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Mélanie Despeisse & Federica Acerbi

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Toward eco-efficient and circular industrial systems: ten years of advances in production management systems and a thematic framework

Mélanie Despeisse [a] and Federica Acerbi [b]

[a]Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden; [b]Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy

ABSTRACT

Environmental sustainability urgently needs to be embraced as a driver of development for society and industry. While researchers and practitioners herald numerous benefits when adopting eco-efficiency and circular economy approaches, these green solutions are yet to become pervasive principles for designing and operating industrial systems. This study reviews the last ten years of research contributions from the International Federation for Information Processing Working Group 5.7 (IFIP WG5.7) on Advances in Production Management Systems (APMS) through its dedicated annual conference. A systematic literature review method was employed to map the APMS conference papers against eco-efficiency principles and to identify how these principles have been addressed by this research community. A cross-thematic analysis further describes the trends around dominant themes in production research. Finally, the paper concludes with an update on eco-efficiency principles applied to manufacturing and a proposed framework to consider more systematically the environmental implications of advances in production research.

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Circular economy; eco-efficiency; environmental sustainability; green manufacturing; sustainable production; systematic review

1. Introduction

Environmental sustainability urgently needs to be embraced by society at large and industry especially to address global challenges caused by emissions and resource consumption exceeding natural ecosystems' assimilative and regenerative capacity (Cumming & Von Cramon-Taubadel, 2018; Velenturf & Jopson, 2019). Eco-efficiency is a powerful approach to tackle such environmental issues. It is commonly defined as 'doing more with less' and characterised by seven guiding principles (World Business Council for Sustainable Development, 1996): (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; and (7) increase the service intensity of goods and services. The fourth, fifth, and sixth principles – recyclability,

CONTACT Mélanie Despeisse melanie.despeisse@chalmers.se Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden

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renewable sourcing, and product durability – align with circular economy principles. Recent developments with circular economy were strongly led by the Ellen MacArthur foundation with three design principles: eliminate waste and pollution, circulate products and materials at their highest value, and regenerate natural systems (The Ellen MacArthur Foundation, 2015).

Circular manufacturing is a sub-concept whereby circular strategies for reuse, remanufacturing, recycling, and other closed-loop pathways are employed by manufacturing companies (Acerbi & Taisch, 2020). While industrial applications have grown significantly in the last two decades, eco-efficiency and circular economy are yet to become an industrial norm to achieve impact at scale (Despeisse et al., 2021; Nujen et al., 2021) and shrink society's footprint to comply within the planetary boundaries (Velenturf & Jopson, 2019).

Several scientific communities in the field of production research are addressing sustainability topics in response to environmental pressures such as climate change. One such community is the International Federation for Information Processing Working Group 5.7 (IFIP WG5.7) on Advances in Production Management Systems (APMS) which aims to promote and facilitate advances in the field of sustainable and smart production management systems (https://www.ifipwg57.org/). The working group is highly interdisciplinary with a collaborative research culture. The community's research contributions are disseminated globally through publications and most notably through the annual APMS conference.

Previous reviews analysed the themes characterising the scientific contributions from the IFIP WG5.7 and its international community through the APMS conferences to clarify the trends in past and current research and to highlight gaps to be addressed in the future (Keepers et al., 2019; Satyro et al., 2017). The present study aims to investigate more specifically the research contributions in advancing the field of green manufacturing, focusing on eco-efficiency and circular economy, from this scientific community through APMS conference papers published since 2012. This systematic review includes theoretical contributions with proposed environmental approaches (development of concepts, frameworks, tools, and methods) as well as their implementation in the manufacturing industry (case studies, demonstrators, cleaner technologies, greener and products processes, etc.). The research question guiding the inquiry is: How has the topic of environmental sustainability been addressed by the research community on Advances in Production Management Systems?

This paper is structured as follows: Section 2 describes the systematic review process to analyse the APMS conference proceedings; Section 3 reports the overall trends observed in the last ten years; Section 4 presents the results from the systematic review showing which eco-efficiency principles have been addressed and to what degree; Section 5 discusses the results with a cross-thematic analysis showing how environmental sustainability issues overlap with dominant production research themes; Section 6 summarises the overall trends observed in the last ten years of APMS proceedings and proposes updated eco-efficiency principles applied to production systems; finally, Section 7 concludes the contribution with a thematic framework to support future research and development for more eco-efficient and circular industrial systems.

2. Materials and methods

This systematic review focused on papers published in the last ten years in the Advances Production Management Systems (APMS) conference proceedings (publication year from 2012 onwards). The bibliometric information of the proceedings was collected using Scopus and imported in two applications for the content analysis: Bibliometrix (Aria & Cuccurullo, 2017) and Rayyan (Ouzzani et al., 2016). Bibliometrix was used as a macro-analysis tool to identify trends, clusters, and dominant themes in how different research topics relate to each other and their evolution over time. Rayyan was used as a text-mining tool to filter papers containing specific keywords associated with the seven principles as listed in Table 1. The text searches were performed on title, abstract, and indexed keywords.

One of the limitations of the coding method employed is the use of specific keywords which may not capture all relevant papers for a given principle. While the terminology associated with energy efficiency, renewable sources and recycling is straightforward, it may be less so for material efficiency, environmental impact, and product-service systems. To minimise the impact of this shortcoming, synonyms and variations were tested to capture additional papers using uncommon terminology. However, it was found that the mainstream terminology from Table 1 captured the majority of relevant papers. Other expressions were used, such as 'material efficiency', 'energy intensity' and 'biodegradable', but yielded no results, therefore not shown in the table.

Each paper containing these keywords in the title, abstract, or indexed keywords was coded manually to include or exclude based on whether the study connected to environmental sustainability. Each included paper was then labelled using the seven eco-efficiency principles as an analytical tool. The coding also expressed the degree to which the eco-efficiency principles were addressed (strong, weak, or no connection). When the title and abstract were ambiguous, the full text was consulted to clarify the strength of the coding.

Table 1. Keywords used to identify papers addressing eco-efficiency based on the principles defined by the World Business Council for Sustainable Development (1996).

Principles	Keywords used for text mining (Number of papers)
Multiple principles	efficiency (188), efficient (176), sustainability (168), sustainable (159), environmental (156), lean (122), life cycle (84), lifecycle (56), green (32), product life cycle (25), ecosystem (18), environmental performance (15), ecosystems (15), sustainable supply (12), eco-efficiency (10), green supply (4), industrial symbiosis (3), natural resources (3), eco-efficient (2), natural resource (1)
EE1. Material intensity	resource efficiency (7), waste management (5), reduce waste (5), resource efficient (4), waste reduction (3), material intensity (1), eliminate waste (1), reduced waste (1)
EE2. Energy intensity	energy consumption (45), energy efficiency (44), energy efficient (21), energy savings (4), energy saving (2), energy reduction (1)
EE3. Toxic dispersion (environmental impact)	environmental impact (32), carbon (22), greenhouse (12), co2 (10), global warming (9), pollution (9), carbon footprint (8), climate change (6), chemical (6), carbon emissions (4), hazards (4), hazardous (3), carbon emission (2), hazard (1)
EE4. Recyclability	recovery (16), recycling (15), recycle (8), recycled (4), recyclability (1)
EE5. Renewable resources	renewable (15), biological (3), regenerative (2), regeneration (1), restoration (1), restorative (1), bio-based (1)
EE6. Durability	circular (26), remanufacturing (17), repair (14), closed loop (12), circularity (8), remanufactured (5), remanufacture (4), durability (3), life extension (2), closing the loop (1)
EE7. Service intensity	service (246), servitization (23), product-service systems (20), service oriented (20), product service system (14), service based (10), product-service system (9)

While a degree of subjectivity is unavoidable when conducting such text analysis, the impact of researchers' bias was reduced by having two researchers coding the papers independently. This double analysis also increased the robustness of the results as multiple iterations of analysis were performed to ensure that both researchers covered the same sample to be included in the results. The coding was compared to resolve conflicts; i.e. decisions to include or exclude, and strong or no connection to a given eco-efficiency principle found. Only a few papers were labelled differently; these conflicting cases were re-analysed jointly to identify the reason for the differences and align the coding. This process allowed the researchers to refine the criteria for labelling the conference papers as well as enrich the principles' definitions to capture more nuanced applications of eco-efficiency in production.

3. General trends in advances in production management systems

The APMS conference is an annual event that started in 2000. A bibliometric study by Keepers et al. (2019) provides a historical review of the APMS conferences with an overview of co-authorships (network diagrams), international collaborations, and the evolution of specific research themes associated with Special Interest Groups between 2000 and 2018. The present study focuses on the trends observed in the APMS proceedings published since 2012 and includes 1846 papers (conference reviews and editorials were excluded). The conference themes for each year are listed in Table 2 along with the number of papers and volumes in the conference proceedings.

Table 2. List of APMS conferences included in the analysis.

Conference date, location	Themes	# of papers	# of volumes
26–28 September 2011, Stavanger, Norway	Value Networks: Innovation, Technologies, and Management	66	2
24–26 September 2012, Rhodos, Greece	Competitive Manufacturing for Innovative Products and Services	184	2
9–12 September 2013, State College, PA, USA	Sustainable Production and Service Supply Chains	134	2
20–24 September 2014, Ajaccio, France	Innovative and Knowledge-Based Production Management in a Global-Local World	233	3
7–9 September 2015, Tokyo, Japan	Innovative Production Management Towards Sustainable Growth	164	2
3–7 September 2016, Iguassu Falls, Brazil	Initiatives for a Sustainable World	112	1
3–7 September 2017, Hamburg, Germany	The Path to Intelligent, Collaborative and Sustainable Manufacturing	122	2
26–30 September 2018, Seoul, Republic of Korea	Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing	68	1
	Smart Manufacturing for Industry 4.0	61	1
1–5 September 2019, Austin, TX, USA	Production Management for the Factory of the Future	88	1
	Towards Smart Production Management Systems	73	1
30 August – 3 September 2020, Novi Sad, Serbia	The Path to Digital Transformation and Innovation of Production Management Systems	77	1
	Towards Smart and Digital Manufacturing	87	1
5–9 September 2021, Nantes, France	Artificial Intelligence for Sustainable and Resilient Production Systems	377	5

Note that the proceedings for the APMS 2011 and APMS 2012 conferences were published the succeeding year (dated 2012 and 2013 respectively). Therefore, papers dated 2013 in the citations are from the APMS 2012 and APMS 2013.

The number of papers per country per year strongly correlates with the hosting countries, often located in Europe explaining the trend observed: most of the papers are from European institutions. Figure 1 shows the distribution of multi-country and single-country papers (MCP and SCP respectively) for the top 15 countries.

A correlation was also found between the conference themes and the indexed keywords reflecting dominant research themes presented at each conference. Figure 2 shows the evolution of the top keywords each year (minimum frequency of 12). For example, research on supply chains and supply chain management (searching titles, abstracts, and keywords) peaked with 74 papers in 2013 with the conference theme 'Sustainable Production and Service Supply Chains' and then reduced to 10–20 papers in later years. Similarly, the topic of knowledge management peaked with 34 papers in 2014 as the conference theme was 'Innovative and Knowledge-Based Production Management in a Global-Local World'.

Sustainable manufacturing and environmental impact also appeared as top keywords at APMS 2012 (publication year 2013 in Figure 2). Sustainable development became a dominant keyword between 2013 and 2016 with APMS 2015 on 'Innovative Production Management Towards Sustainable Growth' and APMS 2016 on 'Initiatives for a Sustainable World', and then increased again recently with APMS 2021 on 'Artificial Intelligence for Sustainable and Resilient Production Systems'. Life cycle research followed a similar pattern with keywords such as product life cycle management and life cycle assessment between 2013 and 2016, and then again in 2021. Product

Figure 1. Number of papers per country (top 15 countries) and international collaborations (MCP: multiple country publication; SCP: single country publication).

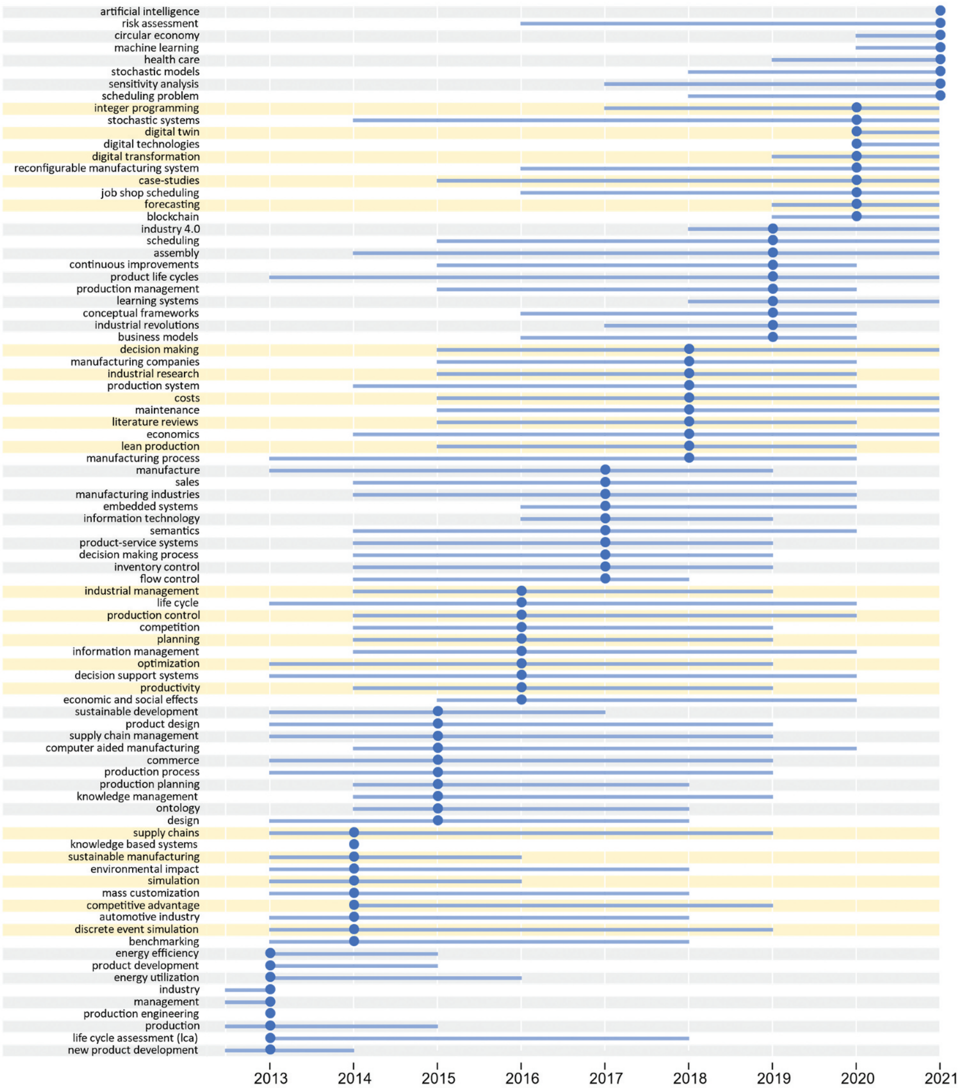

Figure 2. Evolution of dominant research topics over time based on indexed keywords.

life cycle studies are not systematically connected to environmental sustainability but often overlap with environmental management, impact assessments, and circular economy.

The topic of environmental sustainability was less prominent between 2016 and 2020 while smart manufacturing and industrial digitalization became topics interest. Research on environmental sustainability and resource efficiency was still presented at those APMS conferences, but not in the top 12 keywords except for circular economy which appeared as a dominant research topic within the APMS community in 2020. Earlier conferences also tackled circular strategies such as recycling and remanufacturing but

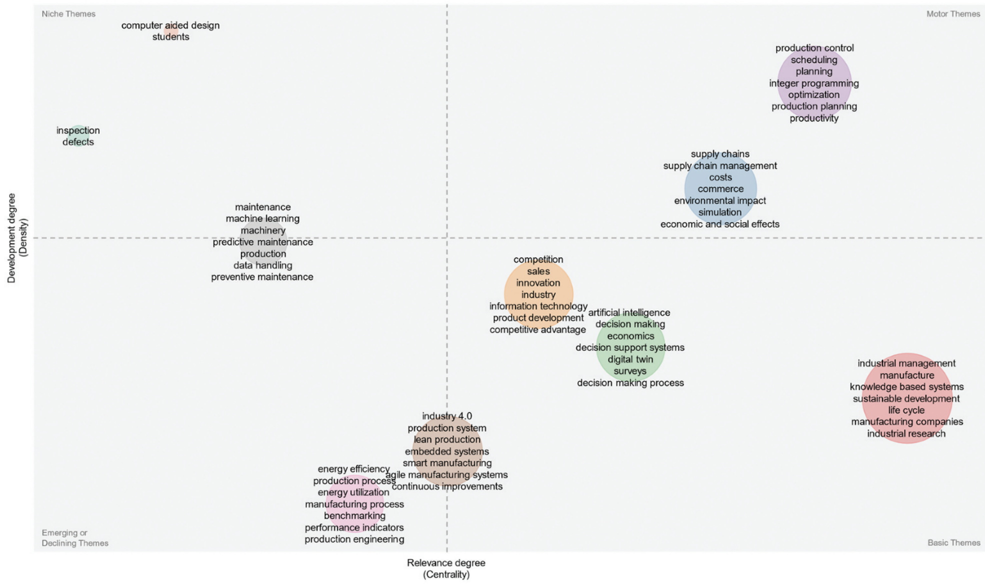

Figure 3. Thematic map of research topics for APMS conference 2012–2021 based on indexed keywords.

with fewer papers. Circular economy is a fast-growing research theme at APMS conferences with eight papers using this keyword in 2020 and 16 papers in 2021, appearing as one of the most recent trending topic in Figure 2.

The thematic map in Figure 3 shows research topics clustered and mapped along two dimensions, centrality (x-axis) and density (y-axis). The notion of centrality corresponds to the intensity of a cluster's connections to other clusters. In other words, centrality measures the degree of external interactions between clusters, indicating which research themes are 'considered crucial by the scientific or technological community' (Callon et al., 1991). Density characterizes the internal connections between themes and keywords making up a given cluster. Stronger connections indicate that the research themes within the cluster 'constitute a coherent and integrated whole' (Callon et al., 1991).

The thematic map shows the relative importance and interconnectedness of the different research topics presented at the APMS conferences. Production planning and control and optimization are both dominant and well-established research topics (motor themes in the upper-right quadrant, high density, high centrality), followed by supply chain management. Preventive and predictive maintenance and machine learning are well-established topics (medium density), but fewer connections to the other clusters (lower centrality). The topics of industrial management, knowledge-based systems, sustainable development, and life cycle studies are less well developed (lower density) but they are broad and highly multidisciplinary topics (high centrality). The cluster on energy efficiency, benchmarking, and performance indicators is less well connected externally (medium centrality) and internally (lowest density).

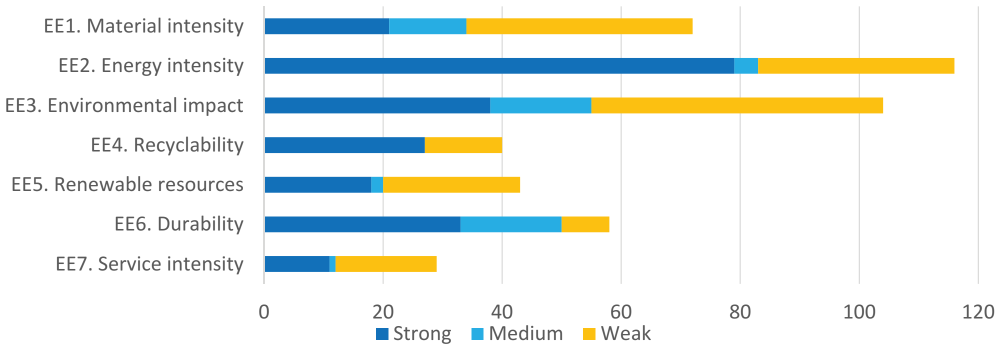

Figure 4. Number of papers (N = 239) addressing eco-efficiency and strength of connection to each principle.

4. Eco-efficiency principles in production research

This section presents the results from the text analysis to identify papers addressing eco-efficiency, using the seven principles defined by the World Business Council for Sustainable Development (1996) as an analytical lens. The number of papers and the strength of connection to each principle is shown in Figure 4. The full list of papers coded as connected to the eco-efficiency principles can be found in supplementary material.

4.1. EE1. Reduce the material intensity of goods and services

The connection to the material intensity principle was relatively weak given the central role of manufacturing in converting natural resources into products and services. Amongst the papers coded with EE1 (73 papers), over half overlapped with EE2 and EE3, showing strong synergies between material efficiency, energy efficiency, and environmental impact management.

At a process level, enhanced material efficiency can be achieved through process improvements, such as zero-defect manufacturing (Psarommatis & Kiritsis, 2018) and factory data analytics (Ball et al., 2013; Ekwaro-Osire et al., 2021), and through advanced manufacturing technologies (Angioletti et al., 2017; Despeisse & Ford, 2015; Taghavi et al., 2015) to manage or reduce scraps, defects, and other forms of production waste. New manufacturing technologies can also support dematerialization through lightweight and multifunctional products to decouple material use from the function delivered (Despeisse & Ford, 2015; Karakoyun & Kiritsis, 2013) .

Material intensity can be addressed at a system level through waste valorisation with industrial symbiosis in connection to recyclability (EE4) (Albino et al., 2013; Benedetti et al., 2017; Chamani et al., 2021; Le Tellier et al., 2017). Material efficiency at supply chain level includes closed-loop supply chain and sustainable mass customization (Nielsen & Brunø, 2013), food waste prevention and reduction along the value chain (Christensen, Dukovska-Popovska, et al., 2019; Owasi & Formentini, 2021) and supply chain for solid waste management (Frimaio et al., 2016; Ghalehkhondabi & Maihami, 2019).

4.2. EE2. Reduce the energy intensity of goods and services

The topic of energy efficiency in manufacturing is relatively mature compared to other environmental issues such as pollution reduction and circular economy. Studies addressing energy and material efficiency overlapped to some extent (both EE1 and EE2, 10 papers); also called resource efficiency to encompass various forms of process inflows such as material, energy, water, and chemicals (e.g. Ball et al., 2013; Jain et al., 2013; Medojevic et al., 2019; Nielsen & Brunø, 2013).

Research on energy-efficient production often relies on data-driven solutions. For example, many studies used modelling and simulation to optimise energy consumption in manufacturing locally or from a life cycle perspective (e.g. Ekwaro-Osire et al., 2021; Heilala et al., 2013; Hibino et al., 2014; Kobayashi et al., 2015; Takasaki et al., 2017). Other studies proposed energy-related performance indicators (e.g. May et al., 2013; McGibbney et al., 2013; Wicaksono, Belzner, et al., 2013) and supporting data management systems (e.g. Brandenburg et al., 2013; Feng et al., 2013; Rippel et al., 2015; Wicaksono, Aleksandrov, et al., 2013). Another topic strongly related to energy efficiency is production planning and scheduling as discussed in Section 5.

4.3. EE3. Reduce pollution and environmental impact

In our analysis, environmental impact assessments were considered as a weak connection to EE3 as they indirectly support impact reduction. Remediation studies were more scarce but considered as a strong connection since they result in direct impact reduction (e.g. Carrières et al., 2021; Cerri et al., 2013). About half of the papers coded as EE3 mentioned or focused on climate impact (e.g. Abdelhalim et al., 2021; Ahmed et al., 2020; Rückert et al., 2018).

Environmental improvements and impact assessments also connected to energy intensity (EE2, 25 strong or medium connections) (e.g. Kemmoe Tchomte & Tchernev, 2014; Mourtzis et al., 2013; de Oliveira Gomes et al., 2013) and renewable sources (EE5, 8 strong or medium connections) (e.g. Ahmed et al., 2020; de Barros Miranda Gomes et al., 2014; Prado et al., 2013). About a third of the papers coded as EE3 mentioned or adopted a life cycle perspective (e.g. Karakoyun & Kiritsis, 2015; Rosich et al., 2013; Rückert et al., 2018) and a fifth of the papers adopted a network perspective beyond a single manufacturing company (e.g. Alewijnse & Hübl, 2021; Carrières et al., 2021; Deniaud et al., 2021; Malhéné & Pourcel, 2014; Mourtzis et al., 2013; Uusitalo et al., 2013).

This principle was less connected to other traditional research themes such production planning and scheduling, except for energy-related emissions from machining operations (Kemmoe Tchomte & Tchernev, 2014) and transport (Gayialis et al., 2018).

4.4. EE4. Enhance material recyclability

Papers considering recycling also addressed other eco-efficiency principles with the exception of one paper on scenario evaluation of recycling initiatives and reverse logistics (Garcia et al., 2019); i.e. recycling is rarely a stand-alone topic in production research. Over half of the papers coded as EE4 connected to material intensity (EE1) since recycling reduces our dependency on virgin resources and increases material efficiency at a system level (e.g. Angioletti et al., 2017; Daaboul et al., 2013; Garcia et al., 2020; Ito et al., 2013; de Oliveira Neto et al., 2016). In addition, since recycling is one of the strategies for circular economy, studies on recycling were often connected to other circular solutions; half of the papers coded as strongly connected to recyclability also addressed product durability issues (EE6) (e.g. Despeisse et al., 2021; Flores, Maklin, et al., 2018; González Chávez et al., 2020; Luglietti et al., 2014).

Studies investigating the impact of recycling on manufacturing systems considered activities both at company and regional level. For example, new approaches for process development, waste and resource management were proposed to apply the concept of eco-design and to stimulate the creation of industrial networks supporting industrial symbiosis (Albino et al., 2013; Benedetti et al., 2017; Chamani et al., 2021; Taps et al., 2013; Le Tellier et al., 2017). Finally, some studies considered the involvement of consumers, the need for more collaboration between stakeholders to ensure that materials and end-of-life products are collected and in turn enable recycling (Bjelkemyr et al., 2015; Despeisse et al., 2021; Ghalehkhondabi & Maihami, 2019; Ito et al., 2013; Kvadsheim et al., 2021; Roy et al., 2021).

4.5. EE5 Maximise sustainable use of renewable resources

Most of the studies on renewable resources focused on energy systems rather than material sourcing. For example, renewable sources of energy (solar or wind energy) from a regional perspective for solar (Carreira Junior et al., 2016; Prado et al., 2013) and wind energy (Beinke et al., 2017; Costa et al., 2016), as well as solutions for energy storage (Schaab et al., 2017; Zanoni & Marchi, 2014). The implications of shifting to renewable energy sources relates to supply security and production systems' response to energy supply fluctuations (Schaab et al., 2017; Schulz et al., 2020; Stich et al., 2014).

Less than half of the studies coded EE5 also covered energy intensity (EE2) (e.g. Costa et al., 2016; de Freitas Bueno et al., 2016; Prado et al., 2013; Schaab et al., 2017; Yabuuchi et al., 2020; Zanoni et al., 2013). Some studies considered the environmental performance of shifting to renewable sources (EE3) (e.g. Ahmed et al., 2020; de Barros Miranda Gomes et al., 2014; Bonilla et al., 2016; Prado et al., 2013); e.g., energy accounting was used to assess biofuel and food production performance (Bonilla et al., 2016; de Freitas Bueno et al., 2016).

Besides studies in the food and agriculture sectors, few studies considered shifting to renewable sources to replace non-renewable and scarce materials; for example, the introduction of bio-based products and the need for increased interactions within supply chains (Sparling et al., 2013).

4.6. EE6. Extend product durability

In recent years, product life extension and durability attracted increasing interest in connection to circular economy applied at process, factory, and network levels. At a process level, durability has been addressed in combination with dematerialization and energy intensity principles (EE1 and EE2); for example, additive manufacturing for superior product quality and durability, lightweighting, multifunctional materials, and repair and remanufacturing (Angioletti et al., 2017; Despeisse & Ford, 2015). Advances in process technologies for e-waste sorting and value analysis can also enable higher value recovery options for end-of-use or end-of-life products (González Chávez et al., 2020; Taghavi et al., 2015).

At a factory level, some studies evaluated how to optimise the scheduling of production, maintenance and remanufacturing activities to extend products' life, accounting for component health, obsolescence, life cycle constraints and workload balancing (Demartini et al., 2019; Foussard et al., 2021; Kuik et al., 2015; Mejía-Moncayo et al., 2021). In addition, a few studies investigated engineering-to-order (ETO) and remanufacturing-to-order (RTO) approaches (Ali et al., 2015; Alqahtani & Gupta, 2016; Mwesiumo et al., 2020). Alqahtani and Gupta (2016) further proposed a model to predict base warranty and extended warranty periods for remanufactured products.

Studies adopting the network perspective investigated product life extension by involving several stakeholders across the value chain; for example, circular economy considerations in forward value chain (Mwesiumo et al., 2020), reverse and closed-loop supply chains (Glennane & Geraghty, 2021; Kuik et al., 2015), circularity indicators for value chains (Acerbi et al., 2021; Kurt et al., 2021) and other stakeholder collaboration issues (Mogos et al., 2021; Ringen et al., 2020).

Finally, the product durability principle was combined with recycling studies (EE4) to move up the waste hierarchy for a more circular economy. However, to enable higher value recovery, circular economy needs to be considered at early product and process design stage. There are strong connections between product durability and service-based business models (EE7) as they support circular strategies by enabling companies to retain control over the product and materials (Colombo et al., 2021; Husniah et al., 2018; Lieckens et al., 2012).

4.7. EE7. Increase the service intensity of goods and services

This principle requires interactions with customers and other stakeholders. For instance, environmental changes from clients' requests to define the engineering requirements and develop the optimal system configuration accordingly (Alix & Zacharewicz, 2013; Wiesner et al., 2017). Mourtzis et al. (2015) emphasised the importance of concept evaluation during the design phase to develop Product-Service Systems efficiently by preventing modifications or redesign. In addition, Colombo et al. (2021) identified 15 circular business models associated with different product-service life cycle stages and different circular strategies.

Industrial services include other forms of service-oriented solutions. They can also be applied to manufacturing processes and machines for extended equipment life (Husniah et al., 2018; Lieckens et al., 2012). Some studies investigated information sharing services across value networks to support service-oriented logistics (Beinke et al., 2017) and manufacturing (Giret & Salido, 2017). Other forms of industrial services potentially leading to more environmentally sustainable production are supporting data management services (Abner et al., 2020; Marquès et al., 2013; Reis & Gonçalves, 2018); e.g. manufacturing equipment maintenance services for durability, high operating efficiency, and capacity utilisation. These studies were not coded as EE7 because they did not match the original definition of the principle; i.e. they are not about physical products or tangible assets.

5. Cross-thematic analysis

Based on the general trends (Section 3) and detailed eco-efficiency trends (Section 4), this section discusses the findings from the thematic analysis of APMS papers addressing at least one eco-efficiency principle while tackling well-established topics in production research. For example, supply chain management, production planning and lean manufacturing are dominant topics in the APMS community with over 270 papers explicitly mentioning supply chain management, over 150 for production planning and control, and over 120 for lean manufacturing. The themes discussed in this section cover many themes from existing production research agendas for (e.g. Galati & Bigliardi, 2019; Machado et al., 2020) with the exception of policy development and studies related to market trends; for example, research avenues for four 'cluster' proposed by Galati and Bigliardi (2019) – business (market, world, global, etc.), operations (supply chain, operation, lean, etc.), technological solutions (platform, real-time, sensor, etc.), work and skills (task, training, experience, etc.) – and sustainability opportunities in five 'areas' proposed by Machado et al. (2020) – business model, production, supply chain, product, and policy development.

5.1. Supply chain management

A total of 273 APMS papers connected explicitly to supply chains. Our analysis revealed that research on supply chain management is more often associated with material intensity (EE1, 16 papers) (e.g. Chamani et al., 2021; Christensen, Mantravadi, et al., 2019; Ghalehkhondabi & Maihami, 2019; Nielsen & Brunø, 2013) and environmental impact management (EE3, 14 papers) (e.g. Ahmed et al., 2020; Brondi et al., 2013; Deniaud et al., 2021; Jørsfeldt et al., 2013) than with other eco-efficiency principles. Studies on circular economy also overlapped with the field of supply chain management, related to some degree to recycling (EE4, 7 papers) (Alblas et al., 2013; Ghalehkhondabi & Maihami, 2019; Hettiarachchi et al., 2021; Marchi et al., 2017; Nielsen & Brunø, 2013; Taps et al., 2013; Umeda, 2013) and other circular strategies for product durability and useful life extension (EE6, 12 papers) (e.g. Glennane & Geraghty, 2021; Kurt et al., 2021; Lieckens et al., 2012; Nielsen & Brunoe, 2015; Tanimizu et al., 2013; Zikopoulos et al., 2010). While industrial networks, forward and reverse supply chains, and value chains represent high-level systems perspectives adopted in production research, company, and process perspectives are the most common as they correspond to the level at which direct improvement actions can be taken.

5.2. Production planning and scheduling

Over 150 APMS papers addressed the topic of production planning and scheduling, of which 19 papers with strong connections to at least one eco-efficiency principle. The relationship with energy intensity was particularly prominent as discussed in subsection 4.2 (EE2, 10 papers). Amongst the papers related to energy efficiency, a few studies aim to minimise energy-related emissions (EE3, 2 papers) in job-shop manufacturing (Kemmoe Tchomte & Tchernev, 2014) and transport (Gayialis et al., 2018). In addition, other studies also integrated planning for reverse supply chains and remanufacturing (EE6, 3 papers) (Kuik et al., 2015; Mejía-Moncayo et al., 2021; Quezada et al., 2021). Finally, waste reduction through a dynamic scheduling tool for zero-defect manufacturing (Psarommatis & Kiritsis, 2018) and waste valorisation through production planning to enable industrial symbiosis (Chamani et al., 2021) connected to material intensity (EE1, 2 papers).

5.3. Lean production

Another dominant topic in production research is Lean with 122 APMS papers connected to Lean principles and tools. However, only a few papers employed the Lean philosophy in connection to eco-efficiency principles (14 papers); for example, applying lean tools and principles to support material efficiency (EE1) and circular strategies (EE4 and EE6) (Demartini et al., 2019; Flores, Golob, et al., 2018; Kanikuła & Koch, 2010; Mangers et al., 2021; Nujen et al., 2021; De Oliveira Costa Neto & De Oliveira Morais, 2016; Pawlik et al., 2013). In addition, Lean studies also connected to environmental impact management (EE3, 4 papers): Bogdanski et al. (2013) considered energy-related CO_2 emissions; Bush et al. (2014) developed a lean methodology called Transformation Distribution and Utilization to reduce the environmental impact of manufacturing processes; Birkie et al. (2018) proposed a green kaizen method called Green Performance Map for pharmaceutical manufacturing; and Serpa et al. (2014) focused on the environmental impact of waste paper in governmental institutions in Brazil. Finally, some studies also employed extended versions of value stream mapping to address energy efficiency (Bettoni et al., 2015; Bogdanski et al., 2013; Bush et al., 2014; Schillig et al., 2015). Additional studies did not explicitly mention Lean but also used VSM to address energy efficiency (Heilala et al., 2013) and circular economy (Nujen et al., 2021).

5.4. Life cycle perspective

Focusing on studies adopting a life cycle perspective, 55 papers connected explicitly to eco-efficiency (e.g. Brondi et al., 2013; Heilala et al., 2013). Environmental impact assessment and management (EE3, 30 papers) was the most common principles addressed with strong to medium connections (e.g. Heilala et al., 2013; de Oliveira Gomes et al., 2013; Toloi et al., 2019) or with weak connections (e.g. Cerri et al., 2013; Despeisse & Bekar, 2020; de Gomes et al., 2015; Ruini et al., 2013). Life cycle studies also overlapped with the topic of circular economy; e.g. recyclability (EE4, 13 papers) (e.g. Bjelkemyr et al., 2015; Daaboul et al., 2013; Karakoyun & Kiritsis, 2013), and other circular strategies for product durability (EE6, 17 papers) (e.g. Colombo et al., 2021; Kuik et al., 2015; Ringen et al., 2020; Zhao et al., 2013), with some overlap between the two principles (EE4 and EE6, 5 papers) (Angioletti et al., 2017; Flores, Maklin, et al., 2018; González Chávez et al., 2020; W. Kim & Simpson, 2013; Luglietti et al., 2014).

5.5. Simulation and optimization

Focusing on modelling and simulation, 27 papers used simulation to assess the performance of production systems considering environmental aspects in the development, planning, and execution phases. The majority of simulation-based studies addressed energy efficiency (EE2, 18 papers) often combined with environmental impact assessments to various degrees (EE3); for example, Discrete Event Simulation to evaluate production networks' performance considering conflicting criteria (cost, time, CO_2 emissions, energy consumption, and quality) and performance indicators (flexibility, throughput, and work-in-process) to compare centralised and decentralised networks for personalised product manufacturing (Mourtzis et al., 2013). Jain et al. (2013) proposed a continuous improvement methodology to increase efficiency and reduce the environmental impact of manufacturing systems. de Oliveira Gomes et al. (2013) proposed computational models to compare different scenarios for layout planning by combining Discrete Event Simulation analysis (DES) with Life Cycle Assessment (LCA). Nadoveza et al. (2013) further proposed a concept and tool for graph-based representation of LCA simulation results to facilitate visual analysis and interpretation. Penagos et al. (2021) simulated the sustainability performance (profitability, environmental impact, and social development) of coffee farms in Columbia to evaluate supply chain alternatives and identify a balance between economic and social benefits against local environmental risks/impacts. Shahrokhi and Bernard (2021) used fuzzy theory to simulate human tasks and assess various risks, including biological, chemical, and physical hazards.

Simulation-based studies sometimes combine energy efficiency measures with productivity and material efficiency measures (EE1); for example, factory modelling and optimization to address both material and energy efficiency (Badakhshan & Ball, 2021; Ball et al., 2013; Sproedt et al., 2013). Heilala et al. (2014) presented a prototype for multi-objective decision making, simulation and optimisation. Their software is based on a proposed approach for 'eco-process engineering system' software combining 'eco-efficiency and eco-innovation aspects in product service system (PSS) development and management' from a life cycle perspective. Kobayashi et al. (2015) investigated the relationship between productivity and process energy usage.

5.6. Digitalization and smart manufacturing

About 40 papers combined at least one eco-efficiency principle with digital/smart solutions. For example, focusing on circular economy, Y.-W. Kim and Park (2013) proposed an integrated data system to improve remanufacturing efficiency to keep products in productive use for longer. Despeisse et al. (2021) and Hettiarachchi et al. (2021) investigated various ways in which digitization can support different circular strategies. In addition, some papers suggested the use of digital technologies to support energy efficiency. For example, Amelete et al. (2021) and Tariq et al. (2013) investigated the adoption of digital technologies in combination with asset management practices on smart grids to extend their service life and to facilitate energy savings. Alvela Nieto et al. (2021) studied how to use digital tools, such as virtual and augmented reality, to provide information to operators about operating conditions and energy consumption to create awareness. Regarding resource efficiency more generally, Badakhshan and Ball (2021) reviewed practices and current limitations with digital twins in manufacturing systems, and suggested further research for digital twins to support sustainable performance management across the product life cycle. Moreover, Psarommatis and Kiritsis (2018) explored the adoption of smart devices to detect defective parts and move towards zero-defect manufacturing.

5.7. Skills, training, and education

About 40 papers focused on education and training in connection to eco-efficiency principles at university level (Baalsrud Hauge et al., 2014; Edl, 2013) and for professional education (Despeisse & Lunt, 2017; Despeisse & Minshall, 2017; Verhulst & Boks, 2012). Sustainability education aims to raise awareness about the environmental impacts of manufacturing activities (EE3) (Moreira Filho & de Oliveira Costa Neto, 2013; Serpa et al., 2014), of various circular economy strategies (Garcia et al., 2020; Halfdanarson & Kvadsheim, 2020) and of sustainability terminology to established a common understanding amongst stakeholders (Ringen et al., 2020). In addition, a few papers made use of innovative educational tools such as gamification (Baalsrud Hauge et al., 2014; Despeisse & Lunt, 2017; Duin et al., 2013) and digitalization to actively engage learners with sustainability principles; for example, using virtual reality for visualization, training, and product development to support energy-efficiency manufacturing (Nabati et al., 2020).

5.8. Organizational change

Given the nature of production research, most of papers are in the field of industrial engineering. However, about 50 papers can be also identified as business research or organizational studies, often connecting to circular economy principles and especially product durability (EE6). For example, many researchers focused on circular business models (Acerbi & Taisch, 2020; Colombo et al., 2021; Halse & Jæger, 2019; Kvadsheim et al., 2019; Mogos et al., 2021; Mwesiumo et al., 2020), sustainable value and service-based business models (González Chávez et al., 2020; Marques et al., 2021; Ringen et al., 2020).

At company level, Flores et al. (2018) and Li and Evans (2019) looked at how process innovation and business model innovation support eco-efficiency. Most of these studies adopt a life cycle perspective to identify value opportunities more holistically; for example, Acerbi et al. (2020) studied how to manage the entire asset life cycle by integrating CE strategies with traditional asset management strategies.

At a system level, some studies proposed new methods to measure the sustainability performance of supply chains and values chains (Brondi et al., 2013; Hettiarachchi et al., 2021; Kurt et al., 2021). Finally, in line with the recent digitalization trend, a few studies investigated the role of digital technologies to manage sustainable supply chain (Deniaud et al., 2021; Hettiarachchi et al., 2021) and lower barriers to CE (Halse & Jæger, 2019).

6. Revisiting eco-efficiency principles

The number of APMS papers linked to eco-efficiency varied over the years with a shifting focus on different principles as shown in Figure 5. Surprisingly, no increasing trend was observed despite growing environmental awareness. A potential explanation for this

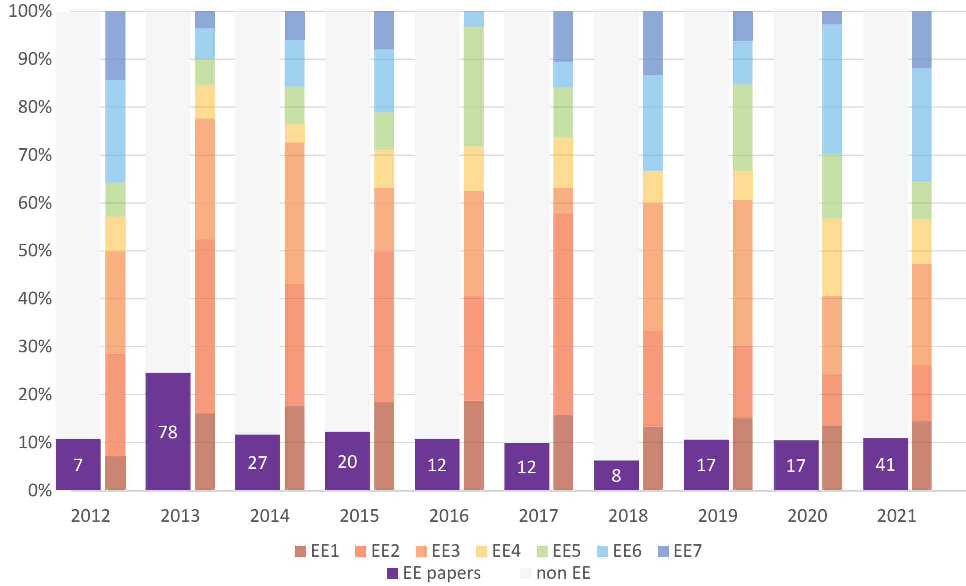

Figure 5. Ratio and number of APMS papers addressing eco-efficiency each year (purple bar) and distribution of across eco-efficiency principles (colourful bars).

trend is the prominence of digitalization and Industry 4.0 as a strong research trend, possibly taking some of the spotlight away from sustainable development. While digitalization has been recognized as an opportunity towards more sustainable industrial systems, it does not always deliver such benefits if not integrated explicitly. Therefore, more attention needs to be placed on the sustainability implications of digitalization.

Interestingly, 2021 and 2012 have a similar distribution of papers across principles, but with more papers focus on energy intensity (EE2) than material intensity (EE1) in 2012, and conversely more focus on material than energy in 2021. Overall, energy efficiency (EE2) is the most common principle addressed and remained a dominant topic until 2017, reflecting a historical trend as sustainable manufacturing initially had a strong focus on reducing energy consumption at operational level. Environmental performance (EE3) was also addressed with mostly papers on environmental impact assessment, only half of which also proposed solution for direct environmental impact reduction. Finally, the topics of product durability, remanufacturing and recycling (EE4 and EE6) are also increasing since 2020 with the uptake of circular economy in production research.

Based on the findings from the systematic review and the authors' own expertise on eco-efficient and circular manufacturing, Table 3 proposes an update on the definition of the seven eco-efficiency principles so they can be considered more systematically in production research. The examples of strategies listed is not meant to be comprehensive as there may be other eco-efficiency and circular strategies not captured here or yet to be developed. However, these examples can guide researchers in integrating eco-efficiency in their own research; i.e. connecting to the dominant research themes identified in section 5. While all dominant themes are relevant for eco-efficiency, two of them are more general (overarching themes) and thus not visible at the level of detail of the principles and examples of strategies in Table 3: (1) *skills, training and education* to develop education programmes accounting for

Table 3. Updated eco-efficiency principles applied to production systems.

Principles and examples of associated strategies
EE1 Reduce material intensity of goods and services
• Dematerialization through product design enabled by novel process technology
○ Lightweight materials and structure, product miniaturisation
○ Multi-functionality, software, and service-orientation
• Material efficiency in production processes
○ Production waste reduction, zero-defect and non-product/by-product/packaging waste
○ Lean and green, waste, and non-value adding process reduction or elimination
○ Material flow modelling and simulation, process optimization
• Material efficiency in supply chains and value networks
○ Supply chain management and reverse logistics for eco-efficient material handling
○ Waste reduction through industrial symbiosis networks, waste exchange
○ Downstream waste avoidance through sustainable and responsible consumption
EE2 Reduce energy intensity of goods and services
• Energy intensity at process and factory levels
○ Energy-efficient production through planning and scheduling, simulation, and optimization
○ Energy-efficient processes through technology development
• Energy intensity at a system level
○ Embodied energy of materials, products and services from a life cycle perspective
○ Energy consumption during product use and end-of-life management (trade-offs across life cycle stages)
EE3 Reduce toxic dispersion (pollution and environmental impact)
• Impact prevention and reduction
○ Substituting for non-toxic sources
○ Toxic emissions handling/management
• Impact assessment
○ Trade-offs across the product life cycle
○ Trade-offs between environmental, social and economic aspects
EE4 Enhance recyclability and material recovery
• Upstream and downstream considerations for circular material flows
○ Eco-design concept – design for the environment, design for disassembly/recycling/remanufacturing, design for X
○ Ensuring recyclability and material recovery at the product end-of-life, downstream circular flows
○ Using circular materials as input for manufacturing, upstream circular flows
○ Supply chain management for the creation of closed and open loops supply chains
• Material recovery for industrial symbiosis
○ Internal synergies within factories
○ External synergies between factories within regions
EE5 Maximise the sustainable use of renewable sources
• Renewable energy sources
○ Renewable energy technology
○ Renewable energy storage to foster security of supply
○ Flexible energy management systems to support supply fluctuations
• Renewable material sources
○ Bio-based products, material sourcing
○ Biodegradable or compostable materials, end-of-life management
EE6 Extend product and component durability
• Product and component quality
○ Product and material integrity for longevity, spare part availability
○ Robust and simpler product assemblies, fewer components
• Closing the loop of material flows
○ Product design for disassembly, repair, refurbish, and remanufacture
○ Design of circular processes – repair, refurbish, and remanufacture
○ Retaining control and collect products/components to enable circular strategies
• Value retention for industrial machines, equipment, and tools
○ Repair, maintenance, and upgradability of industrial assets

(*Continued*)

Table 3. (Continued).

Principles and examples of associated strategies
EE7 Increase the service intensity of goods and services ● Product-service systems ○ Design of the service ○ Delivery of the service – sharing, leasing, and renting of products ○ Digitalization of products to design smart products for service delivery ● Industrial services ○ Asset management, equipment performance monitoring, asset life cycle extension services, leasing, and maintenance contracts, etc. ○ Data management to support environmental impact assessment and resource efficiency ○ Data management for environmental performance management ○ Process digitalization for remote control and monitoring

Figure 6. Thematic framework for eco-efficient and circular industrial systems.

current and future industry needs as well as employee training to align with company's sustainability goals and strategy; and (2) *organizational change* to develop organizational structures required to reap the benefits from the sustainability transition.

7. Conclusion

This study investigated the contributions in the field of eco-efficiency and circular economy from the IFIP WG 5.7 research community by analysing the APMS proceedings published in the last ten years. The aim was to capture the current state of knowledge in this community and to promote eco-efficiency in production research. Research efforts in this community already show that eco-efficiency can be integrated as operating principles for more sustainable production systems. However, environmental sustainability appears to be a stagnant research theme, whereas other trends, such digitalization, are increasing rapidly. This trend is worrying and calls for better support to integrate sustainability more consistently and systematically in production research and development.

To facilitate this integration in future research, we proposed an update on the definition of the seven eco-efficiency principles with more detailed examples of strategies associated with different production research themes. These strategies can be used by researchers and practitioners to set a clear direction for the practical implications of their work. Finally, Figure 6 combines the eco-efficiency principles and dominant themes as a visual synthesis with a simple and clear structure to guide further work towards eco-efficient and circular industrial systems. This thematic framework aims to encourage the uptake of eco-efficiency in production research and development, with the ultimate goal to shrink industrial activities' environmental footprint within the planetary boundary for a more sustainable society.

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ORCID

Mélanie Despeisse http://orcid.org/0000-0002-1772-3884
Federica Acerbi http://orcid.org/0000-0002-0818-4620

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