling for energy-efficient distributed and flexible job shop. J Clean Prod; 2021;293.
[20] Darwish LR, El-Wakad MT, Farag MM. Towards sustainable industry 4.0: A green real-time IIoT multitask scheduling architecture for distributed 3D printing services. J Manuf Syst; 2021;61:196–209.
[21] Kumar A, Baldea M, Edgar TF, Ezekoye OA. Smart manufacturing approach for efficient operation of industrial steam-methane reformers. Ind Eng Chem Res; 2015;54:4360–70.
[22] Vatankhah Barenji A, Liu X, Guo H, Li Z. A digital twin-driven approach towards smart manufacturing: reduced energy consumption for a robotic cell. Int J Comput Integr Manuf; 2021;34:844–59.
[23] Seferlis P, Varbanov PS, Papadopoulos AI, Chin HH, Klemeš JJ. Sustainable design, integration, and operation for energy high-performance process systems. Energy; 2021;224.
[24] Haag S, Bauerdick C, Campitelli A, Anderl R, Abele E, Schebek L. A Framework for Self-Evaluation and Increase of Resource-Efficient Production through Digitalization. Procedia CIRP; 2018.
[25] Schleinkofer U, Laufer F, Zimmermann M, Roth D, Bauernhansl T. Resource-efficient manufacturing systems through lightweight construction by using a combined development approach. Procedia CIRP; 2018;856–61.
[26] Pei S, Zhao J, Zhang N, Guo M. Methodology on developing an assessment tool for intralogistics by considering cyber-physical production systems enabling technologies. Int J Comput Integr Manuf; 2019;32:406–12.
[27] Simeone A, Deng B, Caggiano A. Resource efficiency enhancement in sheet metal cutting industrial networks through cloud manufacturing. Int J Adv Manuf Technol; 2020;107:1345–65.
[28] 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;117:2269–77.
[29] Plank M, Thiede S, Herrmann C. Versatile IT-system architecture for smart manufacturing solutions: the example for green manufacturing. Int J Comput Integr Manuf; 2021;
[30] Sarkar M, Sarkar B. How does an industry reduce waste and consumed energy within a multi-stage smart sustainable biofuel production system? J Clean Prod; 2020;262.
[31] Javied T, Huprich S, Franke J. Cloud based Energy Management System Compatible with the Industry 4.0 Requirements. IFAC-PapersOnLine; 2019;171–5.
[32] Pistolesi F, Lazzerini B, Mura MD, Dini G. EMOGA: A Hybrid Genetic Algorithm with Extremal Optimization Core for Multiobjective Disassembly Line Balancing. IEEE Trans Ind Informatics; 2018;14:1089–98.
[33] Mehrpouya M, Dehghanghadikolaei A, Fotovvati B, Vosooghnia A, Emamian SS, Gisario A. The potential of additive manufacturing in the smart factory industrial 4.0: A review. Appl Sci; 2019;9.

[34] Amjad MS, Rafique MZ, Khan MA. Leveraging Optimized and Cleaner Production through Industry 4.0. Sustain Prod Consum; 2021;26:859–71.
[35] Nesenbergs K, Selavo L. Smart textiles for wearable sensor networks: Review and early lessons. IEEE Int Symp Med Meas Appl MeMeA 2015; 2015;402–6.
[36] Drossel W, Dani I, Wertheim R. Biological transformation and technologies used for manufacturing of multifunctional metal-based parts. Procedia Manuf; 2019;115–22.
[37] Choi S, Kang G, Jun C, Lee JY, Han S. Cyber-physical systems: A case study of development for manufacturing industry. Int J Comput Appl Technol; 2017;55:289–97.
[38] Aggarwal R, Renzi D. Digitalized deepwater production facilities for South America - Challenges and opportunities. Offshore Technol Conf Bras 2019, OTCB 2019; 2020.
[39] Leng J, Ruan G, Song Y, Liu Q, Fu Y, Ding K, et al. A loosely-coupled deep reinforcement learning approach for order acceptance decision of mass-individualized printed circuit board manufacturing in industry 4.0. J Clean Prod; 2021;280.
[40] Ban C, Min X, Xu J, Xiu F, Nie Y, Hu Y, et al. An Artificial Olfactory Memory System for Monitoring and Recording of Volatile Organic Compounds. Adv Mater Technol; 2021;6.
[41] Wójcik M. Three Experiments in Wood and Computational Design. Technol Archit Des; 2017;1:61–72.
[42] Peruzzini M, Gregori F, Luzi A, Mengarelli M, Germani M. A social life cycle assessment methodology for smart manufacturing: The case of study of a kitchen sink. J Ind Inf Integr; 2017;7:24–32.
[43] Farooqi HMU, Khalid MAU, Kim KH, Lee SR, Choi KH. Real-time physiological sensor-based liver-on-chip device for monitoring drug toxicity. J Micromechanics Microengineering; 2020;30.
[44] Zakeri S, Vastamäki T, Honkanen M, Järveläinen M, Vippola M, Levänen E. Fabrication of self-supporting structures made of washcoat materials (γ-Al2O3-CeO2) by ceramic stereolithography: Towards digital manufacturing of enhanced catalytic converters. Mater Des; 2021;210.
[45] Nascimento DLM, Alencastro V, Quelhas OLG, Caiado RGG, Garza-Reyes JA, Lona LR, et al. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. J Manuf Technol Manag; 2019;30:607–27.
[46] Lin K-P, Yu C-M, Chen K-S. Production data analysis system using novel process capability indices-based circular economy. Ind Manag Data Syst; 2019;119:1655–68.
[47] Blömeke S, Rickert J, Mennenga M, Thiede S, Spengler TS, Herrmann C. Recycling 4.0 - Mapping smart manufacturing solutions to remanufacturing and recycling operations. Procedia CIRP; 2020;600–5.
[48] Komoto H, Matsumoto M, Kondoh S. Library of facility models for structural and graphical definition of recycling system simulation considering information flows. Procedia CIRP; 2021;187–92.
[49] Khayyam H, Naebe M, Milani AS, Fakhrhoseini SM, Date A, Shabani B, et al. Improving energy efficiency of carbon fiber manufacturing through waste heat recovery: A circular economy approach with machine learning. Energy; 2021;225.
[50] Joo J-Y, Raghavan S, Sun Z. Integration of Sustainable Manufacturing Systems into Smart Grids with High Penetration of Renewable Energy Resources. IEEE Green Technol Conf; 2016;12–7.
[51] Schel D, Bauer D, Vazquez FG, Schulz F, Bauernhansl T. IT Platform for Energy Demand Synchronization among Manufacturing Companies. Procedia CIRP; 2018;826–31.
[52] Bauer D, Abele E, Ahrens R, Bauernhansl T, Fridgen G, Jarke M, et al. Flexible IT-platform to Synchronize Energy Demands with Volatile Markets. Procedia CIRP; 2017;318–23.
[53] Justo JJ. Intelligent energy management strategy considering power distribution networks with nanogrids, microgrids, and VPP concepts; 2017.
[54] Goubaa A, Khalgui M, Li Z, Frey G, Al-Ahmari A. On Parametrizing Feasible Reconfigurable Systems under Real-Time, Energy, and Resource Sharing Constraints. IEEE Trans Autom Sci Eng; 2021;18:1492–504.
[55] Shimizu N. Process optimization of composting systems; 2017.
[56] Mogas-Soldevila L, Matzeu G, Presti ML, Omenetto FG. Additively manufactured leather-like silk protein materials. Mater Des; 2021;203.
[57] Nocheseda CJC, Liza FP, Collera AKM, Caldona EB, Advincula RC. 3D printing of metals using biodegradable cellulose hydrogel inks. Addit Manuf; 2021;48.
[58] Zheng F, He J, Chu F, Liu M. A new distribution-free model for disassembly line balancing problem with stochastic task processing times. Int J Prod Res; 2018;56:7341–53.
[59] Goodall P, Sharpe R, West A. A data-driven simulation to support remanufacturing operations. Comput Ind; 2019;105:48–60.
[60] Liu C, Zhu Q, Wei F, Rao W, Liu JJ, Hu J, et al. A review on remanufacturing assembly management and technology. Int J Adv Manuf Technol; 2019;105:4797–808.
[61] Bagalagel S, ElMaraghy W. Product mix optimization model for an industry 4.0-enabled manufacturing-remanufacturing system. Procedia CIRP; 2020;204–9.
[62] Kerin M, Pham DT. Smart remanufacturing: a review and research framework. J Manuf Technol Manag; 2020;31:1205–35.

[63] Wang Z, Xu Y, Ma X, Thomson G. Towards Smart Remanufacturing and Maintenance of Machinery - Review of Automated Inspection, Condition Monitoring and Production Optimisation. IEEE Symp Emerg Technol Fact Autom ETFA; 2020;1731–8.
[64] Wan S, Li D, Gao J, Roy R, Tong Y. Process and knowledge management in a collaborative maintenance planning system for high value machine tools. Comput Ind; 2017;84:14–24.
[65] Ratava J, Penttilä S, Lund H, Lohtander M, Kah P, Ollikainen M, et al. Quality assurance and process control in virtual reality. Procedia Manuf; 2019;497–504.
[66] Megahed M, Mindt H-W, N'Dri N, Duan H, Desmaison O. Metal additive-manufacturing process and residual stress modeling. Integr Mater Manuf Innov; 2016;5:61–93.
[67] Traub T, Gregório MG, Groche P. A framework illustrating decision-making in operator assistance systems and its application to a roll forming process. Int J Adv Manuf Technol; 2018;97:3701–10.
[68] Rolinck M, Gellrich S, Herrmann C, Thiede S. Data analytics of energy and compressed air flows for process and quality monitoring in electro-pneumatic handling systems. Sustain Prod Life Cycle Eng Manag; 2020;109–16.
[69] Lerch C, Gotsch M. Digitalized product-service systems in manufacturing firms : A case study analysis. Res Technol Manag; 2015;58:45–52.
[70] Cimini C, Rondini A, Pezzotta G, Pinto R. Smart manufacturing as an enabler of servitization: A framework for the business transformation towards a smart service ecosystem. Proc Summer Sch Fr Turco; 2018;341–7.
[71] Sassanelli C, Rossi M, Pezzotta G, de Jesus Pacheco DA, Terzi S. Defining lean product service systems features and research trends through a systematic literature review. Int J Prod Lifecycle Manag; 2019;12:37–61.
[72] Wang X, Wang Y, Tao F, Liu A. New Paradigm of Data-Driven Smart Customisation through Digital Twin. J Manuf Syst; 2021;58:270–80.
[73] Charro A, Schaefer D. Cloud Manufacturing as a new type of Product-Service System. Int J Comput Integr Manuf; 2018;31:1018–33.
[74] Ye Y, Wang M, Yao S, Jiang JN, Liu Q. Big data processing framework for manufacturing. Procedia CIRP; 2019;661–4.
[75] Shihundla TB, Mpofu K, Adenuga OT. Integrating product-service systems into the manufacturing industry: Industry 4.0 perspectives. Procedia CIRP; 2019;8–13.
[76] Noureddine R, Solvang WD, Johannessen E, Yu H. Proactive Learning for Intelligent Maintenance in Industry 4.0. Lect Notes Electr Eng; 2020;634 LNEE:250–7.
[77] Zhang X, Ming X, Yin D. Application of industrial big data for smart manufacturing in product service system based on system engineering using fuzzy DEMATEL. J Clean Prod; 2020;265.
[78] Chen D, Heyer S, Ibbotson S, Salonitis K, Steingrímsson JG, Thiede S. Direct digital manufacturing: Definition, evolution, and sustainability implications. J Clean Prod; 2015;107:615–25.
[79] Wang XV, Xu X. Cloud manufacturing in support of sustainability. ASME 2014 Int Manuf Sci Eng Conf MSEC 2014 Collocated with JSME 2014 Int Conf Mater Process 42nd North Am Manuf Res Conf. 2014.
[80] Ma S, Zhang Y, Liu Y, Yang H, Lv J, Ren S. Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries. J Clean Prod; 2020;274.
[81] Liu Y, Zhang Y, Ren S, Yang M, Wang Y, Huisingh D. How can smart technologies contribute to sustainable product lifecycle management? J Clean Prod; 2020;249.
[82] Chari A, Duberg JV, Lindahl E, Stahre J, Despeisse M, Sundin E, et al. Swedish manufacturing practices towards a sustainability transition in industry 4.0: A resilience perspective. Proc ASME 2021 16th Int Manuf Sci Eng Conf MSEC 2021. 2021.
[83] Florén H, Barth H, Gullbrand J, Holmén M. Additive manufacturing technologies and business models – a systematic literature review. J Manuf Technol Manag; 2021;32:136–55.
[84] Machado CG, Winroth MP, da Silva EHD. Sustainable manufacturing in Industry 4.0: an emerging research agenda. Int J Prod Res; 2020;58:1462–84.
[85] Crnkovic GD. The cybersemiotics and info-computationalist research programmes as platforms for knowledge production in organisms and machines. Entropy; 2013;15:878–901.
[86] Landscheidt S, Kans M. Evaluating factory of the future principles for the wood products industry: Three case studies. Procedia Manuf; 2019;1394–401.
[87] Pinto R, Gonçalves G, Delsing J, Tovar E. Incremental Dendritic Cell Algorithm for Intrusion Detection in Cyber-Physical Production Systems. Lect. Notes Networks Syst. 2021.
[88] Chen X, Despeisse M, Dahlman P, Dietl P, Johansson B. The environmental implications of digitalization in manufacturing: a case study. Sustain Prod Life Cycle Eng Manag 2021;249–63.
[89] Wiktorsson M, Noh SD, Bellgran M, Hanson L. Smart Factories: South Korean and Swedish examples on manufacturing settings. Procedia Manuf. 2018;471–8.
[90] Rauch E, Vickery AR, Brown CA, Matt DT. SME requirements and guidelines for the design of smart and highly adaptable manufacturing systems. Ind. 4.0 SMEs Challenges, Oppor. Requir. 2020.

[91] Machado CG, Kurdve M, Winroth M, Bennett D. Production management and smart manufacturing from a systems perspective. Adv Transdiscipl Eng. 2018;329–34.
[92] Li L, Qu T, Liu Y, Zhong RY, Xu G, Sun H, et al. Sustainability assessment of intelligent manufacturing supported by digital twin. IEEE Access. 2020;8:174988–5008.
[93] Kurdve M. Digital assembly instruction system design with green lean perspective-Case study from building module industry. Procedia CIRP. 2018;762–7.
[94] Seipel S, Yu J, Periyasamy AP, Viková M, Vik M, Nierstrasz VA. Characterization and optimization of an inkjet-printed smart textile UV-sensor cured with UV-LED light. IOP Conf Ser Mater Sci Eng. 2017.
[95] Senington R, Schmidt B, Syberfeldt A. Monte Carlo Tree Search for online decision making in smart industrial production. Comput Ind. 2021;128.