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Citation for the original published paper (version of record):
Gonçalves Machado, C., Winroth, M., Hans Dener Ribeiro da Silva, E. (2019)
Sustainable manufacturing in Industry 4.0: an emerging research agenda
International Journal of Production Research, In Press
http://dx.doi.org/10.1080/00207543.2019.1652777

International Journal of Production Research

ISSN: 0020-7543 (Print) 1366-588X (Online) Journal homepage: https://www.tandfonline.com/loi/tprs20

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To cite this article: Carla Gonçalves Machado, Mats Peter Winroth & Elias Hans Dener Ribeiro da Silva (2019): Sustainable manufacturing in Industry 4.0: an emerging research agenda, International Journal of Production Research, DOI: 10.1080/00207543.2019.1652777

To link to this article: https://doi.org/10.1080/00207543.2019.1652777

Published online: 20 Aug 2019.

International Journal of Production Research, 2019
https://doi.org/10.1080/00207543.2019.1652777

Sustainable manufacturing in Industry 4.0: an emerging research agenda

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(*Received 8 August 2018; accepted 30 July 2019*)

This systematic review intends to identify how sustainable manufacturing research is contributing to the development of the Industry 4.0 agenda and for a broader understanding about the links between the Industry 4.0 and Sustainable Manufacturing by mapping and summarising existing research efforts, identifying research agendas, as well as gaps and opportunities for research development. A conceptual framework formed by the principles and technological pillars of Industry 4.0, sustainable manufacturing scope, opportunities previously identified, and sustainability dimensions, guided analysis of 35 papers from 2008–2018, selected by a systematic approach. Bibliometrics data and social network analysis complement results identifying how research is being organised and its respective research agendas, relevant publications, and status of the research lifecycle. Results point to that the current research is aligned with the goals defined by different national industrial programs. There are, however, research gaps and opportunities for field development, becoming more mature and having a significant contribution to fully developing the agenda of Industry 4.0.

Keywords: sustainable manufacturing; Industry 4.0; 4th industrial revolution; literature review; industrial development agenda

1. Introduction

In the last years, industrial production systems are being transformed due to a higher level of digitalisation, which leads to an intelligent, connected, and decentralised production. This new level of organisation is often called ‘The fourth industrial revolution’ or ‘Industry 4.0’ (Kagermann, Wahlster, and Helbig 2013; Hermann, Pentek, and Otto 2016). The core idea of Industry 4.0 is to use the emerging technologies in a way that business and engineering processes are deeply integrated making production operate in a flexible, efficient, and sustainable way with constantly high quality and low cost (Wang et al. 2016).

Guidelines for Industry 4.0 implementation, in general, are driven by government programs, such as: Germany – ‘High Tech Strategy 2020’ and ‘Industry 4.0’ (Kagermann, Wahlster, and Helbig 2013); United Kingdom – ‘Future of Manufacturing’ (Foresight 2013); United States – ‘Advanced Manufacturing Partnership’ (President’s Council of Advisors on Science and Technology 2014); France – ‘La Nouvelle France Industrielle’ (Conseil National de L’industrie 2016); European Commission – ‘Factories of the Future’ and ‘Horizon 2020’ (European Commission 2016); Japan – ‘Super Smart Society’ (Keqiang 2015); Sweden – ‘Smart Industry’ and ‘Produktion 2030’ (Ministry of Enterprise and Innovation 2016; Teknikföretagen 2017).

Manufacturing companies need to offer a higher return of investment and at the same time, environmental impacts should be reduced. It is also necessary for them to constitute an attractive workplace for people focusing on collaboration, learning, and development of competencies. Examples of requirements for the development of the Industry 4.0 agenda are listed on Table 1.

According to Ngjeqari (2016) and Beier, Niehoff, and Xue (2018), the 4th Industrial Revolution is an enabler of sustainable development, but the convergence of digital transformation and sustainability remains underdeveloped (Beier, Niehoff, and Xue 2018; Kiron and Unruh 2018). Recently, some studies have identified several interlinks between Industry 4.0 technologies and sustainable operations. For instance, De Man and Strandhagen (2017) discuss the influence of Industry 4.0 on sustainable business models, Kamble, Gunasekaran, and Dhone (2019) focus on the effects of Industry 4.0 technologies on Lean Manufacturing Practices for sustainable organisations, and Ghobakhloo (2019) presents the dependence power of the determinants for Industry 4.0 implementation in the sustainability context. However, our paper innovates while positioning

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Table 1. Examples of sustainability guidelines for Industry 4.0.

Specific goals, capabilities and timelines required
A more sustainable manufacturing in UK (Foresight 2013; Manufacturing Commission 2015)
***Goal**: A sustainable industrial ecosystem*
2013–2025: Efficiency & Resilience
• Minimised material inputs; waste management; energy efficiency; reduced water usage; efficiency in land usage; leadership in low-carbon technology.
• 2025–2050: Experimentation with new systems.
• New forms of value associated with products including sustainability; Products reused, remanufactured, recycled and redesigned with recovery in mind; More durable products designed for shared ownership; Spare capacity built into supply chains to ensure resilience.
2050 & Beyond: A resource constrained world
• Products use smaller amounts of materials and energy; Material is not land-filled but kept in a 'productive loop'; Cleaner and quieter factories close to consumers, suppliers and academic institutions; Supply chains with spare capacity at all stages.
FoF 2020 Roadmap (EFFRA 2016)
***Goal:**Sustainable Value Networks: manufacturing in a circular economy*
2018–2020
• De-and Remanufacturing Systems for Material and Resource Efficiency: manufacturer-centric circular economy strategies; product designed for circular economy; increase quality of remanufactured products with zero defect de-and remanufacturing solutions; innovative human-centric solutions for de-and remanufacturing operations; customer-oriented de-and remanufacturing production control methods and systemic solutions.
• Energy efficiency on factory level: green hybrid and cleaner processes; technologies to empower optimal heat management and industrial symbiosis; environmental assessment and energy control and management of existing production facilities.
• European Circular Economy Open Platform: integration of physical-products and cyber-services during their whole lifecycle.
Sustainable Production for Smart Factories (Ministry of Enterprise and Innovation 2016; Teknikföretagen 2017)
***Goal:**Improving the industrial sector's capacity for sustainable and resource-efficient production.*
2016–2030
• Developing new or improving technologies, products and services focus on reductions in emissions, phasing out of particularly harmful substances, higher energy and resource efficiency, reusability and recyclability and higher environmental performance.
• Exploiting new digital and other technologies enabling the transition to a fossil-free and circular economy.
• Encouraging circular economy business models.
• Ensuring that regulations and governance mechanisms incentivise/facilitate resource-efficient and environmentally friendly production and a sustainable supply of raw materials.

in a broader sense how the different technologies have been used for addressing sustainable operations while linking it to the different guidelines driven by government programs for Industry 4.0 implementation, as well as suggesting a research agenda to fill the gaps in meeting those goals and exploring new research opportunities.

Five questions together have the purpose of mapping the field (RQ1 and RQ2), which is relevant because a broader study was not previous identified; increase understanding about which concepts of sustainable manufacturing are being applied and are supporting the development of the Industry 4.0 agenda (RQ 3 and RQ4); finally, to present a research agenda and trends (RQ5) to support future research. The questions are as follows: (1) Who is working in the research field, when, and where? (2) What is the current research life cycle status? (3) How has sustainable manufacturing theory contributed to the Industry 4.0 drivers? (4) Which are the technologies currently addressing sustainable manufacturing in the Industry 4.0 context? (5) What are the current research efforts and opportunities?

The paper is organised as follows: section two presents a review of sustainable manufacturing and Industry 4.0, and how these two concepts are linked; the section is summarised in a conceptual framing used for later sample selection and content analysis. Then section three presents method discussion, including criteria for sample selection, social networks, and content analysis. Descriptive results, citations, co-citations and keywords networks are presented in section four, as well as literature gaps and research propositions. Concluding remarks, contributions, and implications for further research are discussed in the final section.

2. Basic terminology and conceptual framing

This section aims to present a summary of the concepts which guided the selection and analysis of the papers in order to summarise a construct about the links between Sustainable Manufacturing and Industry 4.0.

2.1. Sustainable manufacturing

Sustainable Manufacturing can be defined as the integration of processes and systems capable to produce high quality products and services using less and more sustainable resources (energy and materials), being safer for employees, customers and communities surrounding, and being able to mitigate environmental and social impacts throughout its whole life cycle. Benefits of sustainable manufacturing include cost reduction through resource efficiency and regulatory compliance improvement, better brand reputation, new market access, less labour turnover by creating attractive workplaces, and long-term business approach by creating opportunities to access financing and capital (Veleva and Ellenbecker 2001; Gunasekaran and Spalanzani 2012; Bonvoisin, Stark, and Seliger 2017; EPA 2018).

Bonvoisin, Stark, and Seliger (2017) define the sustainable manufacturing scope in four areas with its respective objects and applied disciplines, which were used to classify the papers in the sample:

- Manufacturing technologies (how things are manufactured) with focus on process and equipment (machine-tool, facility); linked disciplines are production engineering, factory planning, and operations management;
- Product lifecycles (what is to be produced) with focus on product and services' design; linked discipline is engineering design;
- Value creation networks (organisational context) with focus on organisations of companies and manufacturing networks; linked disciplines are business economics and knowledge management;
- Global manufacturing impacts (transition mechanisms towards sustainable manufacturing) with focus on studies about manufacturing impacts on the world, including society, environment, and economy.

Different aspects can contribute to a positive sustainable manufacturing strategy implementation, among others, the development of sustainability indicators, policies and procedures, companies cultures and internal conditions for sustainability, sustainable design strategies, and stakeholders' engagement for sustainability and technologies (Seliger 2007; Jovane et al. 2008; Rosen and Kishawy 2012; Bogle 2017).

2.2. Industry 4.0

Industry 4.0 concept is associated with the technical perspective of a Cyber-Physical-System (CPS) integrated into manufacturing operations and with Internet of Things (IoT) technologies into the industrial processes, which can be represented by smart factories, smart products, and extended value networks – vertical, horizontal and end-to-end integration. People, machines, and resources are vertically linked, while companies are linked horizontally across the value chain as in a social network created by CPS (Kagermann, Wahlster, and Helbig 2013; Bogle 2017; Waibel et al. 2017).

Terms including Industrial Internet (Bungart 2014), Integrated Industry (Bürger and Tragl 2014), Factory of the Future (Heynitz and Bremicker 2016; Liao et al. 2017), Smart Industry and Smart Manufacturing (Dais 2014; Wiesmüller 2014; Kusiak 2018) are also used to address similar requirements and are subsumed by the concept of 'Industry 4.0'. It is however perceived that they converge about the desirable features relating to being flexible and reconfigurable, low cost, adaptive or transformable, agile and lean (Radziwon et al. 2014).

This new industrial system is run by advanced manufacturing technologies. The set of 'pillars of technological advancement' identified by Rüßmann et al. (2015) will be considered for this research:

- Autonomous Robots – the use of robots in the production is evolving in their utility, increasing autonomy, flexibility, and interaction with humans and other robots.
- Simulation – besides the use for simulating products, materials and production processes, simulation models can be used to improve plant operations creating a virtual model of the factory including all elements (machines, products and humans), also called digital twins.
- Horizontal and Vertical systems integration – IT systems integration in the entire supply chain creating data-integration networks and internal cross-functions integration as well.
- Industrial IoT – devices with embedded computing communicating and interacting in real-time.
- Cybersecurity – integrated networks demanding protection for critical industrial systems, manufacturing lines, and also to secure reliable communication and information flows.
- Cloud – data-driven services and data sharing across different sites will be deployed in the cloud.
- Additive Manufacturing (AM) – AM will enable small batch production of customised and lighter products, also reducing logistics costs and stocks.
- Augmented Feality (AR) – beside various applications, AR can be used to improve work and maintenance procedures and promote virtual trainings.

- Big data and analytics – collection and analysis of large data sets from different sources supporting real-time decisions.

2.3. Links between Industry 4.0 and sustainable manufacturing

Digitalisation and sustainability are transversal themes crossing all parts of the production chain. In fact, both approaches present practices' convergence, such as: design for disassembly, remanufacturing, and recycling applied in the life cycle management; reverse logistics for circular economy, 'lean and green management' for resource efficiency; sustainable design reducing safety risks for workers' and consumers' eliminating the use of toxics parts in the product and production processes (Teknikföretagen 2017; Waibel et al. 2017; Duarte and Cruz-Machado 2017).

In general, sustainability benefits of Industry 4.0 are expected on: improving productivity, flexibility, and resource efficiency (e.g. big data for predictive maintenance and fast production systems reconfiguration); reduction of waste, energy consumption, and overproduction (e.g. renewable energy surplus shared with other plants); servitisation and stakeholders' engagement/collaboration (e.g. closed-loop production systems connecting machines, information systems, products and people in a network); job opportunities related to IT competences; improvement of quality of working environment reducing routine jobs, e.g. creating employment opportunities for disabled and elderly employees (Hermann, Pentek, and Otto 2016; Kiel et al. 2017; Waibel et al. 2017).

According to Stock and Seliger (2016), the Industry 4.0 can support value creation in all sustainability dimensions and, in this matter, they identify opportunities for industry development considering: (1) development of business models driven by smart data, offering new product-services; (2) closed-loop product life cycles and industry symbiosis creating value networks; (3) equipment using CPS for retrofitting SMEs (Small- and Medium-sized Enterprises) digitisation; (4) trainings and competence development supported by ICT technologies; (5) motivation and creativity fomented by programs supported by CPS (e.g. games and individual incentive systems for workers); (6) sustainable-oriented decentralised organisation focused on resource efficiency; (7) sustainable process design using new technologies (e.g. additive manufacturing) promoting closed-loop life cycles and cradle-to-cradle approaches.

To support effects of a solution on the sustainability dimensions, Stark et al. (2014) state that each sustainability dimension represents a specific system evolving around a digital value-creation solution, so one adopted solution can create direct impacts on one dimension system, but also have indirect effects on the other dimension systems of sustainability. The interactions between sustainability systems can occur in three different types: causal relations (effects between a solution and its direct and indirect impacts); magnitude and scale driver (direct and indirect impact is determined by the magnitude and scale of a solution's dissemination); and latency and timely duration dependencies (between effects and impacts). For papers' analysis, only the causal relations will be considered.

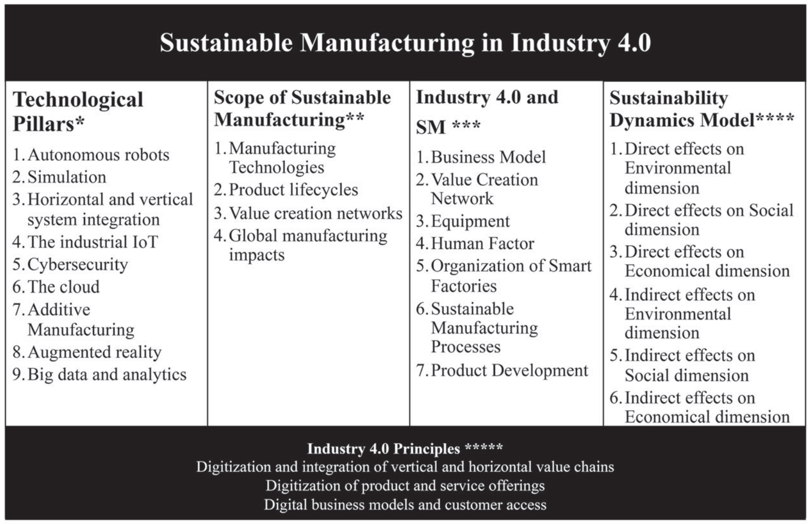
2.4. Conceptual framing for literature review

This study adopts an inductive-deductive approach based on Seuring et al. (2018) using, as a starting point, definitions of core terms and constructs selected from 'accepted' frameworks. As an example, the conceptual study presented by Stock and Seliger (2016) is one of the most cited contribution in the field, as confirmed by the references extracted from the sample (detailed on Section 4). Therefore, previous studies from Stock and Seliger (2016), Waibel et al. (2017) and Kiel et al. (2017) were identified as a reference for the theoretical framing, and to configure and to validate the axes that delineate the sample. Reasons for selecting the papers are based on the content directly linked with the research topic, as well as previous relevant authors' background in sustainable manufacturing and value creation, peer-reviewed evaluation, and citations. Conference papers were not considered as a limitation due to the fact that, as stated by Sarkis (2012), in some cases emergent research may appear in conference papers. The context presented was summarised in a conceptual framework illustrated on Figure 1.

3. Materials and methods

The systematic literature review is characterised as a replicable, scientific, and transparent method, designed to reduce potential bias through exhaustive literature searches. By providing an audit specification of the reviewers' decisions it can bring more reliability to the knowledge development process and methodological rigor to the reviewing process (Mulrow 1994; Cook, Mulrow, and Haynes 1997; Hart 1998; Tranfield, Denyer, and Smart 2003).

Research procedures in this paper follow guidelines provided by the method Knowledge Development Process-Constructivist (ProKnow-C) (Ensslin et al. 2014), structured in sample selection, bibliometric analysis and systematic analysis, summarised on Table 2. Research's axis was defined as 'sustainable manufacturing' and 'industry 4.0', which were tested in two versions (terms combined and one single phrase), to refine the sample. A preliminary investigation enabled



*RüBmann et al., 2015; **Bonvoisin's et al., 2017; ***Hermman, 2014, Stock and Seliger, 2016, Kiel et al., 2017, Waibel, 2017;**** Stark et al., 2016; *****Geissbauer et al., 2016

Figure 1. Conceptual framing for the literature review.

to identify three reference papers for testing adherence of the sample and keywords. Databases for sample collection were defined based on a previous literature review conducted by Liao et al. 2017.

Duplicate papers were found due to journals indexed in more than one database or the same paper was selected from more than one combination of keywords. Other exclusion criteria include: a paper has only its title, abstract, and keywords in English but not its full-text; the paper is not an academic article; and the paper did not explicitly dedicate efforts to discuss sustainability aspects in the Industry 4.0. The initial year of publication was not previously defined, however, after the portfolio approval the research timeline of research from 2008 to January 2018.

Bibliometric data, social and network analysis were performed to provide quantitative evidence about the development of the research and also to position the topic within the context, supporting RQ1. The set of analysis has the purpose to identify: papers' distribution; the relevance of journals and conferences; authors with a higher level of interaction and influence in the sample, analysed by means of their position in the network; research groups and main topics addressed (Hanneman and Riddle 2011). Two softwares were used to extract and organise bibliometric data from the sample: Mendeley® and MC3R®, this last one developed by Kluska et al. 2018. Social networks were generated using UCINET/NETDRAW®.

Systematic analysis seeks to explore the content of the papers following the conceptual framework described o Figure 1. In order to understand the research life cycle status, two different approaches were used: the theory development model by Carlile and Christensen (2005), and the Andrew Pettigrew's contextualist model (Pettigrew 1987, 2012).

Carlile and Christensen (2005) affirmed that the development of a theory can occur in two phases: (1) descriptive, creating familiarity with respect to a fact or phenomenon through literature surveys, interviews, technical visits, and other sources; (2) normative, creating an acceptable theory for a fact or phenomenon, occupied with the 'whys' of facts or phenomena that contribute to determine the occurrence. The development of a theory must go through three steps, in a way that interacts with the descriptive and normative phases: (i) observation (constructs); (ii) categorisation (frameworks); (iii) definition of relationships (models). When passing through the three phases, researchers develop the inductive part and, by using the results they obtained, improve the theory adopting the deductive part.

The model proposed by Andrew Pettigrew (1987, 2012) allows a more holistic analysis of the organisational change from a temporal perspective based on the content ('What' of change), context ('Why' of change), and the process ('How' of change). In this matter, papers were categorised in a way that the 'content' is represented by tangible outputs such as strategy, business objectives, performance measures and intangible benefits, i.e. insights into the business; 'context' is related to internal factors such as antecedent conditions, structure, frames of thought, leadership, culture, etc., and 'external' ones, such as economic and political environments, social trends, etc.; 'process' is represented by tools, frameworks, patterns, practices, etc.

4. Results and analysis

In this section, the results from the bibliometrics and content analysis are presented in order to answer the research questions.

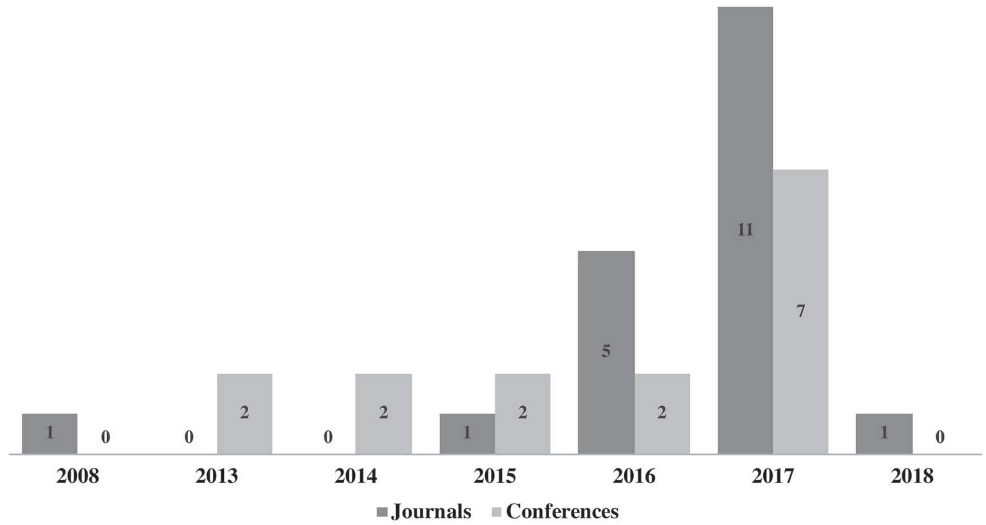
Table 2. Research steps and strategies.

Step	Actions	Results
Portfolio/sample selection	Reference papers selection	Stock, Tim, and Guenther Seliger. 2016. "Opportunities of Sustainable Manufacturing in Industry 4.0." *Procedia CIRP* 40: 536–541. doi:10.1016/j.procir.2016.01.129. Kiel, Daniel, Julian Müller, Christian Arnold, and Kai-Ingo Voigt. 2017. "Sustainable Industrial Value Creation: Benefits and Challenges of Industry 4.0." *International Journal of Innovation Management* 21 (08). doi:10.1142/S1363919617400151. Waibel, Mario, Len Steenkamp, Mankgatho Moloko, and Gert Adriaan Oosthuizen. 2017. "Investigating the Effects of Smart Production Systems on Sustainability Elements." *Procedia Manufacturing* 8 (October 2016). The Author(s): 731–737. doi:10.1016/j.promfg.2017.02.094.
	Search term test and validation	1st version – (industry 4.0; 4th Revolution; smart manufacturing) AND (sustainability; triple bottom line; sustainable manufacture; sustainable manufacturing; sustainable operations; sustainable production) 2nd version – ('industr 4.0' OR 'connect manufactur*' OR 'smart manufactur*' OR 'industrial internet of things' OR '21st manufactur*' OR '4th industrial revolution') AND (sustainab OR 'sustainab operatio*' OR 'triple bottom line' OR 'sustainab manufactur*' OR 'sustainab product*')
	Data basis and search criteria	• EBSCO; ISI Web of Knowledge (Web of Science); Science Direct; Scopus • Only papers from journals and conferences; English language
	Theme alignment	Title, Keywords, Abstract and Full Paper Analysis • 442 papers first selection / 244 (excluding duplicate papers, non-academic or non-English) / 149 (refined after 2nd version of search terms, title adherence and type of paper); 53 (abstract adherence); and 35 (theme alignment). • Three researchers' evaluation in order to minimise bias (2 seniors + 1 junior) in three rounds of analysis.
Bibliometric analysis	Organising and extracting information from the sample	Mendeley®, MC3R® and UCINET/NETDRAW® • 35 papers • 131 authors • 31 publication sources • 1372 references • 2618 authors extracted from the references
	Social networks	Authors' citation and co-citation • Identify centrality in the network • Most cited authors and references Author's co-citation • Identify research clusters Keywords • Identify predominant themes (keywords)
Systemic analysis	Content analysis	To identify the links between Industry 4.0 and sustainability/sustainable manufacturing
Research agenda	Research agenda	Organisation of research gaps and opportunities List of research questions Identify maturity of the field

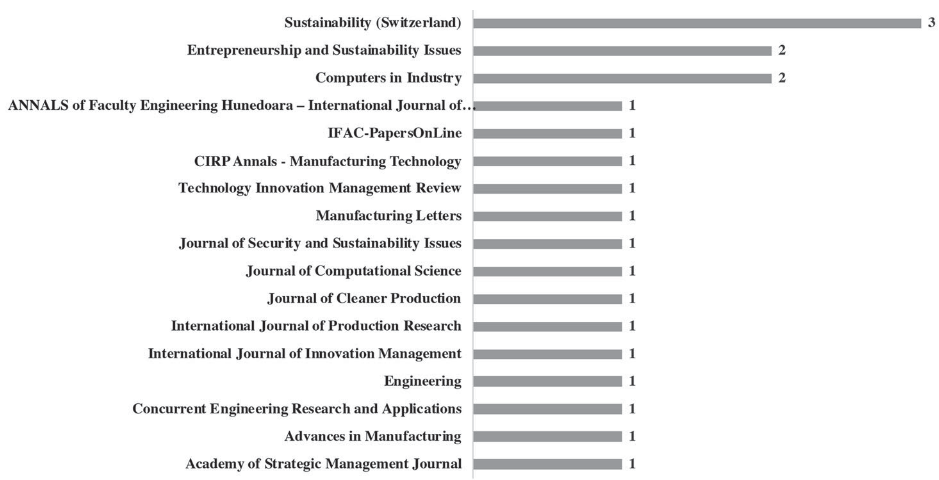
4.1. Descriptive results and bibliometric analysis

RQ1. "Who is working in the research field, when, and where?"

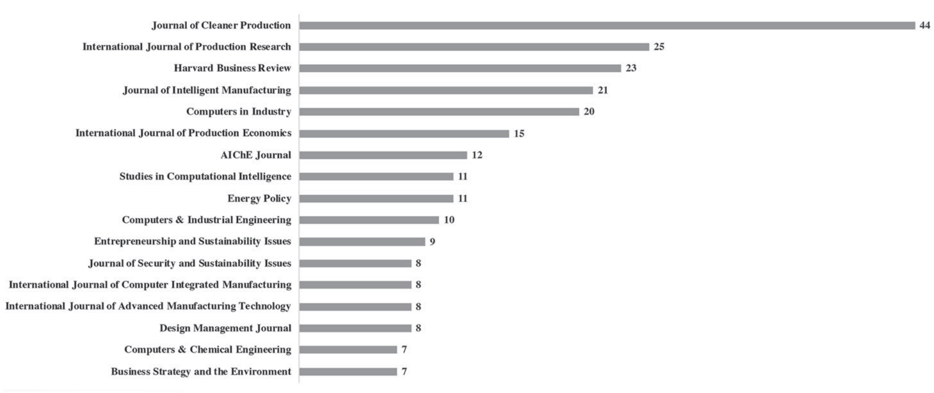
First, an overview of the field is presented positioning the topic within the context and provide results regarding the 'when' in RQ1. The convergence of sustainable manufacturing and Industry 4.0 is a topic which has evolved in recent years, and papers' distribution indicates an evolutionary trend compatible with a new research field (Figure 2(a)). The study by Jovane et al. (2008) represents the first year in the sample's timeline and, besides not using the term Industry 4.0, this paper presents key aspects related to it, however, using different terms. This was also considered when choosing the terms used for sample selection (e.g. 'industr 4.0', 'connect manufactur', 'smart manufactur', 'industrial internet of things', '21st manufactur', '4th industrial revolution').



(a) Papers' distribution over the years



(b) Journals' distribution in 35 papers' sample



(c) Most cited journals based on the references extracted from the sample

Figure 2. Papers and journals' distribution in the sample.

One explanation for the increase in the number of publications after 2013 can be associated with the launch of governmental programs, as identified by Liao et al. (2017). According to the authors, there is a tendency to increasing publications in the following years due to the goals and timelines defined by each program.

Table 3. Conferences listed on the sample.

11th, 12th, 13th, 14th Global Conference on Sustainable Manufacturing 2013–2017	7th Manufacturing Engineering Society International Conference 2017
International Conference on Virtual and Augmented Reality in Education 2013	7th International Conference on Industrial Engineering and Operations Management 2017
3rd International Conference on Through-life Engineering Services 2014	11th International Conference on Management Science and Engineering Management 2017
IEEE International Conference on Industrial Engineering and Engineering Management 2014	4th International Conference on Sustainable Design and Manufacturing 2017
22nd Conference on Life Cycle Engineering 2015	XXVIII ISPIM Innovation Conference 2017
21st Summer School Francesco Turco 2016	50th Conference on Manufacturing Systems 2017

The list of journals and conferences represented in the sample is available on Figure 2(b) and Table 3, allowing to identify a list of addressed topics: resource use – from efficiency to effectiveness; waste management; remanufacturing and recycling; closed – loop-chain; life cycle management; sustainable design; innovation; value-creation; manufacturing systems 4.0; knowledge in manufacturing 4.0; operational excellence; smart factory; and, augmented and virtual reality.

All citations in the sample were listed totalising 1370 references, allowing to identify the most cited journals, listed on Figure 2(c). As identified by Bonvoisin, Stark, and Seliger (2017), the scope and disciplines concerned with sustainable manufacturing are multidisciplinary, and the same trend is being applied in the context of the Industry 4.0. Examples extracted from Figure 2 are listed below:

- Manufacturing technologies: International Journal of Production Research; Sustainability; Engineering; Cleaner Production; Concurrent Engineering and Applications; Computers in Industry, among others.
- Product lifecycles: CIRP Annals – Manufacturing Technologies, Journal of Cleaner Production, Design Management Journal.
- Value creation networks: Academy of Strategic Management Journal, Business Strategy and the Environment.
- Global manufacturing impacts: Harvard Business Review, Journal of Security and Sustainability Issues.

These exploratory results are relevant because the listed journals and conferences can be used for researchers as support for decisions regarding publications and opportunities to enhance research network.

The extracted references also indicates that Germany has a significant influence on the research development, confirmed in four of the five most cited documents: (1) 'Recommendations for Implementing the Strategic Initiative Industrie 4.0' (Kagermann, Wahlster, and Helbig 2013); (2) 'How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective' (Brettel et al. 2014); (3) 'Opportunities of Sustainable Manufacturing in Industry 4.0' (Stock and Seliger 2016); and 'Industry 4.0' (Lasi et al. 2014).

Regarding 'who' is dedicating research efforts in the field, Figure 3 illustrates authors' citation network and its respective research focus. Citations' network represents the relationship between citing and cited authors, in other words, indicates a topic that they have in common through the citations, reflecting how an author is influenced by the research from another author (Hanneman and Riddle 2011; Jeong, Song, and Ding 2014).

Authors with a higher centrality degree were illustrated as larger nodes representing a higher number of connections, tending to have greater influence in the network (Hanneman and Riddle 2011). From the 131 authors in the network, only 16 were not cited by another author, indicating the representativeness of the network. As previously identified, the papers from Jovane et al. (2008) and Stock and Seliger (2016) were listed as the most cited references and the larger nodes confirm their relevance in the field.

Authors' network and list of references, when analysed together, show that research produced by authors in Group 1 and 3 was referred to by the other groups. Results also corroborates with observations from Carlile and Christensen (2005) who noted that knowledge might arise from individual research and carried out by a team of researchers, and also from interactive cycles where individual research are validated by other research teams.

Complementing the results, the co-citation matrix (Figure 4) illustrates the frequency with which documents were cited together, indicating the intellectual structure, or key concepts, of a scientific domain.

In this network, 8 sub-groups were formed by 37 authors, in general, linked by similarity, complementary, and/or overlap (co-authorship). Thus, the co-cited papers listed can be considered relevant in their area, listed in Table 4.

The key concepts listed in Table 4 indicate a conceptual framework of the sustainable manufacturing approach in the Industry 4.0, where the technological advances are allowing sustainable value-creation in all life cycle stages, through sustainable design, resource-efficient production processes, and circular and symbiotic production systems. In order to identify

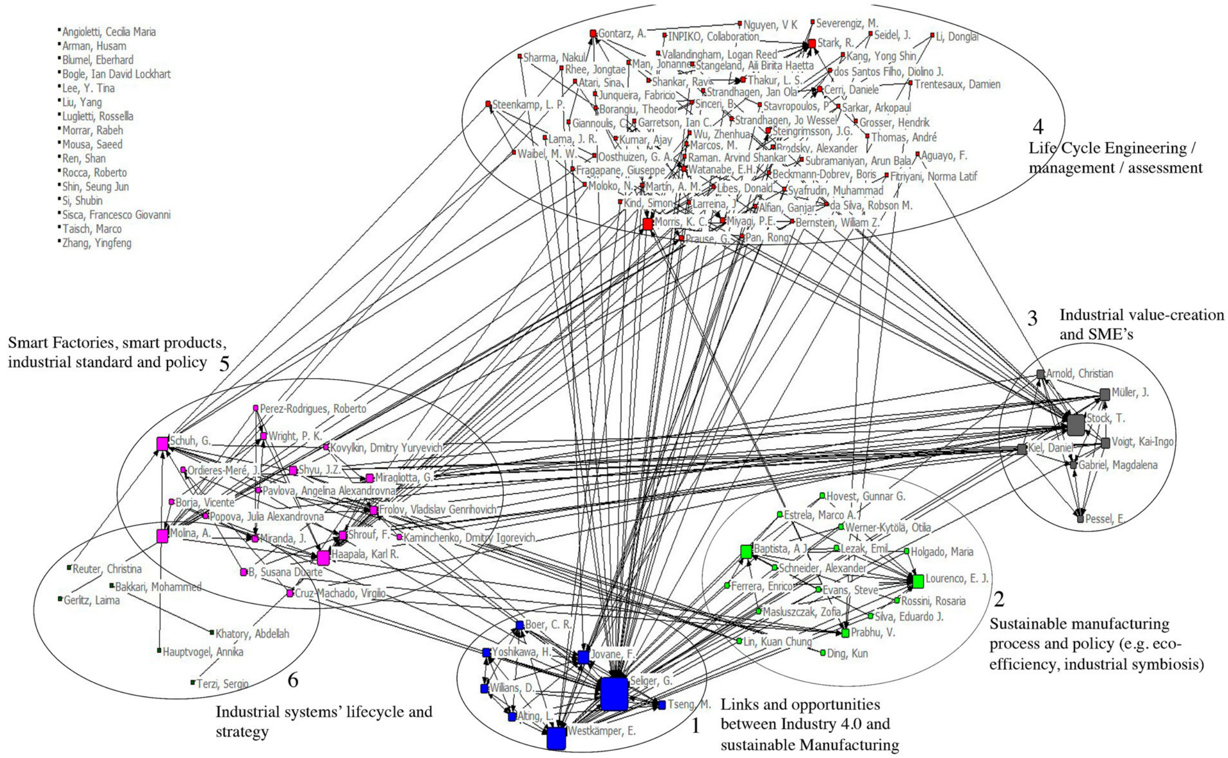


Figure 3. Authors' citation network.

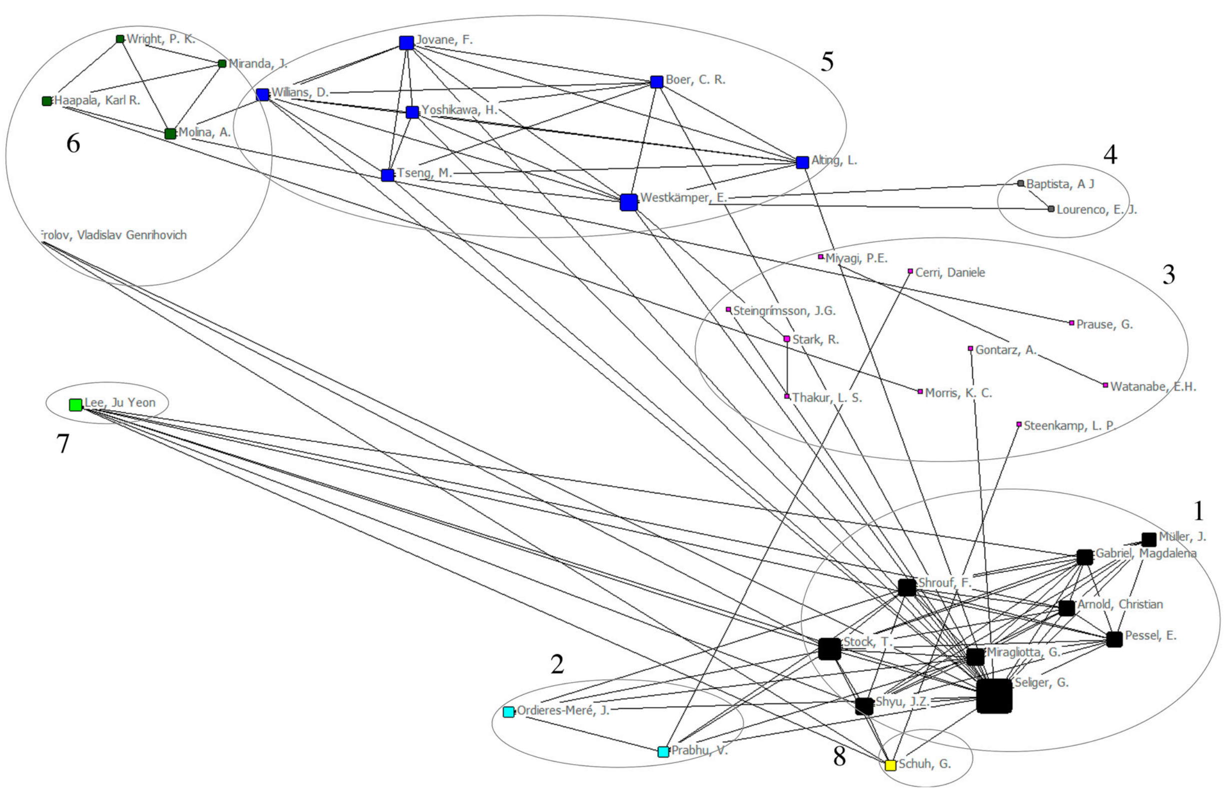


Figure 4. Authors' co-citation network.

Table 4. List of key concepts identified in the co-cited papers.

Group of keywords	Key concepts	References
Group 1	Sustainable value-creation for smart factories	Stock and Seliger (2016), Kiel et al. (2017), Shrouf, Ordieres, and Miragliotta (2014), Gabriel and Pessl (2016)
Group 2	Smart manufacturing systems	Shrouf, Ordieres, and Miragliotta (2014), Bernstein et al. (2017)
Group 3	Sustainable smart production networks and systems considering all stages of life cycle	Bernstein et al. (2017), Prause and Atari (2017), Stark et al. (2014), Cerri and Terzi (2016), Watanabe et al. (2016), Kumar, Shankar, and Thakur (2017), Waibel et al. (2017), Larreina et al. (2013)
Group 4	Digital management system enabling industrial symbiosis	Ferrera et al. (2017)
Group 5	Technological and industrial revolution as enabler of sustainable manufacturing	Jovane et al. (2008)
Group 6	Full integrated network and processes to support sustainable design and life cycle assessment	Bernstein et al. (2017), Miranda et al. (2017)
Group 7	Testbed for sustainable smart manufacturing	Lee et al. (2015)
Group 8	Enablers for Industry 4.0 increases sustainability	Schuh, Reuter, and Hauptvogel (2015)

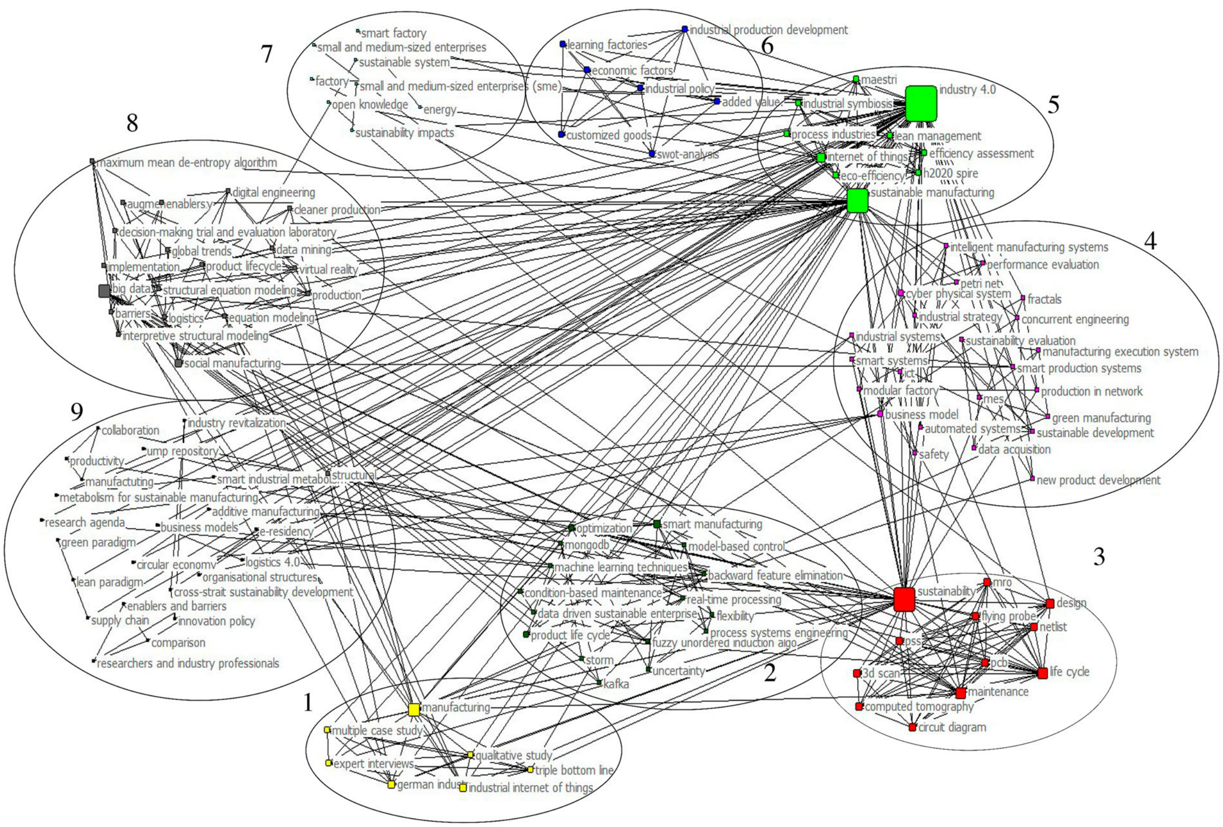


Figure 5. Keywords' network.

what topics are already being consistently related and explore future opportunities in areas that are not yet consolidated, Figure 5 presents the keywords' network.

Nine groups of keywords were identified, and results obtained reinforce insights previously presented, that there is a vision of sustainability within Industry 4.0 enabled by implementation of sustainable manufacturing principles. In this matter, Table 5 presents the underlying logic of each group and examples of the main keywords within each group, delimiting a scope for them; and, an example of a paper that addresses the efforts to discuss the topic within each group scope.

Keywords' network suggests some well-established relationships, for example, between groups 5–8, and 5–9. The first one can be explained based on the relationship between the terms Big Data, Industry 4.0 and Sustainable Manufacturing,

Table 5. Topics extracted from keywords' network.

Groups	Keywords (examples)	Reference (example)
1. IIoT & Sustainability	Industrial Internet of Things (IIoT), german industry, triple bottom line, qualitative study	Kiel et al. (2017)
2. Smart Manufacturing	Smart manufacturing, optimisation, flexibility, uncertainty, data driven, process system engineering, condition-based maintenance, machine learning techniques	Bogle (2017)
3. Sustainability & Life Cycle Management	Sustainability, life cycle, design, maintenance	Stark et al. (2014)
4. Cyber-Physical System (CPS)	Cyber-physical-system, smart systems, modular factory, automated systems, intelligent manufacturing systems, green manufacturing, sustainable development, performance evaluation	Bakkari and Khatory (2017)
5. Industry 4.0 & Sustainable Manufacturing	Industry 4.0, sustainable manufacturing, eco-efficiency, internet of things, industrial symbiosis, lean management, efficiency assessment	Ferrera et al. (2017)
6. Industrial Policy	Economic factors, industrial production development, added value	Frolov et al. (2017)
7. Smart Factories and SMEs	Smart Factory, small and medium-sized enterprises, sustainable systems, energy, sustainable systems, open knowledge	Shrouf, Ordieres, and Miragliotta (2014)
8. Big Data	Big data, cleaner production, decision-making, product lifecycle, logistics, data mining, social manufacturing, augmented and virtual reality	Zhang et al. (2017)
9. Other related topics	Smart industrial metabolism, collaboration, additive manufacturing, circular economy, logistics 4.0,	Angioletti et al. (2016)

and the second one, despite the strong relation, there is a more homogeneous distribution in its different topics, i.e. topics with opportunity to be more explored in the context of sustainability in Industry 4.0. Another example is the relationship between groups 8–2, focused on the use of the big data in the smart factories to support product life cycle, condition-based maintenance, optimisation, and flexibility based on real-time processing.

On the other hand, it is also noticed that some groups are still poorly related to the others suggesting gaps in the literature, that can be explored as research opportunities. For instance, opportunities also can be perceived within Group 7 'Smart Factories and SME', e.g. where sustainable system can be approached by the social dimension, and 'circular economy' (Group 9), which is a well-developed and consolidated topic when it comes to environmental management but is still little explored regarding production implications.

4.2. Content analysis

This section presents results from content analysis seeking to identify how the research is evolving, what are the main contributions and/or impacts of sustainable manufacturing for the development of Industry 4.0, which technologies are being more considered for sustainable manufacturing, and what is the research agenda for the future.

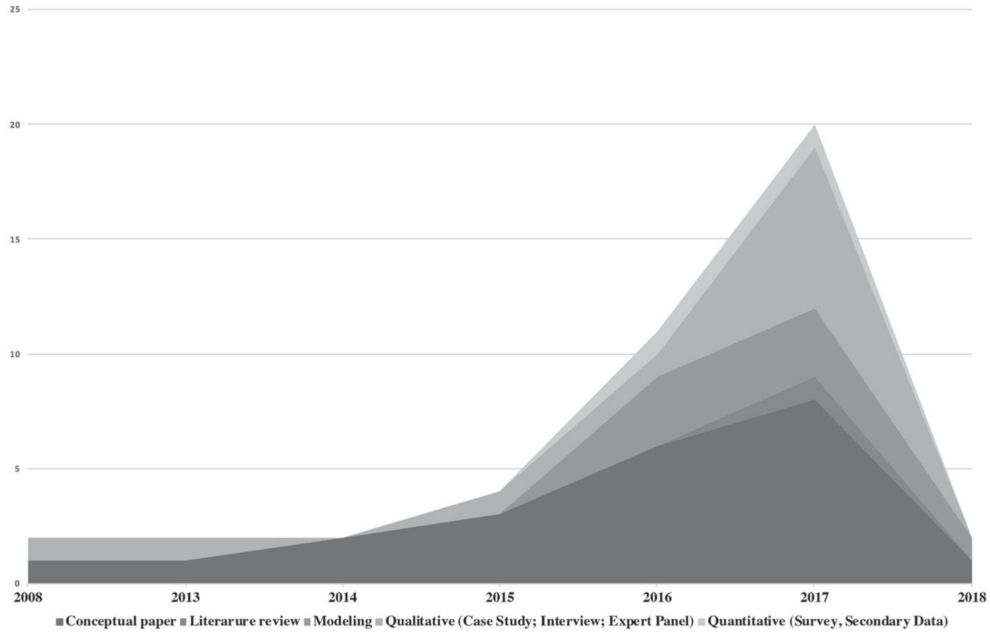
4.2.1. Research life cycle

RQ2. What is the current research life cycle status?

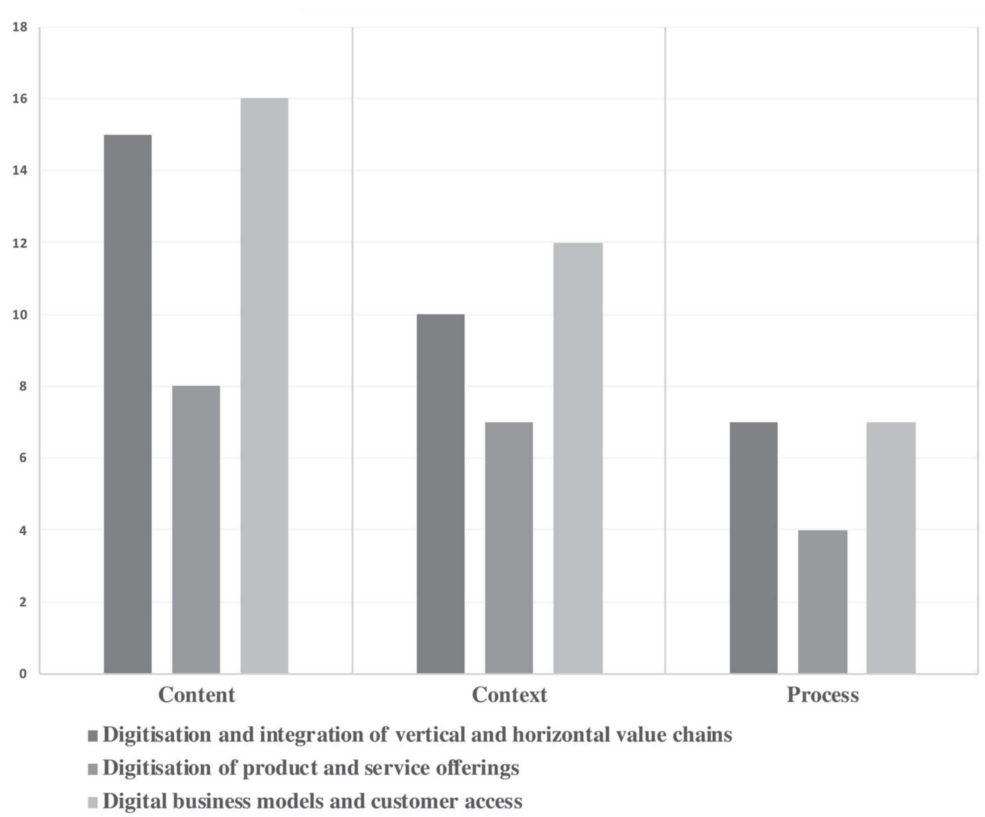
Papers were grouped by year of publication and research method applied, including multimethod approaches. Results indicate that the research conducted in the field has become broader and more comprehensive in terms of the methods used and regarding to the context and content and processes, as illustrated on Figure 6(a,b).

Following Carlile and Christensen (2005) model, the development of a theory must go through a descriptive approach, creating familiarity regarding a fact or phenomenon, to a normative one, creating an acceptable theory for a fact or phenomenon. The evolutionary pattern, illustrated in Figure 6(a), is following the descriptive approach described by Carlile and Christensen (2005), i.e. conceptual papers developing constructs, qualitative research establishing frameworks, and modelling/simulation and quantitative studies defining the models. Conceptual papers represent the majority in the sample and main research drivers identified are:

- Identify opportunities and challenges in a more holistic perspective (e.g. Prause 2015; Stock and Seliger 2016; Müller, Kiel, and Voigt 2018);



(a) Research methods' distribution



(b) Pettigrew's approach vs Industry 4.0 principles

Figure 6. Research methods' distribution.

- Use of the technological pillars (e.g. Blümel 2013; Stark et al. 2014; Watanabe et al. 2016);
- Relating sustainable manufacturing traditional topics such as 'Lean and Green Supply Chains', and 'Life Cycle Engineering' within the Industry 4.0 demands (e.g. Stark et al. 2014; Duarte and Cruz-Machado 2017);

- Development of Business Models (e.g. Prause 2015; De Man and Strandhagen 2017);
- Development of National Policies (e.g. Lin, Shyu, and Ding 2017).

Papers were also classified using Pettigrew's approach and following the descriptive approach. According to Sminia (2016), '(. . .) the content of strategic change cannot be understood separately from the process by which it is realized and from the context in which it takes place'. Results illustrated on Figure 6(b) point out that the context and content of the sustainability approach in Industry 4.0 are being more developed in the context of vertical and horizontal integration and business models' development, for example, the variables of context and content identified in Müller, Kiel, and Voigt (2018):

- Context (Why): competitiveness; flexibility; quality; and, efficiency.
- Content (What): process transparency in intra- and inter-firm logistics, and in the production processes; customer orientation and service-based business models.

This categorisation is relevant because help to understand the motivations and drivers (Context) guiding the sustainable manufacturing approach in the Industry 4.0 research, and what are the enablers for implementation (Content), but also points out gaps on how to implement it (Processes). More examples of context-content variables and categorisation by paper can be found in Appendixes 2 and 3.

Therefore, the results indicate that the sample represents the descriptive phase in the research life cycle. Moving forward in the evolution process to become more normative, future research can direct efforts on 'How' to implement a sustainable Industry 4.0, applying and testing theories and frameworks already developed in the field, e.g. Miranda et al. (2017).

4.2.2. Drivers and technologies

RQ3. How has sustainable manufacturing theory contributed to the Industry 4.0 drivers?

To answer this question, Figure 7 illustrates how Industry 4.0 principles are being approached in the sustainable manufacturing scope.

Some examples of the papers' characterisation: Larreina et al. (2013), Blümel (2013), and Lee et al. (2015) are examples of the links between 'Manufacturing Technologies' and 'Vertical and Horizontal value chains', 'Product and Service Offerings' and 'Business models', respectively. Miranda et al. (2017) and Severengiz et al. (2015) represent the links between Product Lifecycles and 'Product and Service Offerings' and 'Business models'.

As described by Bonvoisin, Stark, and Seliger (2017) sustainable manufacturing seeks to ensure that production will be performed with economy of resources securing social standards. In the Industry 4.0 context, this definition can be linked with production systems developed in order to be interoperable, conscious, transparent, intelligent, efficient, flexible, agile, collaborative, responsive, and sustainable. These characteristics are represented by the 'Value Creation Networks', where the

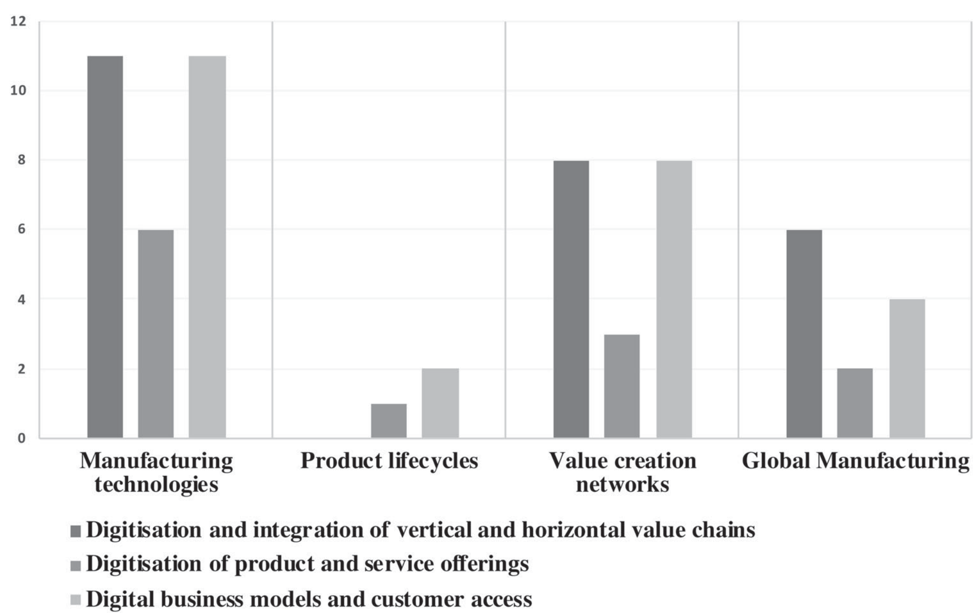
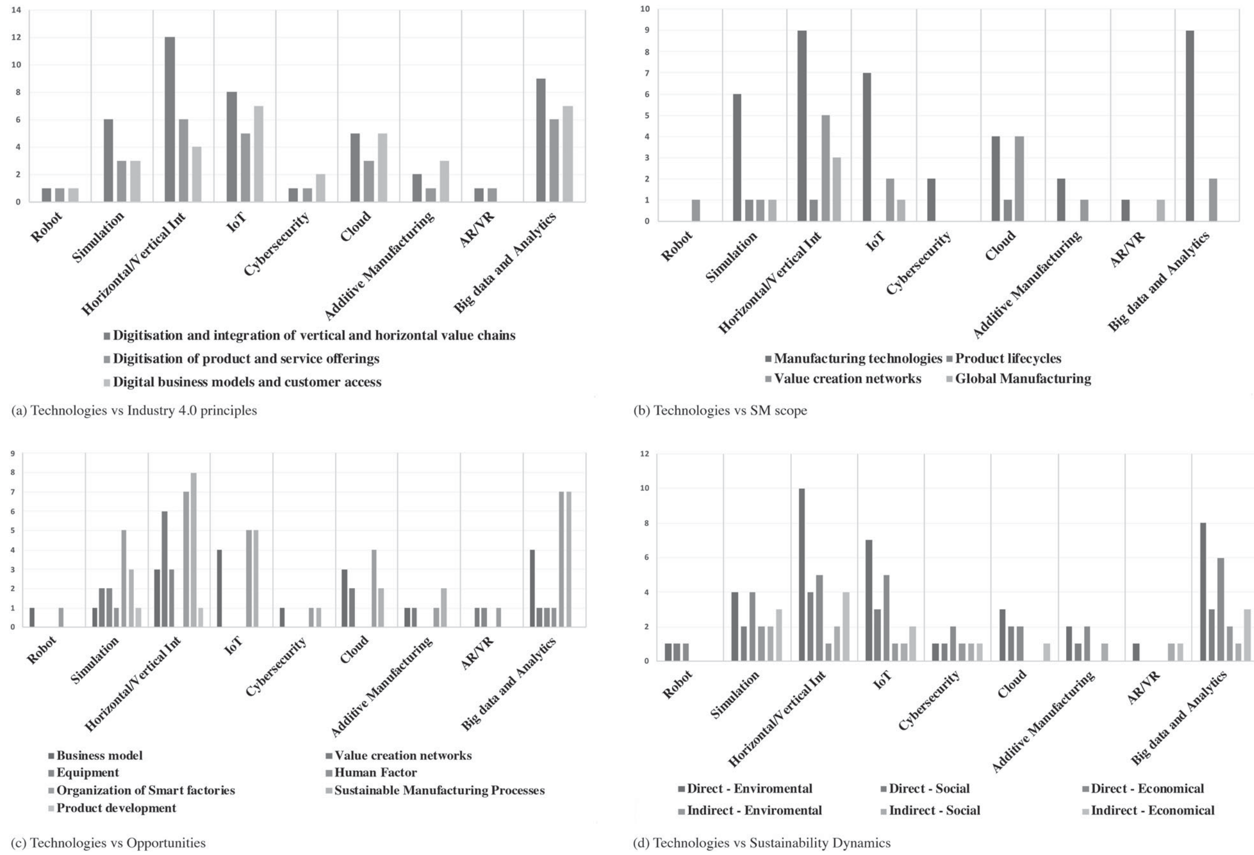


Figure 7. Sustainable manufacturing vs Industry 4.0 principles.



(a) Technologies vs Industry 4.0 principles
(b) Technologies vs SM scope
(c) Technologies vs Opportunities
(d) Technologies vs Sustainability Dynamics

Figure 8. Technologies linked with sustainable manufacturing in Industry 4.0.

business models and organisational infrastructure are fully integrated by CPS, e.g. in the sustainable industrial value creation models presented by Jovane et al. (2008), Stock and Seliger (2016), Kiel et al. (2017) and Müller, Kiel, and Voigt (2018).

Exploring more examples of manufacturing technologies is also a strong trend in the field, as listed below:

- Application of additive manufacturing enabling circular economy through more efficient production processes (Angioletti et al. 2016; Müller, Kiel, and Voigt 2018);
- Smart sensors for retrofitted milling machines (Stock and Seliger 2016);
- Smart manufacturing execution system for energy monitoring (Larreina et al. 2013);
- Big data collection and analysis for predictive maintenance (Kumar, Shankar, and Thakur 2017).

In addition, it was possible to identify sustainable manufacturing theories that have been contributing to the Industry 4.0 drivers: Eco-efficiency and Industrial symbiosis (Ferrera et al. 2017); Cleaner Production (Zhang et al. 2017); Green and Lean Supply Chains (Duarte and Cruz-Machado 2017), Sustainable Logistics (Strandhagen et al. 2017); and, Life Cycle Management (Cerri and Terzi 2016).

The value creation scope of sustainable manufacturing is strongly related to the manufacturing networks, and examples can be seen in the following studies: Severengiz et al. (2015) proposed a sustainable manufacturing web-based platform for open knowledge, supporting vertical and horizontal integration; Schuh, Reuter, and Hauptvogel (2015) presented the elements of the virtual engineering of value chains, e.g. connecting different ERP systems along the supply chain; Ferrera et al. (2017) presented a management system framework for complex production systems formed by integration of multiple production units of a single company or even multiple companies.

RQ4. Which are the technologies currently addressing sustainable manufacturing in the Industry 4.0 context?

The technology pillars represent main components of Industry 4.0 and this section explores how they have been applied to address sustainable manufacturing in Industry 4.0. As noted by Rüßmann et al. (2015) some of these technologies are already being used in manufacturing, however, due to the integration promoted by the CPS, they enable relevant changes in production. Figure 8(a) illustrates results on how the sustainable manufacturing research is addressing industry 4.0 technologies.

Results presented on Figure 8(b,c) reinforce the relevance of horizontal and vertical systems integration and also big data for real-time management, enabling closed loop production processes and product life cycle management, e.g. the framework proposed by Zhang et al. (2017) apply IoT technologies for product life cycle as the enabler for information exchange in a real time with reliability. Regarding studies about the benefits and use of IoT, Shrouf, Ordieres, and Miragliotta (2014) can be cited as an example, who presented a framework for an 'IoT-based Smart Factory' and a model for energy management improvement supported by smart sensors and meters.

Big data is also one of the main technological pillars, and there are different examples of application in the sample such as: smart manufacturing execution system (Larreina et al. 2013); maintenance prediction (Kumar, Shankar, and Thakur 2017); cleaner production and product life cycle (Zhang et al. 2017); value creation networks (Shrouf, Ordieres, and Miragliotta 2014; Kiel et al. 2017); classification of defect and non-defect products (Syafrudin et al. 2017). One last example is the framework presented by Bakkari and Khatory (2017) with three essential levels for a CPS: the smart objects connected by IoT, the cloud (topology of the factory, 3-D models, process data, among other applications), and the services provided based on the data available.

However, this technological pillar need to be more explored in the context of SMEs due the high cost, risks and demands of technical skills (Zhang et al. 2017). Another limitation is the need of an adequate repository to support large quantities of data collected per machine tool and originated by different other connected systems (Larreina et al. 2013).

Simulation and modelling applications aims also to be relevant in the context of sustainable manufacturing. According to Ferrera et al. (2017) and Müller, Kiel, and Voigt (2018) simulations can support improvements in the factory to reduce energy consumption, and to optimise and add value to operations by simulating all activities within the entire supply chain. Lee et al. (2015) also highlight the critical role of the modelling and simulation in different stages of a testbed system for sustainable manufacturing that can be used for validating emerging methods, tools, and systems, and also testing smart manufacturing systems.

As previously presented, Stock and Seliger (2016) have mapped opportunities to address sustainability in Industry 4.0, and results confirmed that they are being tackled and considered relevant in the field, e.g. Zhang et al. (2017) propose a sustainable product-service business models based on smart data; Prause and Atari (2017) investigate value creation networks framed for closed-loop product life cycles and industrial symbiosis; Shrouf, Ordieres, and Miragliotta (2014) analyse the use of IoT technologies, as sensors and meters, installed in already existing machines and tools; Blümel (2013) investigates the use of virtual and augmented reality to improve human-machine interaction and learning; Duarte and Cruz-Machado (2017) discuss the organisation of smart factories based on lean and green supply chain management; Ferrera et al. (2017) propose a holistic resource efficiency models; Miranda et al. (2017) develop a framework for design of sensing (monitoring), smart (interconnected) and sustainable (ethical and environmental positive) products.

Complementing analysis on the technological pillars, Figure 8(d) shows that 'horizontal and vertical integration', 'IoT', 'big data and analytics', and 'simulation' are directly linked with impacts on the environmental and economic dimensions, e.g. connected with resource and energy efficiency in the smart factories organisation (e.g. Shrouf, Ordieres, and Miragliotta 2014). However, the most important insight from Figure 8(d) is that all technological pillars can enable direct or indirect impacts on the sustainability dimensions and the challenge is to find suitable and best solutions, which enable industry to create and add value on all three dimensions.

It is possible to visually identify gaps in the social dimension. As previously presented, there are divergences related to jobs creation, tasks, and competencies required for Industry 4.0, which need to be more explored, as discussed by Stock and Seliger (2016) and Waibel et al. (2017).

4.2.3. Research agenda

RQ5. What are the current research efforts and opportunities?

Based on the previous analysis, some topics are more developed and are moving towards a normative approach, such as energy efficiency, life cycle management, use and analysis of big data, and systems integration models; while others present opportunities to be more explored, such as human factors, sustainable products and service development, and global manufacturing impacts of Industry 4.0.

Therefore, research is dedicating efforts to the development of business models, systems, and networks' integration, and digital processes solutions and equipment. On the other side, increasing research related to human factors and product-service offering will bring a valid contribution to the Industry 4.0 agenda.

Table 6 proposes an organisation of the current research contributions in five main areas, originated from the conceptual background (e.g. Table 1 and Figure 1) and results from the literature review (e.g. Table 4). The identified areas were: business models, production, supply chain management, product, and policy development.

Table 6. Research efforts addressed on sustainability requirements for Industry 4.0.

Area	Sustainability opportunities[a]	Research contribution
Business Model	Integration of physical-products and cyber-services during their whole lifecycle; new business model focused meeting consumer needs – mass customisation, exploiting new digital and other technologies enabling the transition to a fossil-free and circular economy	• Business model for SM systems based on performance management indicators (Watanabe et al. 2016). • Business modelling for design integration (Gerlitz 2016). • Smart data for offering new services and a sustainable-oriented decentralised organisation (Stock and Seliger 2016). • IT infrastructure, standardised data interfaces, and communication protocols for vertical and horizontal connection across entire value chains (Kiel et al. 2017). • Technological progress to improve working conditions (Bakkari and Khatory 2017). • Circular business models (Martín et al. 2017).
Production	Reconfigurable, adaptive and evolving factories capable of small-scale production; high performance production; zero-defect; near-to-zero emissions; energy, water, land usage, heat management and resource efficiency; material kept in a 'productive loop'; low-carbon technology; cleaner factories; circular economy strategies; symbiotic manufacturing; sustainable, safe and attractive workplaces; highly vertical integrated; workers with right knowledge and highly skilled	• Sustainability indicators for manufacturing execution systems (Larreina et al. 2013). • Smart meters and sensors for energy efficiency in the factory (Shrouf, Ordieres, and Miragliotta 2014). • Testbeds for SM to evaluate the sustainability performance of Industry 4.0 (Lee et al. 2015). • Recovery methods enabling closed and optimised material cycles (Gabriel and Pessl 2016). • System lifecycle and maintenance reducing safety issues (Trentesaux, Borangiu, and Thomas 2016). • Energy models for green factory design (Duarte and Cruz-Machado 2017). • Big data analysis for condition-based maintenance prediction (Kumar, Shankar, and Thakur 2017). • Pillars for total-efficiency (Ferrera et al. 2017). • Real-time big data processing applied to predict quality (Syafrudin et al. 2017). • Additive manufacturing for energy and material efficiency (Angioletti et al. 2016). • Virtual technologies to support on-the-job qualification and training (Blümel 2013). • Changing skills of production employees (Gabriel and Pessl 2016).
Supply Chain	Supply chains with spare capacity at all stages; energy and resource efficient; higher level of collaboration and cooperation; highly horizontal integrated.	• CPS creating complex and intertwined manufacturing networks (Prause 2015). • CPS for knowledge management in production networks (Severengiz et al. 2015). • Highly adaptive supply networks (Gabriel and Pessl 2016). • Cross-company production process (Prause and Atari 2017). • Stakeholders equipped with integrated tools for smarter-decision-making (Bernstein et al. 2017). • Logistics 4.0 (Strandhagen et al. 2017). • Sustainable value-proposition for supply chains (Man and Strandhagen, 2017).
Product	New forms of value including sustainability; reused, remanufactured, recycled; shared ownership; reduce use of materials and energy; phasing out harmful substances; cradle-to-cradle approach.	• Life Cycle Engineering for value creation (Stark et al. 2014). • Design integration for extensive value in manufacturing, products and services (Gerlitz 2016). • Sustainable design of products towards realisation of closed-loop life (Stock and Seliger 2016). • Products designed to be sensing, smart and sustainable (Miranda et al. 2017).
Policy development	Regulations and governance mechanisms incentivise/facilitate resource-efficient and environmentally friendly production; transparent, clear and effective permit and supervisory processes;	• Politics and public institutions promoting legal conditions (Müller, Kiel, and Voigt 2018). • Governments and policy makers creating safeguards and policies for sustainable manufacturing (Morrar and Arman 2017). • Countries considering cybersecurity major national priority (Bogle 2017). • Cooperation with universities and research organisations as a condition for the implementation of Industry 4.0 projects (Frolov et al. 2017). • Innovation to development of global industry (Lin, Shyu, and Ding 2017).

[a]Source: Stock and Seliger (2016), Kiel et al. (2017), Teknikföretagen (2017), Waibel et al. (2017), Duarte and Cruz-Machado (2017).

As illustrated and discussed on the keyword's network, there are also other research topics that present higher development opportunities, such as: logistics 4.0, industrial symbiosis, circular economy, sustainable performance measurement, standards, policies, and new educational curricula development. Therefore, in order to contribute to the research agenda in the field, a list of research questions that can be approached in future research is presented:

- RQ1 – How can collaboration between man and machine improve workers' health and safety, while at the same time promoting positive impacts in the social and economic dimensions?

- RQ2 – How to develop a CPS using IoT technologies to enable a sustainable production system in SMEs?
- RQ3 – How to use smart technologies to include the full production network and consumer behaviour in the product development focusing closed-loop life cycles, and consumer satisfaction and well-being?
- RQ4 – What are the most relevant cybersecurity protocols and standards for designing a sustainable Industry 4.0 production system in order to secure information flows in the sustainable value-chain networks?
- RQ5 – How to implement and develop industrial symbiosis and circular economy enabling factories to contribute for countries' development?
- RQ6 – How to design sustainable value-creation networks for product-service offerings in industry 4.0?
- RQ7 – What are the social impacts on job creation and employment of Industry 4.0?
- RQ8 – How design a sustainable manufacturing system that enables industry 4.0 to have a positive impact in all three dimensions of sustainability?

Results indicate that the research is aligned with the goals and timelines listed on Table 1, and opportunities for a higher alignment remains on the development of systems, tools and methods to recover, reuse, add new functions and materials, focused on industrial waste and post-consumer products, human-machine solutions, development of standards and policies for sustainable production and circular economy, and design of new business models for decentralised decision-making processes.

Theories' development, following the descriptive and normative cycles, will create conditions to explain, in an in-depth and comprehensive manner, the relevance of this research topic, consolidating sustainable manufacturing's boundaries in the Industry 4.0. Using Sminia's (2016) as an inspiration, we affirm that the content of change for a sustainable Industry 4.0 cannot be fully explained separately from the digital processes enabled by the technological pillars, and also from the sustainable context established by guidelines, projects and goals for industrial development.

5. Conclusion

This paper contributes to advances on Industry 4.0 research identifying that the concepts of sustainable manufacturing and the use of the new technologies can enable Industry 4.0 to have positive impacts on all the sustainability dimensions in an integrated way, and also supporting the implementation of the Industry 4.0 agenda in the following aspects: developing sustainable business models; sustainable and circular production systems; sustainable supply chains; sustainable product design; and policy development to ensure the achievement of the sustainable goals in the Industry 4.0 agenda.

Results allow to conclude that the field is legitimated but not consolidated, however, is evolving based on the development of new business models, and value-creation-chains integration. Results also allowed to design a research agenda and scenario for further development of the field towards more normative studies focused on the processes of implementation of the Industry 4.0 agenda.

This study is not meant to provide more in-depth analysis on specific topics and limitations rely on the limited number of papers analysed, the decision to not use statistical analysis, and not considering cross-disciplinary topics that possible are being developed by other research fields. Future research can focus on the implementation of about the different opportunities to link both approaches, enabling industries to achieve full goals of the Industry 4.0.

Acknowledgements

The authors would like to thank Prof. Dr. Edson Pinheiro de Lima, and MSc. David Lubel from the Pontifical Catholic University of Paraná for the valuable contribution on papers selection. Authors also would like to thank MSc. Rafael Araujo Kluska for technological support on developing the citations matrix and bibliometric data extraction using the MC3R software, and the Chalmers Production Area of Advance (AoA Production).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Elias Ribeiro da Silva wish to thank, for providing financial support, the Coordenaçao de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Ministry of Education [grant PDSE 88881.135805/2016-01]. Carla Machado and Mats Winroth also wish to thank VINNOVA [grant number 2018-01583].

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Appendix 1. List of the twenty most cited references extracted from the sample

Publication	Author(s)	Citations
Recommendations for Implementing the strategic initiative Industrie 4.0: securing the future of German manufacturing industry	Kagermann, Wahlster, and Helbig (2013)	22
How virtualisation, decentralisation and network building change the manufacturing landscape: An industry 4.0 perspective	Brettel et al. (2014)	10
Opportunities of Sustainable Manufacturing in Industry 4.0	Stock and Seliger (2016)	7
Our Common Future	Brundtland (1987)	6
Industry 4.0	Lasi et al. (2014)	5
Smart manufacturing, manufacturing intelligence and demand-dynamic performance	Davis et al. (2012)	4
Sustainable manufacturing: Trends and research challenges	Garetti and Taisch (2012)	4
Service innovation and smart analytics for Industry 4.0 and big data environment	Lee, Kao, and Yang (2014)	4
Recent advances and trends in predictive manufacturing systems in big data environment	Lee et al. (2013)	4
How Smart Connected Products are Transforming Competition	Porter and Heppelmann (2014)	4
Data mining in manufacturing: A review based on the kind of knowledge	Choudhary, Harding, and Tiwari (2009)	3
The lifecycle of active and intelligent products: The augmentation concept	Sallez et al. (2010)	3
Collaboration mechanisms to increase productivity in the context of industrie 4.0	Schuh et al. (2014)	3
Business model generation. A handbook for visionaries, game changers, and challengers	Osterwalder and Pigneur (2010)	3
Enterprise integration and interoperability in manufacturing systems: Trends and issues	Panetto and Molina (2008)	3
Implementing Smart Factory Industrie 4.0: An Outlook	Wang et al. (2016)	3
Smart Factory-Towards a factory-of-things	Zuehlke (2010)	3
Design principles for Industrie 4.0 scenarios: A literature review	Hermann, Pentek, and Otto (2016)	3
Produktionsarbeit der Zukunft Industrie 4.0	Spath et al. (2013)	3
How Big Data Can Improve Manufacturing	Auschitzky, Hammer, and Rajagopaul (2014)	2

Appendix 2. Examples of context-content's variables

Reference	Context – Why?	Content – What?
Jovane et al. (2008)	• Competitiveness • Sustainability	• Generation and diffusion of innovation; • Policy and action plan development on a national level; • Product Life Cycle Management approach.
Blümel (2013)	• Sustainable smart manufacturing • Smart logistics processes	• Production and environment; • Energy and living; • Mobility and transportation; • Safety and security.
Prause (2015)	• Competitiveness • Innovation • Productivity • Job creation • Increase exports	• Open innovation in production networks; • Sustainable service design covering the entire life-cycle of products.
Stock and Seliger (2016)	• Meet worldwide demand for capital and consumer goods • Ensure sustainable development	• Horizontal integration across the entire value creation network; • End-to-end engineering across the entire product life cycle; • Vertical integration and networked manufacturing systems vertical integration and networked manufacturing systems.
Bakkari and Khatory (2017)	• Instability of the market • Short duration of the life of the product • Individualisation of the product and globalisation • Sustainability of resources	• Industrial technology investments; • Countries' industrial strategies in the long term; • Interdisciplinary organisation.
Müller, Kiel, and Voigt (2018)	• Industrial value creation and competitiveness • Flexibility and customisation • Increase profit with higher efficiency and quality • Improve workplace conditions	• Process transparency in intra- and inter-firm logistics and production processes; • Customer orientation and service-based business models.

Appendix 3. Pettigrew's categorisation vs. Industry 4.0 principles

Title	Vert. and Horiz. value chains	Product and Serv. offer.	Digit. Busin. Mod. and Cust. Access	Content	Context	Process
Jovane et al. (2008)	✓			✓	✓	
Larreina et al. (2013)	✓					✓
Blümel (2013)	✓	✓		✓	✓	
Shrouf, Ordieres, and Miragliotta (2014)	✓			✓		
Stark et al. (2014)			✓	✓	✓	✓
Lee et al. (2015)			✓			✓
Severengiz et al. (2015)			✓	✓		✓
Schuh, Reuter, and Hauptvogel (2015)	✓			✓		
Prause (2015)	✓	✓	✓	✓	✓	
Stock and Seliger (2016)		✓	✓	✓	✓	✓
Cerri and Terzi (2016)	✓					✓
Gabriel and Pessl (2016)	✓			✓	✓	
Angioletti et al. (2016)	✓		✓	✓		
Trentesaux, Borangiu, and Thomas (2016)	✓		✓		✓	
Watanabe et al. (2016)		✓	✓	✓		✓
Gerlitz (2016)		✓	✓			
Frolov et al. (2017)	✓			✓	✓	
Bakkari and Khatory (2017)			✓	✓	✓	
Miranda et al. (2017)		✓	✓	✓	✓	✓
Prause and Atari (2017)			✓	✓	✓	
Martín et al. (2017)	✓			✓		
Kiel et al. (2017)	✓	✓	✓			
Morrar and Arman (2017)			✓	✓	✓	
De Man and Strandhagen (2017)	✓	✓	✓	✓	✓	
Strandhagen et al. (2017)	✓	✓	✓	✓	✓	
Zhang et al. (2017)	✓	✓		✓	✓	✓
Ferrera et al. (2017)	✓					✓
Kumar, Shankar, and Thakur (2017)	✓			✓		✓
Waibel et al. (2017)			✓			✓
Syafrudin et al. (2017)	✓					✓
Lin, Shyu, and Ding (2017)			✓	✓	✓	
Bernstein et al. (2017)	✓			✓	✓	✓
Bogle (2017)			✓	✓		
Duarte and Cruz-Machado (2017)	✓		✓	✓		
Müller, Kiel, and Voigt (2018)			✓	✓	✓	