sustainability

MDPI

Review

Sustainable Production Planning and Control in Manufacturing Contexts: A Bibliometric Review

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Abstract: Production planning and control (PPC), responsible for all the activities that keep production running regularly, plays an essential role in the transition to more sustainable manufacturing systems. PPC decision-making processes need to be driven by sustainable principles even if this makes them more effortful and complex from the strategic to operative level. This study aims to review the scientific literature relating to sustainable PPC. A bibliometric analysis of 437 papers published on the Scopus database was performed to identify the most relevant articles, authors, and journals and to provide the current topic trends and future research themes and gaps. The findings revealed the increasing interest in this topic mainly since 2018. China and the USA are the most productive countries, whereas the Journal of Cleaner Production and Sustainability are the most productive journals. The analysis has also highlighted the ways to address sustainability issues in PPC, e.g., by integrating in scheduling models objectives related to sustainability or by removing barriers to reverse logistics and circular economy at the PPC level. The following topics, instead, deserve further research: attention to the social issues in PPC and the development of decision support systems that will improve companies' PPC decision-making capabilities in sustainable optics.

Keywords: production planning and control; sustainable manufacturing; operations management; bibliometric literature review

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1. Background and Motivation

Sustainability in manufacturing systems is becoming increasingly important for many companies due to several established and emerging causes such as environmental challenges (e.g., air and water pollution, resource depletion, and climate change), a growing tightening regulation, and an increase in consumers' preference for environmentally friendly products. Consumers are beginning to take action to live more sustainably, purchasing products made from sustainable materials and processes and supporting companies with environmentally friendly, but also human rights and fair-trade, practices and policies. Companies are under more and more pressure, promoted by external (such as governmental regulations, etc.) and internal (such as safety, the well-being of employees, productivity, etc.) factors, to include sustainability in their manufacturing practices, starting with Production Planning and Control (PPC) tasks.

1.1. Sustainable Manufacturing

The concept of "sustainable manufacturing" has been developed over the years starting from a series of reports and meetings conducted since the 1970s to save the environment and is now aimed to meet the Sustainability 2030 Agenda [1]. Manufacturing companies are responsible not only for the economic growth of the nations but, given their impacts on the environment and society, they must also integrate all the sustainable issues in the

systems management, and this represents a priority to address. The most known framework defined for sustainability is the "Triple Bottom Line" (TBL), introduced by Elkington (1997), which considered sustainability as a fragmented three-dimensional relationship between social, environmental, and economic factors that need to be considered simultaneously [2]. The United Nations 2005 World Summit Outcome Document [3] clarifies the TBL concept—referring to economic and social development as well as environmental protection, defining them as "interdependent and mutually reinforcing pillars"—and also emphasizes the concept of the "three Ps"—People, Planet, and Profit. To be sustainable, an enterprise needs to consider these three concepts holistically. Technologies, processes, and products in manufacturing systems must be compatible and in balance with these three dimensions that are considered pillars of the TBL. The TBL framework's economic line refers to the impact of business practices on the economic system based on the concept that the growth of a single organization contributes globally to the growth of the economy. Companies providing economic value to the surrounding system can support future generations. The economic aspect of production is mainly related to the minimal use of resources to achieve minimal costs. The social line of the TBL, instead, refers to beneficial practices for labour, human capital, and the community (such as fair wages and health insurance). "Being good in society" not only denotes a moral aspect to follow but also affects the performance of business. In manufacturing environments, the social aspect focuses on the "human" element, i.e., working conditions at the workplace for employees, such as ergonomics and customer requirements. Lastly, the TBL environmental line refers to practices that do not compromise the environment for future generations, e.g., the efficient use of energy resources, a reduction in Greenhouse Gas (GHG) emissions, and a reduction in the ecological footprint, etc. In manufacturing, environmental aspects to consider are, for example, the composition of the energy used (conventional vs. renewable energies) and the usage of recyclable materials in production.

The overall so-called "sustainable development", defined by the *Brundtland Report* [4] as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs", has been an important focal point in recent years for the decision makers in industrial contexts [5]. Becoming and being "sustainable" is essential in the eyes of investors, regulators, customers, and communities with lots of potential problems in case of "unsustainable" approaches. The challenge remains open and complex. Failure in sustainability will imply fines, penalties, and customers choosing to go elsewhere; success, instead, will imply saving money, building a strong reputation, attracting investment, more loyal customers, and bringing new business. It is also interesting to focus on the regulations and reports that are becoming increasingly tight for companies (above all the manufacturing ones), even if not yet completely defined all over the world. For example, European Union (EU) rules require, with the Corporate Sustainability Reporting Directive (CSRD) [6] entered into force from January 2023, that companies and listed companies must publish regular reports on the social and environmental risks they face and on how their activities impact people and the environment in the Environmental, Social, and Governance (ESG) optics based on the standard defined by the European Financial Reporting Advisory Group (EFRAG). Among the reporting laws and regulations that have already taken effect in the EU, there is the Sustainable Finance Disclosure Regulation (SFDR), which regulates investment management sustainability reporting, and the EU Taxonomy for Sustainable Activities, i.e., a classification system establishing a list of environmentally sustainable economic activities. At present, there is no global definition of regulation on sustainability all over the world. Most sustainable regulatory requirements are not shared internationally, and each country has different standards to follow. For example, the requirements of The United States Securities and Exchange Commission (SEC) are different from the European ones even if they include information on ESG-related risks. Governments around the globe are increasingly issuing regulations, guidance, and incentives related to sustainability and ESG, and organizations worldwide will need to value the potential impacts on their strategies, operations, and

reporting. It seems clear that the transition to a more sustainable manufacturing context is not only a slogan but is also a need of enterprises from a regulatory point of view.

1.2. Sustainable Production Planning and Control

Until now, researchers have focused on the general concept of sustainability in manufacturing, highlighting the different functions and tasks that can help in facing the issues in this field [1,7–9] or on specific kinds of application domains such as maintenance [10–12] and quality [13,14]. However, managers might simultaneously incorporate environmental, social, and economic issues not only in these domains but also in the decision-making processes at the basis of the production and delivery of goods [15]. From a more general perspective, all the choices taken in terms of planning and controlling manufacturing systems impact sustainability, and in some cases, managers are not conscious of what this means or implies. Production planning and control, responsible for making several decisions regarding the monitoring, scheduling, and reprogramming of production planning ensuring the delivery of the products of a manufacturing company [16], is one of the main pillars of production activities. It plays a key role in keeping all production running regularly and is also responsible for lot sizes and managing disturbances, reducing their impact on the entire system [17]. PPC is a value-adding process of manufacturing activity that must continually adapt to operational and strategic environments, complex customer requirements, and new supply chain opportunities [18]. Nowadays—given the increasing variety of products, decreasing product life cycle, rapid changes in market demand, and decreasing delivery times—the PPC function is fundamental for the success of manufacturing companies and needs to be dynamic and adaptive [18–20].

The main purposes of this fundamental function include a reduction in Work in Progress (WIP), the minimization of Shop Floor Throughput Times (SFTT) and lead times, the lowering of stockholding costs, and the improvement of the responsiveness to changes in demand [20]. The main activities of a generic PPC are demand forecasting, Sales and Operations Planning (S&OP)/aggregate planning, Master Production Scheduling (MPS), Material Requirements Planning (MRP), inventory and capacity planning and control, production scheduling, and Shop Floor Control of production (SFC) activities [18]. PPC is often represented by hierarchical frameworks that include the various elements or activities of the process at varying levels of detail and time horizons [21]. Given its fundamental role in the manufacturing processes, this function—and in particular the choices taken in this context—can significantly affect the overall consumption of resources contributing to the overall sustainable growth of the company. The conventional PPC systems consider several resources (e.g., material, labour, production capacity, and their costs) but generally neglect the role of sustainability aspects [22,23]. Addressing them in terms of emissions, renewable resource usages, and social issues surely adds complexity and more effort to take in different PPC tasks [24]. Common planning goals need to be extended by sustainability ones, and the real problem is their integration [22]. Although the main function of PPC is to maximize the economic dimension in the operational processes, there is also the need to use strategies in PPC to value the environmental [17,24] and social dimensions [24]. For sustainable decision-making purposes, the economic, environmental, and social aspects must be described in more detail by considering, for example, specific production costs, GHG emissions, and employees' safety and health [24]. The integration of the sustainable aspects could ensure that the entire process is guided by principles of social responsibility (human well-being), green system design (environmental cleanness), and economic success [25].

Even though sustainability, whose achievement is affected by PPC processes and choices taken, represents a vital aspect of the modern manufacturing industry, it also encompasses our entire lives. The integration of three different sustainable pillars in all of the processes, from manufacturing to construction or public administration, is complex and difficult. Sustainability is not only about the environment, but it also concerns economic and social criteria that need to be balanced to achieve overall sustainability. Above all, the consideration of the social pillar is still limited either as a single pillar or when integrated

with other ones. Until now, researchers have focused on specific processes of PPC [19,22] and, only in recent years, some of the literature reviews have been conducted on the sustainability issues in PPC [26,27].

1.3. Research Aim

Although the issue of sustainability is increasingly in the spotlight, it is not yet apparent how to properly include it within corporate policies in the planning of production systems. The choices taken at the planning stage impact the potentially achievable level of sustainability, and nowadays, there is an increasing need to include sustainable issues in PPC tasks. However, a comprehensive state-of-the-art of research themes in this field and the possible future steps have not been provided in the literature. To the best of the authors' knowledge, no extensive bibliometric study of the literature on sustainable production planning and control has been conducted until now, and this represents the knowledge gap that this research study wants to address.

Bibliometric methods, useful in guiding the researcher to the most influential studies and in mapping the research field without subjective bias, use a quantitative approach to identify, evaluate, and monitor published research studies. Bibliometric analysis is a scientific computer-assisted review that summarizes a large amount of bibliometric data to provide the state of the overall intellectual landscape and emerging trends of a research topic or field [28]. Covering all the publications related to a given topic or field, this kind of analysis allows the identification of core research or authors, as well as their relationships [29]. It is widely applied to analyse the research status, frontier directions, and development of trends of specific research fields [30]. It is useful when the scope of the review is broad. Differently from the systematic literature review that works on a restricted set of publications and implements a deep content analysis, the bibliometric analysis has advantages in providing abundant and relational information on a specific topic and helps researchers predict the forward trends of disciplines [29,30].

For this reason, this research study provides a comprehensive bibliometric review of the sustainability issues in PPC tasks to investigate the trends and main research themes, explore the most significant contributions, and identify possible shifts in research. The main research questions to address are as follows: how has research in the field of sustainable production planning and control developed over the years and what are the most relevant themes? What could the potential future research trends and agenda include? Therefore, the main innovative contribution of this paper is to examine the scientific literature on the sustainable issues involved in production planning and control in manufacturing systems, methodologically providing a bibliometric analysis and highlighting the main research themes. The aim is to both define the state-of-the-art literature and a picture of the future themes in this research area.

The remainder of this article is organized as follows. Section 2 describes the research methodology providing the details related to the search for relevant articles and how they have been analysed; Section 3 reports the results of the carried-out analysis, and Section 4 discusses the results obtained and their implications for future scientific research. Lastly, Section 5 provides the main conclusions of this work and its main limitations.

2. Research Methodology

The research methodology, developed to investigate the most relevant research themes in the field of sustainable production planning and the potential future research trends and agenda, is depicted in Figure 1.

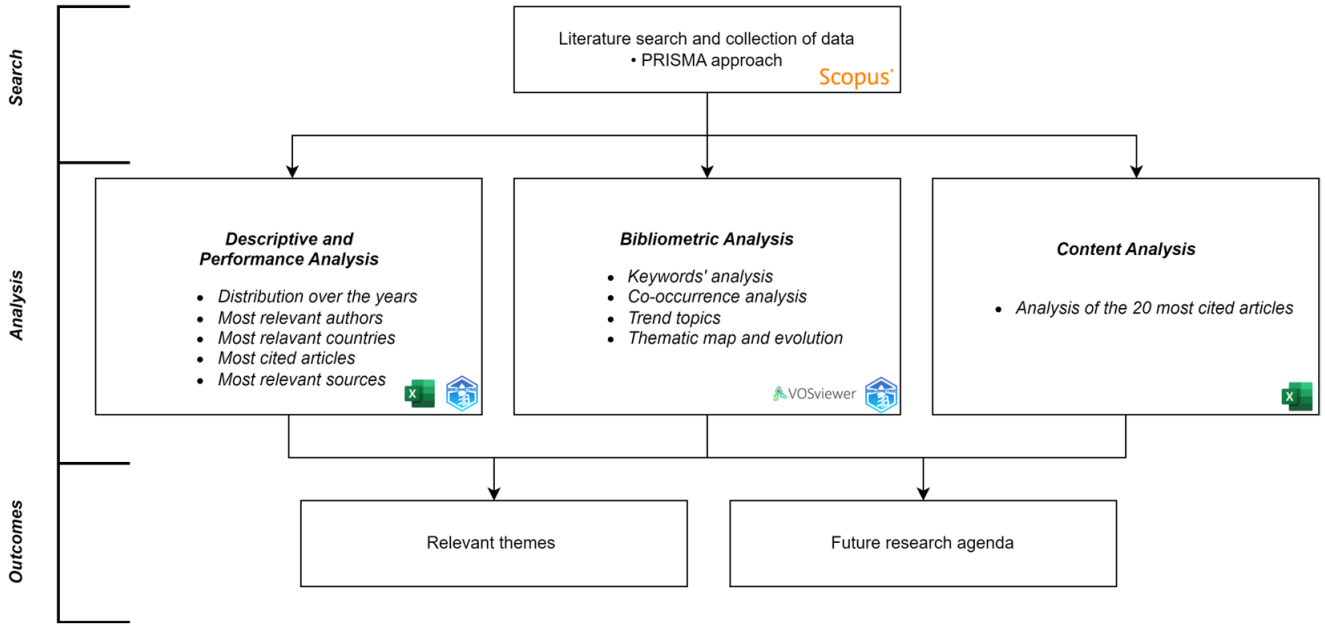

Figure 1. Research Methodology.

2.1. Search

The Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA), i.e., a technique that provides a roadmap to study systematic reviews objectively, clearly, and transparently, has been adopted in this research study for the establishment of an eligible set of articles to analyse [31]. The Scopus database, one of the largest peer-reviewed databases of multidisciplinary research publications, was used to search for the relevant literature related to the research topic of this study. Initially, a search string was developed including all the terms related to the two main topics (A) "sustainability" and (B) "production planning and control". In particular, the query used was as follows:

TITLE-ABS-KEY ((“sustainab” OR “triple bottom line” OR “TBL”) AND (“production planning” OR “production control*” OR “manufacturing planning” OR “manufacturing control*”))*

To identify the most significant literature from a qualitative point of view, the document types were restricted to articles and reviews. Furthermore, the search was limited to articles written in English and published in the last 20 years (timespan 2003–2023). After the exclusion of the articles that belonged to subject areas not directly or indirectly related to manufacturing environments (e.g., agriculture, medicine, neuroscience, medicine, etc.), which resulted in 474 articles, a second-round selection was carried out by reading the title and abstract of each document. The exclusion criteria for this step focused on whether the document was consistent with the research topic. For example, all the articles that were not related to the manufacturing sector, did not consider sustainability and PPC simultaneously, or focused exclusively on a method/technology and not on results in terms of sustainable PPC, were excluded from the analysis. In the end, 437 articles made up our reference portfolio. The PRISMA flowchart for this research study is depicted in Figure 2.

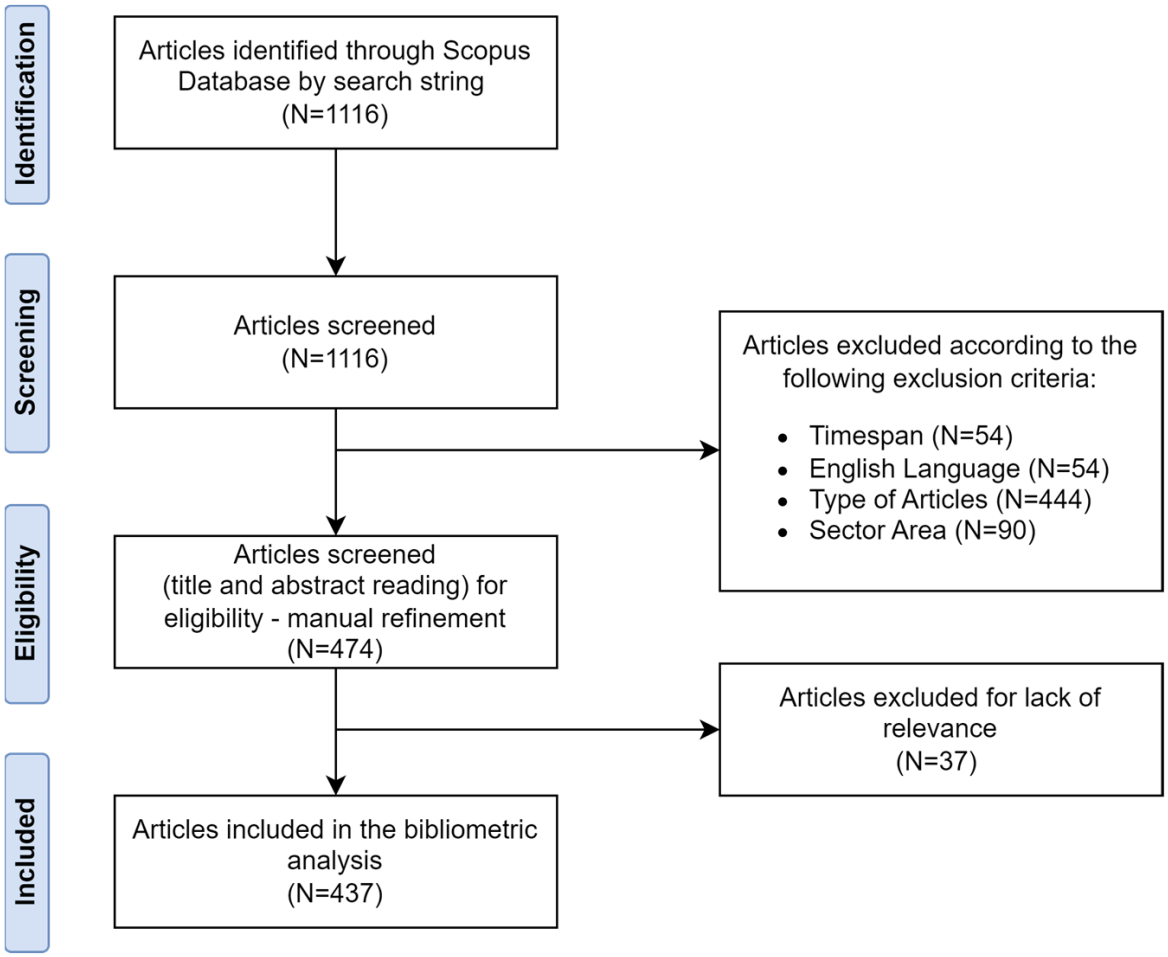

Figure 2. PRISMA flow chart for bibliometric analysis on sustainable PPC.

2.2. Analysis

Once having collected the relevant articles for the review, three types of analyses were performed as reported in Figure 1.

- Descriptive and performance analysis: This analysis, focusing on the publications and their main characteristics, aims to examine the contribution of researchers in a given field [28]. In this way, the most relevant authors, sources, articles, etc. can be identified objectively. Over a Microsoft Excel spreadsheet, Bibliometrix R-package software (version 3.2.1) was employed. It is an open-source software that provides a set of tools for conducting quantitative research in bibliometrics developed by Aria and Cuccurullo [32] and is nowadays more accessible thanks to the web interface app "Biblioshiny".
- Bibliometric analysis: Focusing on keywords as a unit of analysis, the existing and possible future relationships between the topics were investigated. Keywords, co-occurrence, trend topics, and thematic map analysis revealed the main themes on which researchers have focused over the years and that dominate the research landscape. Bibliometrix R-package was used for keywords, trend topics, and thematic map analysis, whereas VosViewer (version 1.6.16), i.e., a freely available software developed for constructing and viewing bibliometric maps with significant attention to the graphical representation, was employed for the co-occurrence analysis.
- Content analysis: Focusing on the top 20 articles by number of citations (most cited), a deeper and more qualitative analysis was performed, defining for each paper the main aim, the type of scientific contribution, and the relationship to sustainable pillars. This

analysis allowed us to investigate better the themes and provide more information regarding the topics already highlighted by the other two kinds of analysis.

The results related to the three different carried out analyses are described in detail in the following sections.

2.3. Outcomes

The combination of the results obtained was useful in defining the most relevant themes in the field of sustainable production planning and control and the potential future research agenda, discussed in detail in Section 4.

3. Results

3.1. Descriptive and Performance Analysis

At the end of the screening process, 437 articles, published on 192 different sources and divided into 391 articles and 46 reviews, were selected for the bibliometric analysis to be performed.

3.1.1. Distribution over the Years

Figure 3 shows the evolution of scientific production in the research field investigated. It is possible to observe that more than half of the selected articles have been published in the last 6 years (2018–2023, 227 out of 437 papers) with a peak of publications in 2021 (57). This highlights the increasing attention provided by researchers on sustainable requirements and issues in manufacturing planning and control processes.

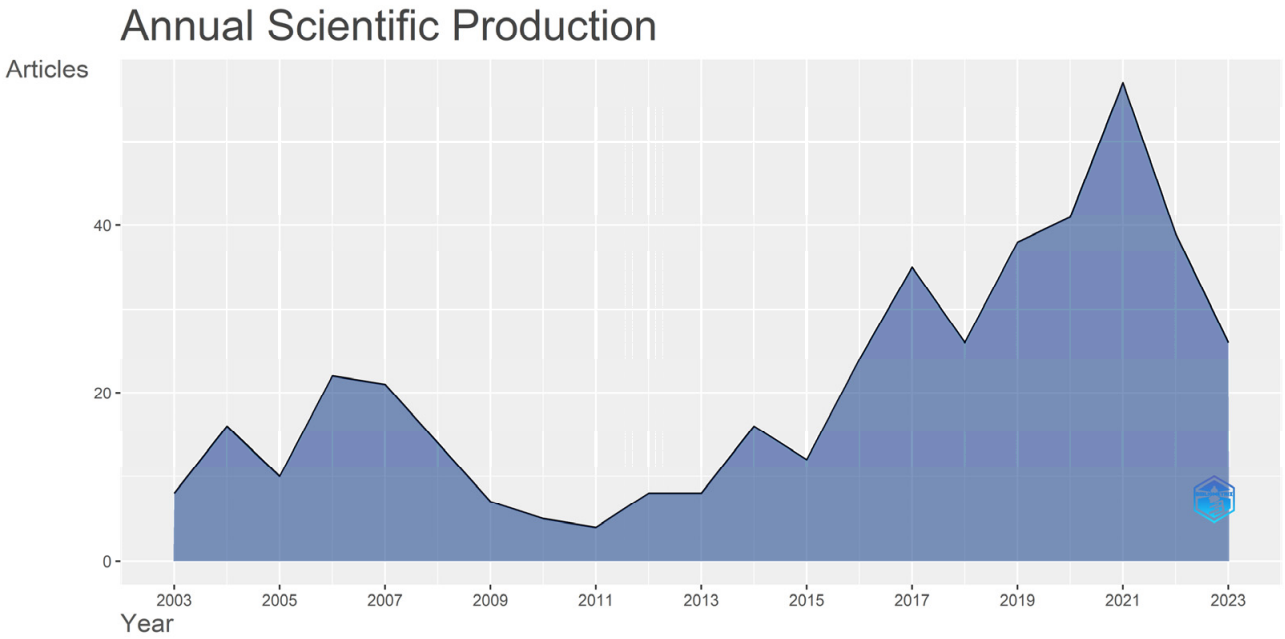

Figure 3. Distribution over the years of publications.

3.1.2. Most Relevant Authors

The top 10 authors with the highest number of publications are reported in Table 1. A total of 24 out of 39 (more than half) papers related to the following authors have been published since 2018 to date. It is interesting to highlight that the most productive authors (from the point of view of the number of publications) collaborated in research activities such as in the case of Zarte Maximillian, Pechamnn Agnes, and Nunes Isabel L. [24,25,33–35] or Li Lin and Yun Lingxiang [36–39].

Table 1. Most relevant authors.

#	Author	Affiliation	Country	H-Index	Articles
1	Li, Lin	University of Illinois at Chicago	USA	33	10
2	Pechmann, Agnes	Department of Mechanical Engineering, University of Applied Sciences	Germany	10	6
3	Yildirim, Mehmet Bayram	Wichita State University	USA	17	6
4	Lanza, Gisela	Karlsruher Institut für Technologie	Germany	26	5
5	Zarte, Maximilian	Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa	Portugal	9	5
6	Nunes, Isabel L.	Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa	Portugal	12	5
7	Babaee Tirkolaee, Erfan Babaee	İstinye Üniversitesi	Turkey	31	4
8	Yun, Lingxiang	University of Illinois at Chicago	USA	3	4
9	Liu, Yang	Linköpings Universitet	Sweden	32	4
10	Chaturvedi, Nitin Dutt	Indian Institute of Technology Patna	India	11	4

3.1.3. Most Relevant Countries and Collaborations

An analysis related to the corresponding author's country in this research field has been also carried out. The first 15 countries, in terms of the highest number of publications, are reported in Table 2. It could be noted that China and the United States have the highest number of publications, followed by Germany. Under the top three, the number of publications strongly decreases for the other countries.

Table 2. Most relevant countries.

#	Country	Articles	SCP	MCP	Total Citations (TC)	TC/Articles
1	China	53	30	23	1289	24.3
2	USA	52	40	12	3360	64.6
3	Germany	40	30	10	809	20.2
4	India	22	16	6	647	29.4
5	France	15	9	6	567	37.8
6	Canada	14	11	3	521	37.2
7	United Kingdom	14	9	5	514	36.7
8	Italy	11	9	2	349	31.7
9	Spain	10	4	6	341	34.1
10	Turkey	9	7	2	122	13.6
11	Iran	8	7	1	49	6.1
12	Korea	8	6	2	101	12.6
13	Brazil	6	6	0	81	13.5
14	Denmark	6	6	0	257	42.8
15	Japan	6	5	1	207	34.5

The top three countries for the higher number of articles have also achieved the highest number of total citations. However, if the total number of citations is reported to the number of articles, this classification seems to not be respected. Under USA, Denmark, France, and Canada represent the most relevant countries with fewer publications in number but are more effective from a citational point of view.

3.1.4. Most Cited Articles

Table 3 reports the publications with the highest number of citations in this study. The higher the number of citations, the more influential the article is for researchers who develop and study the specific field [40]. The most cited articles, as expected, are not very recent. However, if the total number of citations is reported to the number of years of publications, the most effective and relevant articles are [41–44] with two papers published

in 2020 [41,43] and one in 2019 [44]. This highlights that the research attention has focused on this topic in recent years, and some of the articles have become relevant for all the scholars in the field.

Table 3. Most cited articles.

#	Title	Ref.	Year	Source	TC	TC/Years
1	Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study	[42]	2007	*International Journal of Production Economics*	735	43.2
2	Operational methods for minimization of energy consumption of manufacturing equipment	[45]	2007	*International Journal of Production Research*	471	27.7
3	A review of engineering research in sustainable manufacturing	[15]	2013	*Journal of Manufacturing Science and Engineering*	277	25.2
4	A framework to minimise total energy consumption and total tardiness on a single machine	[46]	2008	*International Journal of Sustainable Engineering*	275	17.2
5	An investigation into minimising total energy consumption and total weighted tardiness in job shops	[47]	2014	*Journal of Cleaner Production*	234	23.4
6	Production planning of a hybrid manufacturing/remanufacturing system under uncertainty within a closed-loop supply chain	[48]	2012	*International Journal of Production Economics*	224	18.7
7	Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance	[41]	2020	*Resources, Conservation and Recycling*	208	52.0
8	Sustainability in manufacturing operations scheduling: A state of the art review	[22]	2015	*Journal of Manufacturing Systems*	187	20.8
9	Multi-objective genetic algorithm for energy-efficient job shop scheduling	[49]	2015	*International Journal of Production Research*	184	20.4
10	Energy-efficient dynamic scheduling for a flexible flow shop using an improved particle swarm optimization	[50]	2016	*Computers in Industry*	182	22.8
11	Functional and systems aspects of the sustainable product and service development approach for industry	[51]	2006	*Journal of Cleaner Production*	181	10.1
12	Time-of-use based electricity demand response for sustainable manufacturing systems	[52]	2013	*Energy*	179	16.3
13	Human factors: Spanning the gap between OM and HRM	[53]	2010	*International Journal of Operations and Production Management*	159	11.4
14	Incorporating green purchasing into the frame of ISO 14000	[54]	2005	*Journal of Cleaner Production*	158	8.3
15	Towards more sustainable management systems: through life cycle management and integration	[55]	2008	*Journal of Cleaner Production*	151	9.4
16	Single-machine sustainable production planning to minimize total energy consumption and total completion time using a multiple objective genetic algorithm	[56]	2012	*IEEE Transactions on Engineering Management*	149	12.4
17	Circular economy business models and operations management	[44]	2019	*Journal of Cleaner Production*	141	28.2
18	Systematic literature review of decision support models for energy-efficient production planning	[57]	2016	*Computers and Industrial Engineering*	140	17.5
19	Empowering and engaging industrial workers with Operator 4.0 solutions	[43]	2020	*Computers and Industrial Engineering*	138	34.5
20	Periodic review, push inventory policies for remanufacturing	[58]	2003	*European Journal of Operational Research*	135	6.4

3.1.5. Most Relevant Sources

Figure 4 depicts the most important journals publishing on the topic of sustainable production planning and control. The importance is derived from the number of published articles. *Journal of Cleaner Production* is ranked first followed by *Sustainability*. The reason behind the relevance of this journal with respect to the other journals could lay in the direct addressing of both the issues of sustainability as well as production in the title. This journal aims to provide and discuss theoretical and practical solutions for a "cleaner production", i.e., systems more careful of a reduction in waste and, in general, of "unsustainable" effects. This journal was expected to be among the most influential in the field of study investigated since the topic also covered the ways to make more sustainable production processes and the environmental and sustainable assessment methods to practice. Instead, other journals like *Sustainability,* which is second-scored, surely include production and sustainability in a larger-purpose scope. This transdisciplinary journal provides studies on sustainability related to areas such as applied sciences, engineering, economics, and social sciences. Different from the *Journal of Cleaner Production*, the main topic of this journal is represented by sustainable development provided by a wide range of applications that include, but is not completely focused on, industrial production or manufacturing. This could be the reason behind the second place of *Sustainability* among the sources. Ranked third, with less than 20 articles on the topic, the *International Journal of Production Research*, a leading journal in the areas of manufacturing, industrial engineering, operations management, and logistics covering, and in particular the topic of production planning and scheduling. Our findings revealed that even if not as a main scope of the journal, the sustainability issues related to this topic are sought by the journal.

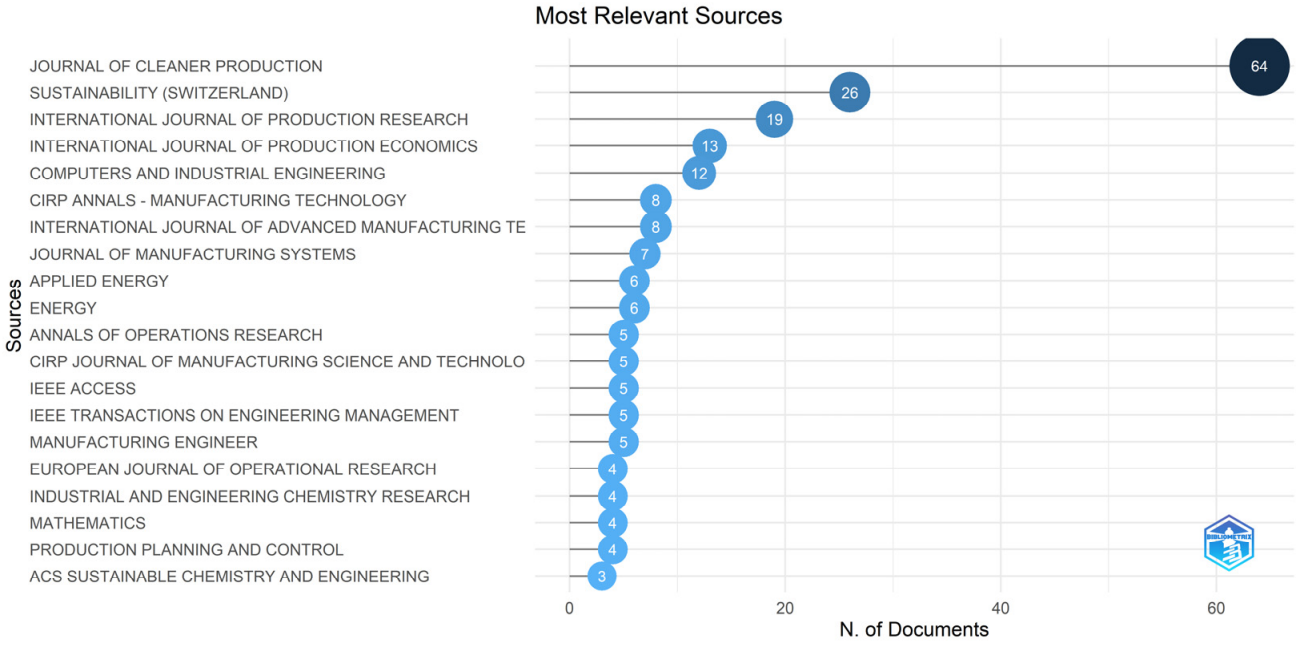

Figure 4. Most relevant sources.

3.2. Bibliometric Analysis

The bibliometric analysis aims to investigate the main themes on which researchers have focused over the years and that dominate the research landscape of sustainable production planning and control.

3.2.1. Keywords' Analysis

First, to investigate the trending topics, a keyword analysis was carried out. Keywords can be considered as basic elements of knowledge concepts representation [59]. They are

generally used to reveal the knowledge structure of research domains [60]. The word cloud in Figure 5a shows authors' frequently used keywords, i.e., the keywords chosen by the authors since they seem the most representative of their works; instead, the word cloud reported in Figure 5b represents the results obtained through the analysis of the most frequent keywords plus, i.e., words or phrases that frequently appear in the titles of an article's references, but do not appear in the title of the article itself.

(**a**) (**b**)

Figure 5. Authors' keywords analysis (**a**); keywords plus analysis (**b**).

The initial analysis performed on the author's keywords has highlighted the new trends in remanufacturing and the circular economy and classical scheduling problems, whereas—among the technologies provided by Industry 4.0—only Machine Learning seems to be one of the most investigated. Regarding the methods and tools, optimization, simulation, decision support systems, and mathematical programming are the most frequent. Lastly, even if the prevalence of the environmental/energetic consideration (both for authors and keywords plus) was expected, the cost and social aspects are not significantly prevalent. They only appear, but with a low frequency, in the keywords plus ("cost effectiveness" and "economic and social effects").

3.2.2. Co-Occurrence Analysis

Starting from the global results obtained via the keywords' analysis, to define the main thematic clusters, a co-occurrence network analysis has been conducted. If the analysis of keywords reveals in an absolute way the main significant topic of interest, the co-occurrence analysis is much more representative of the relationship between different topics, being based on the examination of the frequency of occurrence and the strength of the link between specific keywords. The combination of keywords can bring to light more complex and articulated research topics in a field.

With a minimum number of 10 occurrences for keywords, 76 over 3591 keywords (considering both the index and authors' keywords) have been included in the network. The results, obtained using Vos Viewer as described in Section 2, are depicted in Figures 6 and 7. Four main clusters have been identified (Figure 6): "environmental sustainability in scheduling" (green), "production control for sustainable development" (blue), "new trends in sustainable production planning" (red), and "planning in circular economy contexts" (yellow).

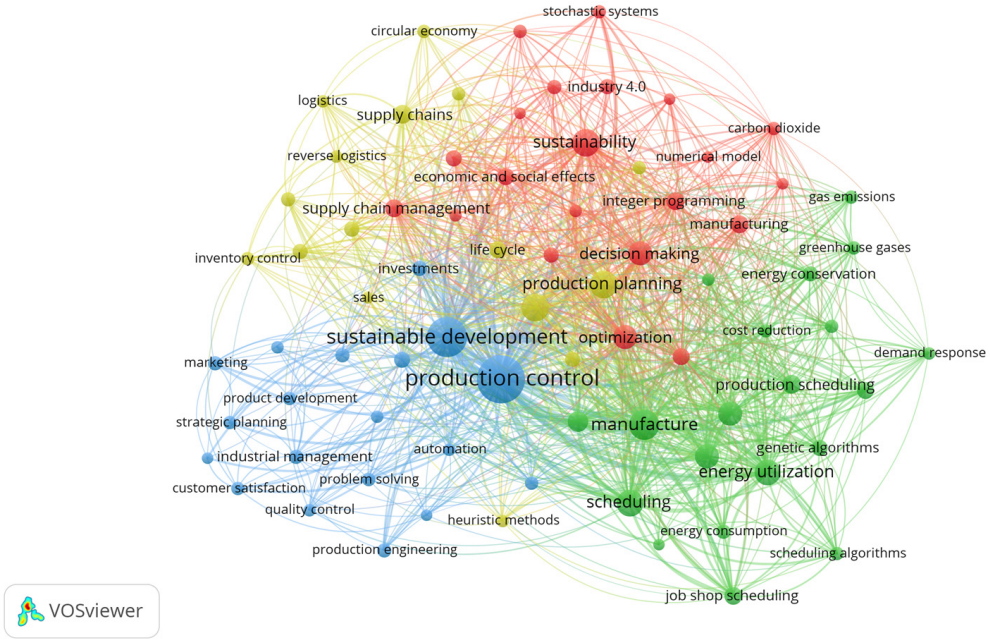

Figure 6. Co-occurrence analysis—network visualization.

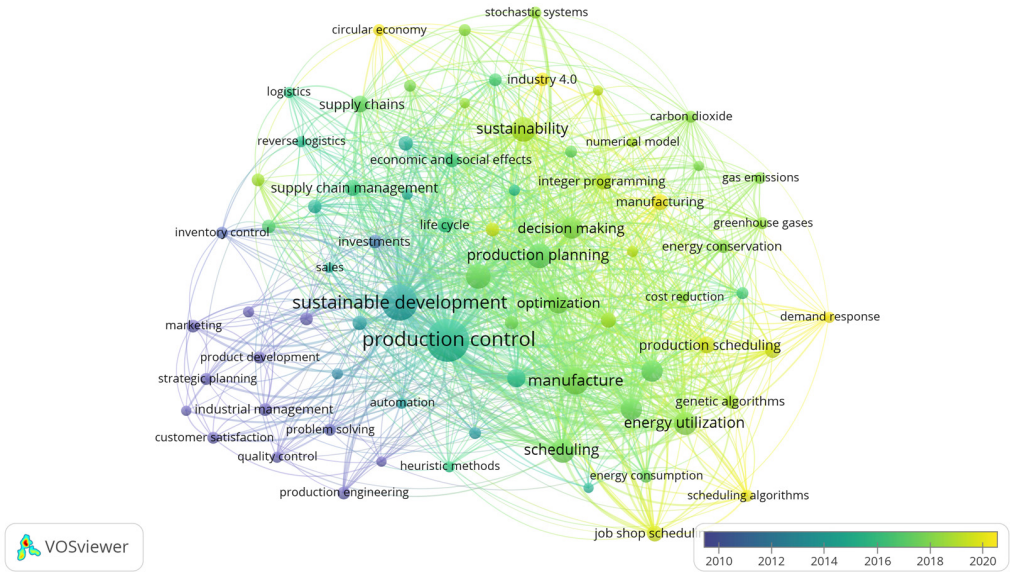

Figure 7. Co-occurrence analysis—overlay visualization.

Figure 7 instead, depicts how the words have evolved. It is interesting to note that even if the documents selected for the analysis are related to the time range 2003–2023, the most relevant keywords identified referred to the last 10 years. The "oldest" research themes seem to be related to cost-effectiveness in different industrial application fields, whereas in recent years the attention has shifted to the new circular economy and remanufacturing paradigm/model. The concept of sustainable development, aimed at the achievement of Sustainable Development Goals (SDGs), has initially been linked to production control. This is probably because the first step was the activity of monitoring and controlling any particular production processes. Only since around 2016, researchers have focused on how to make more efficient decisions in production planning and improving sustainable strategies.

3.2.3. Trend Topics

The trend topics are reported in Figure 8. The size of the circles shows the frequency of the term, whereas the length of the lines shows how long it has been studied. Several trends, in an absolute way, have been revealed. From a technological point of view, Industry 4.0 and Machine Learning seem like very recent topics in the overall picture. Instead, remanufacturing and circular economy first appeared in 2017, whereas the topic of reverse logistics has been studied since 2012. As expected, the theme of energy efficient planning, directly linked to the environmental and economic pillars of sustainability, has been investigated for a long period (about 15 years).

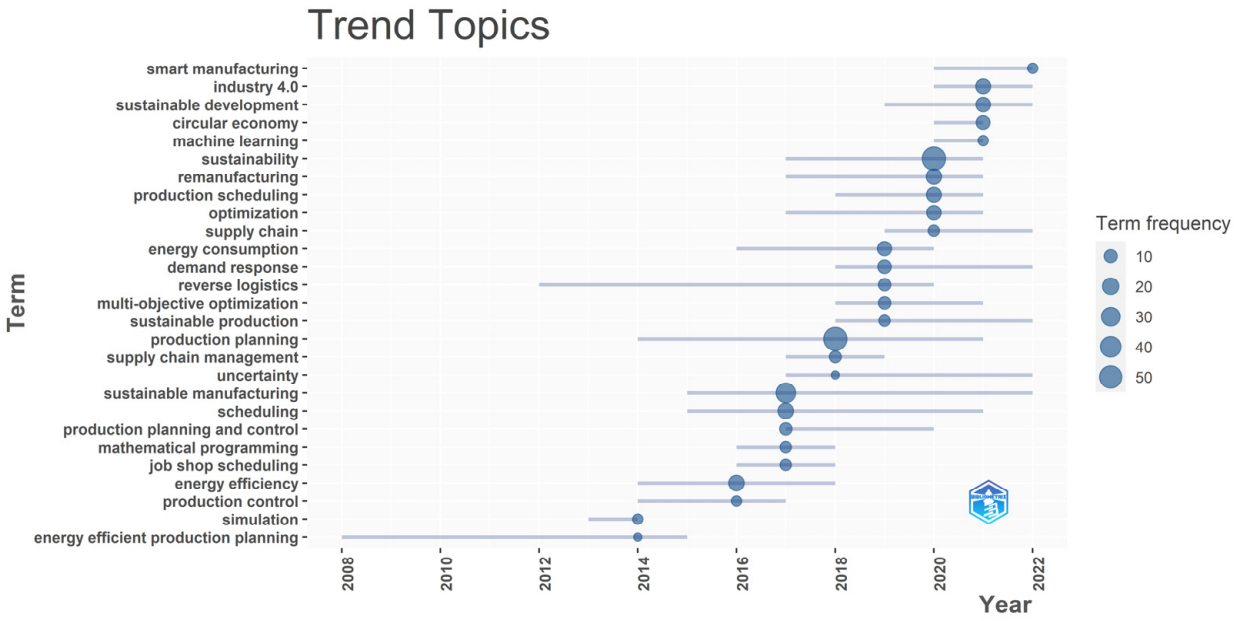

Figure 8. Trend topics.

3.2.4. Thematic Map and Evolution

The main aim of a thematic map analysis is to gain insight into the field status and its future, identifying the most consolidated themes and the emerging ones. A thematic map has been defined according to centrality (i.e., the importance of a theme) and density (i.e., a measure of the development of a single theme) rank values along two axes concerning the authors' keywords. These two properties measure whether certain topics are well-developed or not or are important or not. The size of the cluster is proportional to the number of occurrences of the keywords, whereas the labels chosen using the software correspond to the predominant keywords. The main themes are classified into the following: Motor (high centrality and high density), i.e., the most developed themes; Niche (low centrality and high density), i.e., the well-developed and very specialized themes; Emerging or Declining (low density and centrality), i.e., undeveloped and marginal themes; and Basic (high centrality and low density), i.e., important themes for the research field but are still not well developed. The thematic map (Figure 9) reveals that an important body of research focuses on Industry 4.0 (and in general on the use of new enabling and smart technologies) to support and improve production planning and control processes and on scheduling processes aimed at the achievement of lower levels of energy consumption. The development of decision support systems for the achievement of sustainable production, thanks to planning, represents the new emerging themes, whereas production planning and manufacturing for the achievement of sustainable goals represent basic themes investigated in the literature. Remanufacturing and a circular economy, which will significantly affect the traditional approaches to PPC, seem to be important themes for researchers but not yet motor themes. The uncertainties (above all in supply chain management) to face in the

actual world and, in general, the decision-making processes related to these tasks instead represent a niche area that needs to be developed.

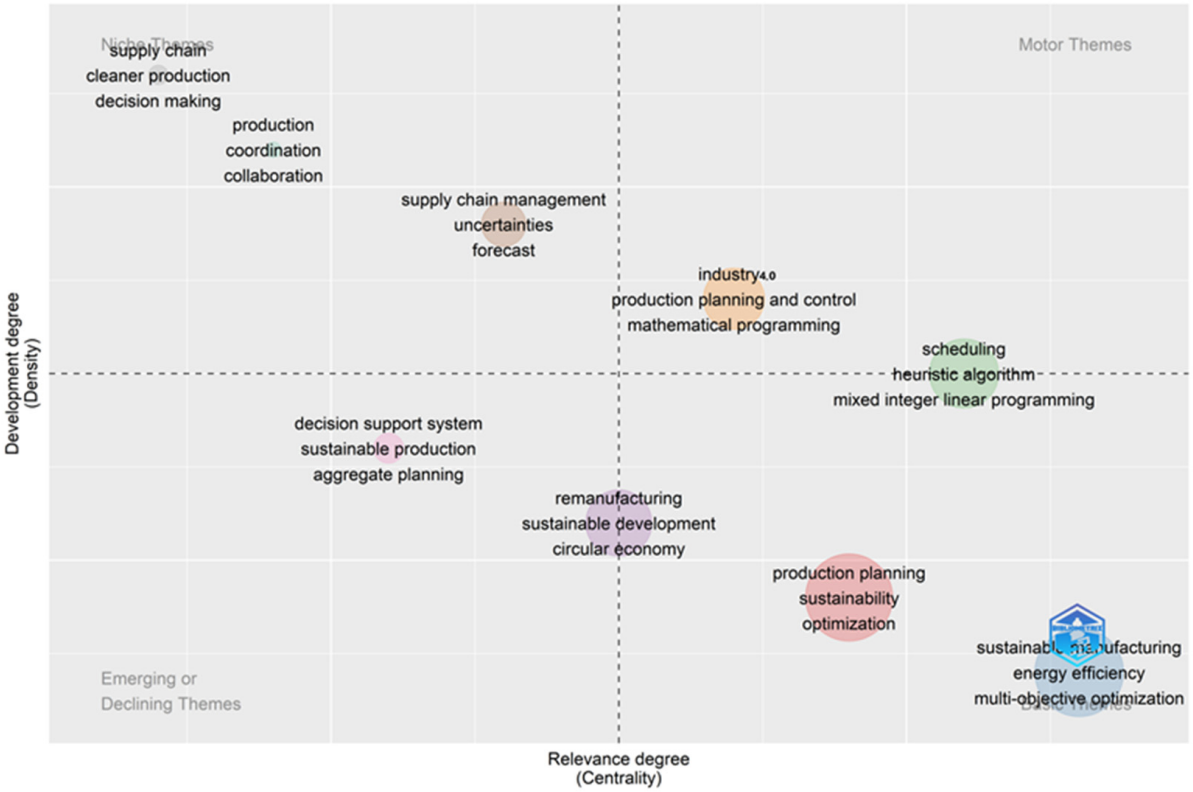

Figure 9. Thematic map.

The thematic evolution, depicted in Figure 10, reveals how the different themes have diverged over the years and which ones are the newly explored fields.

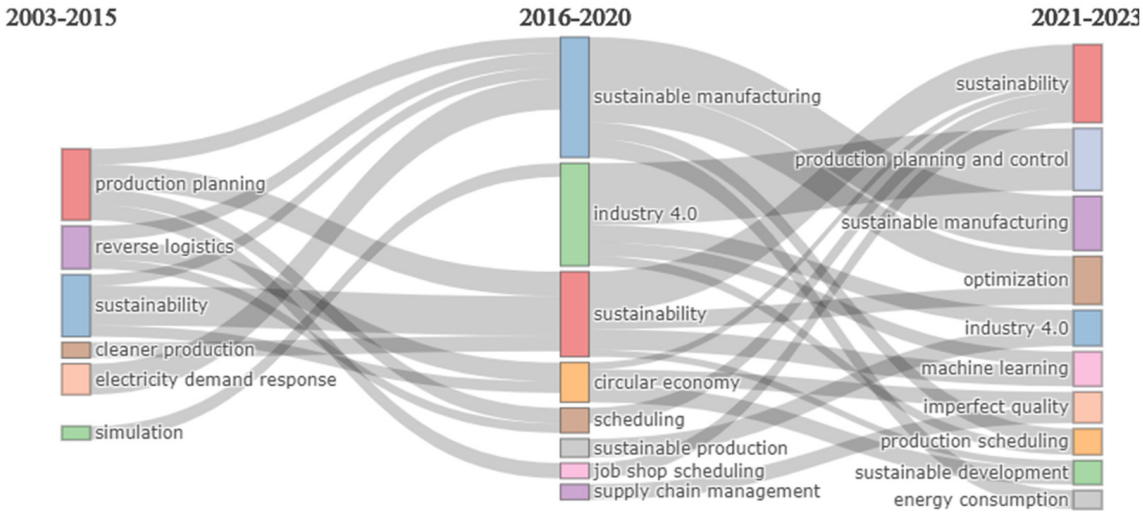

Figure 10. Thematic evolution.

3.3. Content Analysis

Starting from the bibliometric analysis, a qualitative review of the first 20 most cited articles has been conducted, analysing their contents. The main characteristics, in terms of aims, type of scientific contribution, research field, and the eventual direct or indirect sustainable pillar involved, are reported in Table 4.

Table 4. Content analysis results of the first 20 most cited articles.

#	Ref	Aim	Type of Scientific Contribution	Field	Sustainable Pillar Involved
1	[42]	Development of a simulation model for the managers in a steel industry to quantify the benefits gained from using lean tools and techniques	Development of a model	General	General
2	[45]	Development of operational methods for the minimization of energy consumption	Development of a model	Scheduling	Environmental
3	[15]	State-of-the-art analysis of research trends in sustainable manufacturing	Review	General	Environmental
4	[46]	Development of a framework for the definition of a set of efficient solutions that minimizes the total energy consumption and total tardiness of jobs on a single machine	Development of a framework	Scheduling	Environmental
5	[47]	Development of a model for the job shop scheduling problem to minimize total weighted tardiness and total energy consumption	Development of a model	Scheduling	Environmental
6	[48]	Proposal of a manufacturing/remanufacturing policy to minimize the sum of the holding and backlog costs for manufacturing and remanufacturing products	Development of model	Reverse logistics	Economic
7	[41]	Integration of I4.0, reverse logistics, and lean approach in the scheduling of the remanufacturing	Development of a framework	Reverse logistics	Environmental/ Economic
8	[22]	State-of-the-art review of sustainable manufacturing operations scheduling	Review	Scheduling	Environmental/ Economic
9	[49]	Development of an algorithm for job shop scheduling including objectives as productivity and energy consumption	Development of a method	Scheduling	Environmental
10	[50]	Development of an approach to address the dynamic scheduling problem reducing energy consumption and makespan for a flexible flow shop scheduling	Development of an approach	Scheduling	Environmental
11	[51]	Development of a pragmatic approach for supporting Sustainable Product and/or Service Development (SPSD) in industry	Development of an approach	General	All
12	[52]	Development of a systems approach for Time of Use based electricity demand response for sustainable manufacturing systems under the production target constraint	Development of a system approach	Scheduling	Environmental
13	[53]	Investigation of improvements both in human well-being and operations system performance by human factors	Review	General	Social
14	[54]	Development of a framework of guidelines for green purchasing and related implementing procedures	Development of a framework	Purchasing	Environmental
15	[55]	Discussions of standards for management systems and their integration	Development of a framework	General	General
16	[56]	Development of a framework for the choice by decision maker for the most efficient schedule with an appropriate energy-consumption level	Development of a model	Scheduling	Environmental
17	[44]	Implications of the adoption of the circular economy on operations management decision-making processes including production planning and control	Review	PPC	General
18	[57]	State-of-the-art of decision support models integrating energy aspects into mid-term and short-term production planning	Review	PPC	Environmental

Table 4. *Cont.*

#	Ref	Aim	Type of Scientific Contribution	Field	Sustainable Pillar Involved
19	[43]	Design implications for empowering and engaging Operator 4.0 solutions	Overview/Results from case studies	General	Social
20	[58]	Development of heuristics based on traditional inventory policies and analysis of remanufacturing system performance	Development of a model	Inventory management in remanufacturing	General

Most of the research studies included in this content analysis dealt with the development of models or frameworks, mainly aimed at improving production from an environmental point of view. Reviews and overviews, which generally receive the highest number of citations easily, are reported in only 6 out of 20 papers, and among them, only 2 have been published in the last 5 years [43,44]. In particular, the link between circular economy and operations management with a focus on PPC is emphasized in [44], whereas [43] deals with the introduction of Operator 4.0 in manufacturing and its implication on PPC too.

4. Discussion

The carried out analysis of the scientific literature, methodologically based on three different analyses (descriptive and performance, bibliometric, and content) and whose results were described in Section 3, has revealed three different ways to address sustainability issues through operations: (i) by including in scheduling models objectives related to sustainability; (ii) by removing barriers and issues to reverse logistics and circular economy at the PPC level, and (iii) through process improvement to remove wastes in production processes. Additional details are noted as follows:

i. In the PPC field, scheduling, i.e., the allocation of human and technical resources to tasks over given periods to optimize one or more criteria [61], is one of the most studied problems by operations researchers. There is increasing attention to identifying how manufacturing scheduling can contribute globally to manufacturing sustainability by addressing environmental, social, and economic goals even if this makes the related decision processes much more complicated [15,22]. Traditional approaches to scheduling problems have generally focused exclusively on throughput time, productivity, tardiness, and related metrics [15]. However, starting from 2007 [45], among the TBL pillars, as revealed by the keywords (Section 3.2.1), co-occurrence (Section 3.2.2), and trending topic (Section 3.2.3) analyses, researchers have introduced the minimization of energy consumption into scheduling problems [46,47,49,50,56], making them more challenging and complex, due to the need to save cost and also to become more environmentally friendly [47]. Probably, in the beginning, the minimization of energy consumption has been seen as one of the ways to reduce overall manufacturing costs, whereas in recent years the main drivers to this challenge are represented by the reduction in reserves of energy and global warming [56]. In general, the models try to solve the scheduling problems using multi-objective optimization models to minimize energy consumption but also the total completion time. However, reducing energy consumption may imply a decrease in the performance of operations [22]. It is quite impossible, even if desirable, to minimize the use of means (in an absolute way) to produce something thanks to a sustainable manufacturing schedule. Manufacturing companies can achieve partially this objective at lower energy consumptions, lower energy costs, and less energy-related GHG emissions [57]. Lastly, it is also interesting to highlight the neglect of the social pillar for the scheduling even if needed for the complete respect of sustainable principles as reported in [22]. Even after 8 years from this publication, the situation has not radically changed from a scientific point of view. In the development of sustainable scheduling models, addressing a combination of economic, environmental, and social indicators in the constraint set or objective function seems to be an interesting research field [26].

ii. Over the inclusion of sustainable objectives in scheduling, an interesting topic revealed from the analysis is related to the barriers and issues in the circular economy paradigm related to planning and controlling processes, as highlighted by the thematic map and evolution (Section 3.2.4) and the carried-out content analysis of the 20 most cited articles (Section 3.3). The circular economy (CE) is a production and consumption system that aims to maintain the circulation of products, components, materials, and energy to continue to add, restore, and maintain their value over a long time [44]. Remanufacturing represents, instead, the vital component of the circular economy aimed at "returning a used product to at least its original state with a warranty that is equivalent to or better than that of a newly manufactured product" [48,62]. The role of PPC in this new productive paradigm needs to be prepared to incorporate the use of recovered materials, obtained thanks to reverse logistics, into material planning, ensuring operations have sufficient capacity to reconcile conventional manufacturing with remanufacturing [44]. Disassembly and reverse flows, the most significant changes brought by the circular economy, present challenges for production scheduling. There are problems such as uncertainty regarding the quality, quantity, and timeframe for the return of materials and components to be remanufactured, refurbished, or reused and how to produce, plan, and generate demand for manufactured and remanufactured products simultaneously that significantly affect PPC processes [41,44,63]. As reported in [44], the main implications of circular economy in the PPC field are the new capabilities required (such as a system of indicators and dematerialization strategies), work procedures (cleaner production, flexibility of systems, and supply uncertainty), variability of process orders and reprocessing times, and the use of new technologies (Big Data, etc.).

iii. Lastly, the carried-out analysis revealed how companies can use technology and lean tools in sustainable-driven decision-making processes. The keywords (Section 3.2.1) and the trending topics (Section 3.2.3) analyses have spotlighted new and recent topics related to technological innovation (such as "smart manufacturing", "Artificial Intelligence", and "Machine Learning"). As reported in the thematic evolution (Section 3.2.4), starting from 2016, "Industry 4.0" has become a relevant theme in this research field, and today, it is still already fundamental in the achievement of sustainability. It seems evident that the context of Industry 4.0—and the possibility to automate the acquisition, processing, and analysis of data—can help in decision-making processes. In recent research, smart manufacturing has increased since it can be a driver of sustainable production systems, but, even in this case, the literature confirms the prevalence of environmentally sustainable oriented operations decisions provided by the Industry 4.0 technological innovation [41]. Nowadays, manufacturing systems can rely heavily on information and communication technology thanks to the ongoing development of cyber systems and smart technologies such as Big Data, the Internet of Things (IoT), cloud computing, Cyber–Physical Systems (CPSs), and Digital Twin (DT). This can aid in the transition to sustainable manufacturing practices more aligned with the "Triple Bottom Line". If on the one hand, the use of technologies seems to be relevant, on the other, the analysis of the literature also revealed the use of lean approaches among the possible strategies to adopt to reduce waste. These different approaches also have different costs and impacts on the overall manufacturing systems. Lean strategies allow the improvement of production conditions by eliminating waste, maintaining better inventory control, improving product quality, and obtaining better overall financial and operational control [42,64] within restricted resources [65]. Since the main aim of lean approaches is the reduction/elimination in "wastes", it is clear that many of the tools and techniques of lean manufacturing (e.g., just-in-time, cellular manufacturing, total productive maintenance, etc.) can be used to make the manufacturing systems [42] more sustainable, and they can be integrated into planning and decision-making processes. For example, the change in production control can provide less inventory and improvement in lead times [64].

Lean approaches can be combined with smart manufacturing to improve production planning and focus on sustaining product quality and diversity at a competitive cost as reported in [66].

From the point of view of the TBL pillars addressed, the environmental one is the more discussed while the social one is, as very often happens, quite neglected. This aspect is evident not only from the analysis of the most cited articles (Section 3.3) but also from the analysis of the keywords (Section 3.2.1) and the thematic map (Section 3.2.4). For the environmental pillar, the focus is especially on how to reduce or optimize energy consumption. Back in 2008, Seuring and Muller [67], the leading researchers on the topic, had highlighted that studies were failing in integrating the Triple-Bottom-Line dimensions, as they still give priority to the economic dimension, and the social dimension is very often neglected. The situation has not improved that much. Social sustainability is based on the identification and management of all impacts on people. Although there is attention to the "human" element provided by Industry 4.0 [68] and emphasized by the emerging Industry 5.0, generally, researchers do not focus on this aspect. Differently from the environmental pillar, this sustainable pillar is probably more unclear, and it is more complex to justify models and frameworks in this field. For this reason, many researchers excluded this pillar from their analysis. In the field of PPC, for example, planning shifts, which is a complex task that affects workers' social life and health, needs to include important preferences for co-workers, shifts, and machines in addition to abilities and competencies in worker models and adaptation approaches [43]. Only in recent years, researchers have begun to investigate this kind of sustainability issue [69–71].

Research Agenda

In general, it looks like including sustainability within the PPC process has not fulfilled the task of making it a substantial part of the decision process. It is still limited by focusing only on a specific PPC process (scheduling) and by addressing mostly the environmental pillar. Sustainability will be pervasive in manufacturing when each pillar will play a role in each phase of the decision process. This study, however, has provided an overview of the research topic and can represent a starting point for new researchers and scholars in the field. Some interesting aspects should be investigated by researchers in the future. The implications of decision-making processes on sustainability seem to not be systematically addressed in the literature. How the decision taken in the planning field affects the entire manufacturing system from a sustainable point of view and how to measure this kind of effect are not clear or emphasized at the moment.

Several standard and indicator sets have been developed over the years such as the Global Report Initiative (GRI) or the National Institute of Standards and Technology (NIST), as already reported in 2013 by Juang [72]. However, how to correlate and integrate these indicators in planning and control processes has been not investigated until now. A path to explore to achieve the objective could be the integration with the standard already recognized and appreciated. Similar to what occurred with the quality and ISO 9000 [73] standard that was able to promote quality as not only an operative matter but something affecting the whole company at every level. From the analysis of the main research topics, it seems that researchers have not given significant importance to standards according to planning and control tasks.

Another interesting point to further investigate is how technology can help in sustainable decision making and which technologies mainly can support sustainable development from this point of view. More attention needs to be paid to the development of decision support systems that can improve a company's decision-making capabilities in sustainable optics.

Moreover, the prevalent sustainable issues reported in the analysis are environmental and, in some cases, economic ones. Although the shift to the new Industry 5.0 paradigm, which complements the existing Industry 4.0 focusing on a more sustainable, human-centric, and resilient system, the social concerns related to workers, even if highlighted

by researchers from times, seem to be not well investigated still and developed probably because it is not easy to include these aspects in the planning given the difficulty and complexity of defining, and above all, measuring the connection to the social aspects affected by these processes. Generally, and historically, energy consumption and costs have been easier to manage from this point of view. Manufacturing enterprises affect employees by different PPC choices taken defining the real utilization and workload, both physical and mental. The physical workload is easier to manage, whereas the mental one, i.e., the overall amount of mental resources required to perform a set of tasks, is much more complex to assess and include in PPC choices, besides being influenced by the digitalization level achieved in the production processes. PPC is affected by these aspects and the related consequences in terms of productivity and availability of workers. For this reason, much strong consideration of social issues can not only improve human conditions but also the performance of the entire manufacturing system. A potential research field to investigate can be the evaluation of the impacts on workers of PPC choices and the definitions of improvement strategies in this field.

Finally, the remanufacturing paradigm and the new challenges related to planning and controlling processes should be further investigated. The uncertainties related to recoverable products add complexity to the processes, and all decisions taken from the strategic to operative level need to be revised from a different perspective. This does not mean restarting but adapting and facing new challenges in the manufacturing context.

5. Conclusions

In this study, a bibliometric analysis has been carried out to offer a broad spectrum of research on sustainable production planning and control identifying the past and current trends of research. The thematic trend and potential areas of interest have been obtained by reviewing 437 papers taken from the scientific database Scopus and analysing the most influential authors, countries, and research topics. To provide details related to our quantitative results, we also conducted a qualitative review of the 20 most cited articles. The results revealed increasing attention in this research field (overall in the last 10 years). China, the United States, and Germany are the most influential countries, whereas, among the authors, Li Lin, Pechmann Agnes, and Yildirim Mehmet Bayram are the most "productive" authors in the field. The most influential journals, instead, are the *Journal of Cleaner Production* and *Sustainability*.

The results obtained from three different analyses (descriptive and performance, bibliometric, and content) have revealed the most relevant themes in the field of sustainable production planning and control defining three main research streams.

First, researchers have mainly focused until now on how to get energy savings in production scheduling, enhancing environmental sustainability but also providing economic advantages. Secondly, in the new paradigms of circular economy and remanufacturing, which allow for a reduction in the amount of waste and extend the life cycle of products, the planning and controlling processes have to be revised according to a non-standard way of producing, which takes the variability in processes to extremes. Lastly, the growth in the use of technologies (such as Artificial Intelligence and Machine Learning), provided by Industry 4.0, can significantly help achieve a high level of sustainability in planning and controlling.

In addition, some research themes that would merit further attention have been identified. For example, the social concerns in PPC and the implications of PPC decision-making processes on sustainability seem to be yet not systematically addressed. Furthermore, attention needs to be paid to the development of decision support systems that can improve a PPC company's capabilities in sustainable optics considering technologies and their use in the manufacturing context.

Thus, this study provides a helpful guide to researchers and scholars to define future lines of work, studies, frameworks, and tools to improve PPC capabilities in sustainable optics. By providing a state-of-the-art and future research agenda, it could be possible to

direct researcher efforts to the development of this fascinating and actual topic focusing on the real needs of industrial companies. Industrial companies will benefit from the scientific studies since decision makers can define more sustainable processes in PPC, and this will help in the overall transition to a sustainable manufacturing context more in line with the strengthening regulations.

However, this study presents some limitations. First, although Scopus is one of the most comprehensive scientific databases, it would be useful to explore other databases such as Web of Science, Engineering Village, Wiley, and EBSCO for evaluating further studies on the topic. Furthermore, the search string has been developed to focus on sustainability in production planning and control processes. Given the broadness and complexity of the research field, not all the relevant studies on the topic could have been included in the analysis. Also, the screening process revealed some limitations. For example, all the articles not written in English have been excluded, simplifying our analysis. Moreover, in the reading of the article title and abstract, subjective choices taken by the authors could have affected the overall number of studies analysed. In addition, other bibliometric analyses (e.g., co-citation analysis, bibliographic coupling, co-authorship analysis, etc.) could be performed also using other software tools such as CiteSpace (version 6.2.R4) or SciMAT (version 1.1.04). Finally, for the content analysis, only the top 20 most cited articles were investigated in detail. This threshold could be increased to provide a clearer and bigger picture of the topic. Focusing on specific PPC tasks and defining a more heterogeneous dataset of articles, a meta-analysis could be performed.

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Nomenclature

CE	Circular Economy	**MRP**	Material Requirements Planning
CPSs	Cyber–Physical Systems	**NIST**	National Institute of Standards and Technology
CSRD	Corporate Sustainability Reporting Directive	**PPC**	Production Planning and Control
DT	Digital Twin	**PRISMA**	Preferred Reporting Items for Systematic Reviews and Meta-analysis
EBSCO	Elton B. Stephens Company	**S&OP**	Sales and Operations Planning
EFRAG	European Financial Reporting Advisory Group	**SDGs**	Sustainable Development Goals
ESG	Environmental, Social, and Governance	**SEC**	Securities and Exchange Commission
EU	European Union	**SFDR**	Sustainable Finance Disclosure Regulation
GHG	Greenhouse Gas	**SFC**	Shop Floor Control
GRI	Global Report Initiative	**SFTT**	Shop Floor Throughput Times
IoT	Internet of Things	**TBL**	Triple Bottom Line
MPS	Master Production Scheduling	**WIP**	Work in Progress

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