Integration of Sustainable Production Criteria into Production Scheduling: A Systematic Search and a Critical Review

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Abstract: Production scheduling plays a pivotal role in shaping and optimizing production processes to promote sustainability in manufacturing companies. Understanding how current studies consider sustainable production criteria in scheduling objectives can help companies transition from a reactive to a proactive production mode. This paper presents a systematic and critical analysis of 120 articles to examine the extent to which sustainable production criteria have been applied to scheduling problems in manufacturing systems. The analysis categorizes articles based on the type of scheduling problem, problem formulation, resolution method, and sustainability aspects considered, while also tracking the evolution of each sustainability indicator to identify trends. The study reveals the use of diverse sustainability indicators in production scheduling. Indicators such as "Makespan" and "Energy consumption" are prevalent, while social indicators related to employee well-being and safety are still emerging and rarely considered. Notable gaps identified in this review include the absence of real-world applications, unclear criteria for indicator selection, and limited holistic assessments linking production improvements to overall sustainability. The review emphasizes the need for practical and strategic approaches, serving as a guide for the manufacturing sector and informing future research directions.

1 INTRODUCTION

In recent years, there has been significant attention to the concept of sustainable production in both academic and business alike. This increased focus is propelled by the forces of economic development, social transformation, and increased concerns regarding environmental degradation (Lu et al., 2017). In striving for a delicate harmony between economic, social, and environmental elements within production, a holistic approach is crucial. Within the context of a circular economy and Industry 4.0, Viles et al. (2022) delineated ten pivotal principles that define sustainable production for manufacturing firms. This holistic perspective recognizes the interdependence of these pillars and ensures the long-term viability and sustainability of manufacturing systems (Abedini et al., 2020).

Within the realm of the Sustainable Production paradigm, production planning and scheduling play a pivotal role in shaping and optimizing production processes (Khaled et al., 2022). It serves as a key driver in operational decision-making, enabling manufacturers to optimize resources, enhance efficiency, and minimize waste, among others. The integration of sustainable production principles into production planning and scheduling holds the potential to advance the Triple Bottom Line objectives of economic viability, social equity, and environmental stewardship (Lu et al., 2017).

This paper presents a systematic and critical review of academic literature aimed at examining the extent to which sustainable production criteria have been applied to address scheduling problems in manufacturing systems.

The importance of conducting this review stems from the need for manufacturing companies to transition from a reactive approach to a proactive

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mode of sustainable production, recognizing that the latter is essential for the long-term success of businesses (Piwowar-Sulej, 2022). Through an exploration and synthesis of existing knowledge, this review aims to provide manufacturing companies with valuable insights into the integration of sustainability principles within the production scheduling process.

While a few previous studies have examined sustainability aspects concerning production scheduling there remains a significant gap in providing a comprehensive critical review of existing research (Giret et al., 2015). In this comprehensive study, we aim to bridge existing gaps by conducting a thorough examination of 120 articles that incorporate sustainability criteria into production scheduling.

Our objective is to deepen our understanding of sustainable production in manufacturing, encompassing economic, social, and environmental dimensions. We will also examine recent trends, evaluate commonly used sustainability indicators, and analyse prevalent challenges in the field. Through this critical assessment, we aim to provide valuable insights for future research and practical applications, making this review a valuable resource for manufacturing companies seeking state-of-the-art sustainable production practices in production scheduling.

The remainder of the paper follows this structure. Section 2 presents a background on the research topic, while Section 3 outlines the review methodology. Section 4 presents the results of the literature review. Section 5 delves into the discussion, and Section 6 provides some concluding remarks.

2 RESEARCH BACKGROUND

2.1 Previous Reviews

In recent years, Sustainable Production has emerged as a pivotal consideration in the domain of manufacturing systems. It encompasses a holistic approach aimed at achieving economic, environmental, and social sustainability in manufacturing processes (Abedini et al., 2020). To realize the ideals of sustainable production, manufacturers must address numerous challenges, including those related to production scheduling. Production scheduling plays a central role in manufacturing operations (Khaled et al., 2022). It involves the allocation of resources, such as machines, labour, and materials, to tasks or jobs over time to optimize various objectives, such as meeting customer demands, minimizing production costs, and maximizing resource utilization (Adhi et al., 2018). However, it is crucial to recognize that production scheduling problems are inherently complex, and most of them are classified as NP-hard. This complexity implies that is not possible to find optimal solutions for large-sized datasets in reasonable computational time (Adhi et al., 2018). Such complexity arises due to the combinatorial nature of scheduling, where numerous variables, constraints, and objectives must be considered simultaneously.

To tackle the complexity of production scheduling, researchers have developed a range of resolution algorithms. These algorithms aim to find near-optimal solutions within reasonable computational time. The most used approaches include heuristic and meta-heuristic algorithms. The former are problem-solving strategies that do not guarantee optimal solutions but provide good-quality solutions quickly, while the latter are higher-level strategies that explore the solution space efficiently and can be adapted to various scheduling problems (Janga Reddy & Nagesh Kumar, 2020).

The link between Sustainable Production and production scheduling is evident when considering the optimization of manufacturing processes with sustainability objectives in mind. Sustainable production scheduling aims to incorporate principles of sustainability into the scheduling decisions. Previous research in sustainable production and production scheduling has been shaped by the work of Giret et al. (2015), Biel & Glock (2016), Khaled et al. (2022), Renna & Materi (2021), and Akbar & Irohara (2018). These authors conducted extensive literature reviews to examine how researchers are integrating sustainability aspects into production scheduling. Table 1 summarizes these reviews by presenting the focus of the study, the sustainability aspects considered, the covered period, and the number of articles analysed.

Biel & Glock (2016) focus primarily on energy efficiency within sustainable production planning. The authors point out the surge in research in Energy-Efficient Production Planning and highlight the need to better integrate existing modelling approaches within this emerging field. Giret et al. (2015) point out the imbalances currently existing in research efforts to address all three dimensions of sustainability. As sustainability encompasses economic, social, and environmental issues, these authors noted a predominant focus on a specific input, namely energy. Furthermore, they underscore the neglect of real-time responsiveness in manufacturing operations, which is often overlooked in sustainable production planning.

Table 1: Previous literature reviews.

Reference	Focus	Sustainability aspects covered	Nº of reviewed articles	Period of review
(Giret et al., 2015)	Sustainable manufacturing operations scheduling	Economic and Environmental	45	2007-2015
(Biel & Glock, 2016)	Decision support models for energy-efficient production planning	Economic and Environmental	89	Up to 2015
(Akbar & Irohara, 2018)	Scheduling for sustainable manufacturing	Economic, environmental, and Social	50	Up to 2018
(Renna & Materi, 2021)	Energy efficiency and sustainability in manufacturing systems	Economic and Environmental	186	2007- June 2021
(Khaled et al., 2022)	Sustainability of Production Planning	Economic, environmental, and Social	45	2011-2021

Continuing with energy-dominant studies, Renna & Materi (2021) provide an overview of the integration of renewable energy sources into manufacturing systems. They categorize the studies based on manufacturing system typology and energy-saving policies and discuss the main approaches proposed in the short-listed papers. The analysis helps shed light on the diverse strategies and methodologies applied in the field of sustainable production planning.

The study conducted by Khaled et al. (2022) takes a comprehensive approach to sustainable production planning, emphasizing the consideration of multiple sustainability indicators. Their study stands out for its broader scope by considering all three sustainability aspects. They recognize the need for future research to address various optimization methods and the challenge of balancing conflicting sustainability objectives.

Similarly, the literature review conducted by Akbar & Irohara (2018) delves into the economic, environmental, and social aspects of sustainable production. It identifies sustainability indicators, assesses production systems, and outlines future directions. As some of the main findings, the authors conclude that the integration of these factors into scheduling models yields significant sustainability improvements and that the use of sustainable indicators empowers manufacturers to track progress effectively. Additionally, the review highlights the need for further research, especially in complex manufacturing systems, emphasizing sustainability's crucial role in shaping future scheduling practices.

2.2 Paper Positioning

While both Khaled et al. (2022) and Akbar & Irohara (2018) explored the social aspects of sustainable production scheduling, their studies have inherent limitations. The work presented by Akbar & Irohara (2018), dating back to 2018, may not fully encompass the latest developments in integrating sustainability. Indeed, as shown later in this paper, there has been a surge in contributions since 2019. Likewise, Khaled et al. (2022) made commendable efforts; however, their study had a narrower scope, encompassing only 45 articles and identifying 8 indicators. Furthermore, while Akbar provides a comparison between the indicators that are being used together, how these indicators are evolving is not considered. Additionally, it's noteworthy that none of the previously mentioned authors delve into the critical aspect of applying indicator selection criteria in real-world scenarios, which is needed for determining whether the ongoing improvements align with the overarching goal of enhancing the company's sustainability.

These limitations highlight the necessity for a more comprehensive understanding of sustainability's role in production scheduling. The research question, '*How have the criteria of sustainable production been employed to solve scheduling problems in manufacturing systems?*' remains pertinent and calls for further investigation. Our research seeks to identify the main gaps in this knowledge area by exploring sustainable production scheduling. We analyse 120 articles and identify recent trends, common challenges, and evolving strategies by offering a comprehensive view of sustainability in production scheduling.

3 REVIEW METHODOLOGY

This study employed a systematic literature review methodology, following the PRISMA guidelines, to

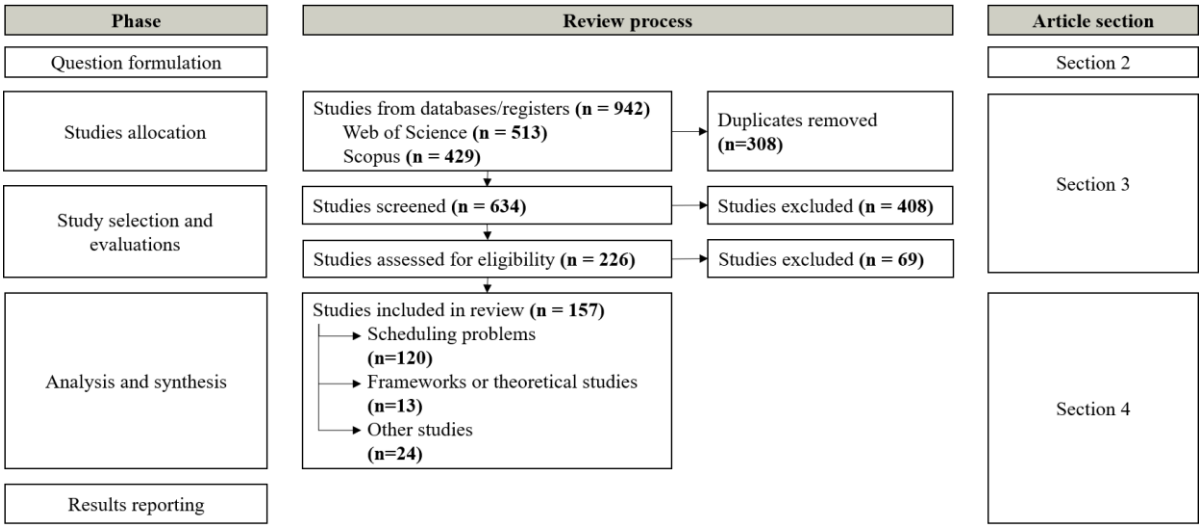


Figure 1: Literature review.

Group 1	Group 2	Group 3	Group 4
• sustainab*	• production	• design process	• optimization
• circular economy	• manufacturing	• redesign process	• simulation
• triple bottom line		• scheduling	• modelling

Figure 2: Employed keywords.

Inclusion criteria	Exclusion criteria
• **Research Focus:** The study focuses on the analysis of a production process in a manufacturing industry (at least a part of the production process). • **Sustainable Production:** The study considers at least one aspect of sustainability in the process design or redesign. • **Reviews:** The study presents reviews on the design or redesign of processes or activities related to sustainable production and circular economy. • **Design/Redesign Criteria:** The study discusses criteria to be included in the design or redesign of processes related to sustainable production and circular economy.	• **Production Time Focus:** Studies that solely consider production times as the primary factor without addressing sustainability or circular economy principles. • **Theoretical Studies:** Studies that are purely theoretical in nature and do not have practical implications or applications in the design or redesign of processes or activities. • **Supply Chain Focus:** Studies that primarily analyze supply chain design without including specific production aspects.

Figure 3: Inclusion and exclusion criteria.

address the research question mentioned previously. This methodology is widely recognized in research for its ability to provide insights into prior work, identify research gaps, synthesize related studies, and enable hypothesis testing, theory development, and critical evaluation of existing research (Xiao & Watson, 2019).

After the systematic literature review was conducted, a critical analysis was performed to address the research question. The objective of this analysis is to thoroughly examine the collected information, extracting insights and perspectives from the literature to facilitate the development of fresh theoretical constructs and novel viewpoints.

The five phases proposed by Tranfield et al. (2003) to conduct the review were used: 1) question formulation, 2) locating studies 3) study selection and evaluations, 4) analysis and synthesis, and 5) reporting and using the results. Figure 1 shows a scheme of what each phase covers and in which section of this paper each is developed.

To select relevant studies, inclusion and exclusion criteria were defined. The search was conducted using the Web of Science and Scopus databases, limiting the search to articles published in English between 2000 and July 2023. Since the aim of the study is to analyse how manufacturing companies design or schedule their production processes through optimization approaches, the search strategy involved search strings using a combination of the groups of keywords given in Figure 2. Throughout the process, the inclusion and exclusion criteria were considered, as explained in Figure 3. The search in both databases initially yielded 942 references. After removing 308 duplicates, 634 studies were considered. These studies were then screened against the title and abstract based on their relevance to the research question; this resulted in the exclusion of 408 studies. The remaining 226 studies were assessed for full-text eligibility. Out of these, 69 studies were excluded because they did not meet the study design criteria. Thus, a total of 157 studies were finally short-listed for further analysis and classification. Out of the studies included, 120 were specifically scheduling problems while the remaining 37 studies were classified as frameworks/theoretical studies or other studies, such as problems related to layout configurations, or process design, among others.

Finally, data extraction was conducted using the Covidence software, facilitating the systematic collection of relevant information from the selected studies. This software streamlined the process of managing and organizing the extracted data, ensuring accuracy and consistency.

4 RESULTS

In this section, the research question formulated previously is addressed through an analysis of the short-listed papers. General information about the included studies is presented first for context, followed by a review of the sustainability indicators considered in the scheduling problems.

4.1 Study Overview

In Figure 4, a notable trend is observed concerning articles related to sustainable production within the manufacturing sector, specifically focusing on production scheduling. While scheduling problems first appeared in 2008, it wasn't until 2013 that they began to gain significant momentum. However, it wasn't until 2019 that a substantial surge in published articles became evident. In 2018, the first article considering all sustainability dimensions was published and only a few have been published since then.

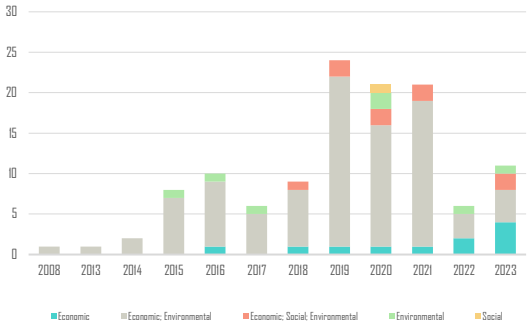


Figure 4: Evolution of publications and sustainability aspects over the years.

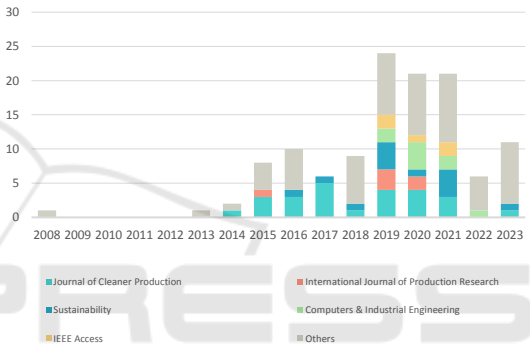


Figure 5: Publishing journals over the years.

Articles considering economic and environmental aspects combined are predominant, which indicates that research is still needed in this area.

As for the journals in which these articles were published, a striking diversity was noted. 58 articles have been published across five distinct journals, as shown in Figure 5. Importantly, this accounts for nearly 48% of the total short-listed articles, underscoring the wide array of publication outlets chosen by researchers in this field.

Concerning the sectors that are most advanced in this theme, the metal sector and the engineering sector are being prominently highlighted. However, the majority (65%) of the studies were not specific in terms of the sector, either being based on literature reviews or having the problem presented in a general manner without delving into the specific sector of the production process. Figure 6 displays the distribution of sectors in the remaining articles.

Directed toward the types of scheduling problems that are most studied, job shop and flow shop problems are brought to the forefront (see Figure 7). The third-largest group corresponds to the category

"Other" indicating studies where the scheduling problem is either not identified or the type of process does not fit into the presented categories.

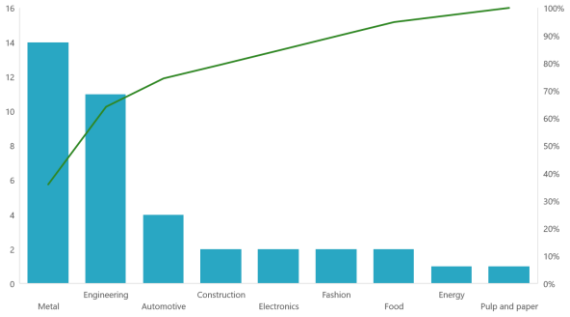


Figure 6: Distribution of sectors.

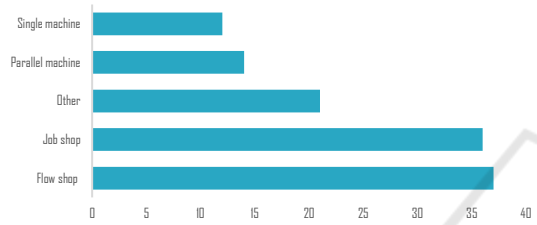


Figure 7: Types of scheduling problems.

Figure 8 provides a classification of the different approaches used to formulate and solve the scheduling problems. Among the studies focusing on a single-objective (SO) problem, they were classified by exact or approximate resolution method. Meanwhile, for studies addressing multi-objective (MO) problems, they can be classified into three distinct types. Type 1 (T1) studies involve formulating a mathematical problem and subsequently solving it. Typically, they employ methods such as epsilon-constrained optimization, goal programming, or solver tools to obtain an exact solution. Type 2 (T2) studies formulate the mathematical model of the problem but propose a resolution method. Typically, due to the complexity of these problems, the resolution methods involve heuristics or metaheuristics to find solutions. Finally, Type 3 (T3) are studies that, without explicitly formulating the mathematical model, suggest a resolution method. These methods also tend to rely on heuristics or metaheuristics for problem-solving.

The heuristics and metaheuristics commonly used are the Genetic Algorithm and its variations (36 studies), Particle Swarm Optimization and its variations (7 studies), and Simulated Annealing (4). However, there is a vast number of different methods being used, as well as modifications to those methods. This indicates that research related to sustainable scheduling is focused on improving resolution methods.

Figure 9 showcases how the optimization problems are being covered regarding the sustainability aspects that are addressed. In a broad overview, it becomes apparent that the multi-objective approach is prevalent, along with a predominant use of resolution methods categorized as Type 2 and Type 3, which can be easily justified by the NP-harness of most scheduling problems. Specifically, those problems that address two or more sustainability aspects are mainly formulated as multi-objective problems. On the other hand, in the context of single-objective approaches, the predominant technique for resolution is through approximate methods.

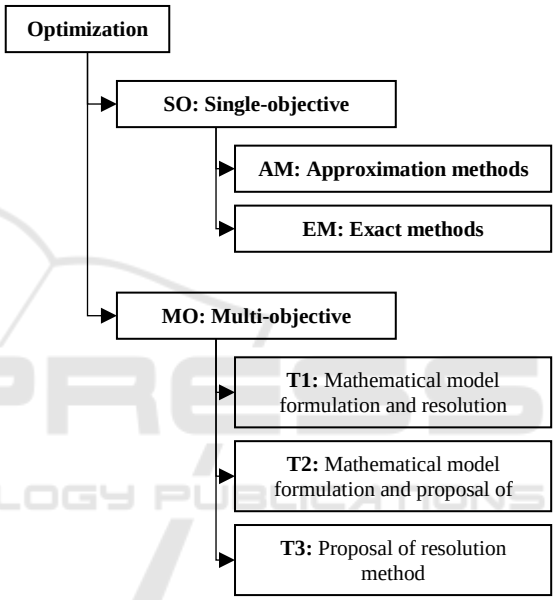


Figure 8: Classification of optimization problems.

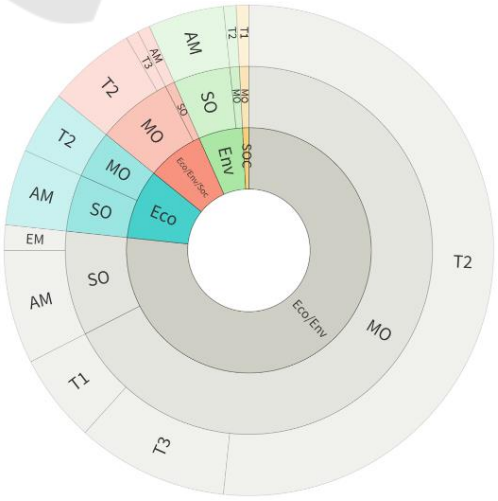


Figure 9: Sustainability aspects and types of problems.

4.2 Sustainable Production Criteria Included in Scheduling Problems

To reveal how sustainable production criteria are integrated into scheduling problems, a categorization process was carried out on the diverse indicators found in the literature. These indicators, which often measured similar aspects, were grouped. For instance, indicators related to production time, such as "Makespan," "Completion time," and others, were consolidated and labelled as "Makespan" for analysis. Similarly, environmental indicators concerning waste were merged under the label "Waste" and social indicators like "Training" and "Personnel skills" were merged as "Skills and training." This categorization approach was adopted to ensure a more organized and accessible presentation of the results, which can be found in the Appendix.

4.2.1 Evolution of Sustainability Indicators in Scheduling Problems

Figure 10 shows how indicators related to sustainability in scheduling problems have changed over time. These indicators are divided into economic, environmental, and social categories, represented by blue, green, and orange dots next to their names. It is essential to note that this review exclusively focuses on studies related to sustainability, excluding those solely centred on one of the dimensions (e.g., only economic factors).

The order in which the indicators are listed corresponds to their chronological appearance in the literature. The ones listed at the beginning of the list are those that emerged earliest, whereas those at the end of the figure represent the most recent additions. In the early stages, economic and environmental indicators were primarily used. Although the first article on this topic dates to 2008, it was only after 2013 that the gradual integration of environmental indicators into scheduling problems began to take shape.

The graph illustrates that "Energy consumption" and “Makespan” saw a significant increase in their utilization between 2019 and 2021. Additionally, other commonly used economic indicators included “Tardiness” and “Operating cost,” while within the environmental indicators’ category, "GHG

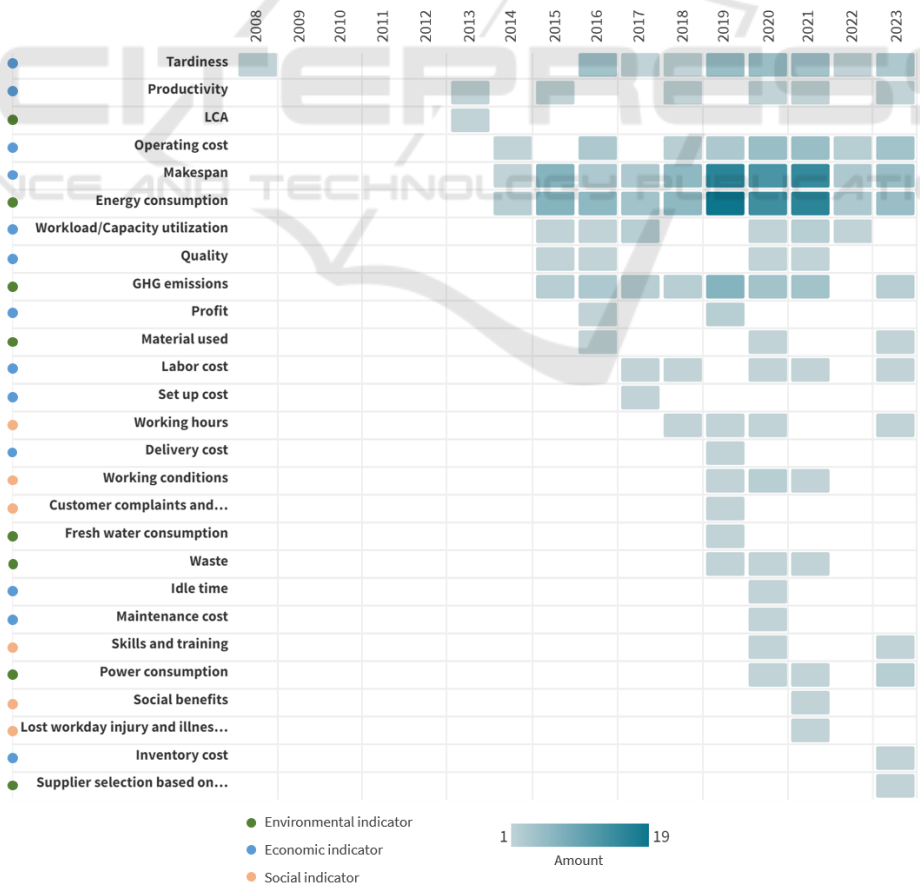


Figure 10: Evolution of indicator utilization.

emissions" were also frequently employed. For instance, “Material used” made its debut in 2016 but has not been widely used. Similarly, “Fresh water consumption,” introduced in 2019, has been employed sparingly, as has “Waste”, which has been used only three times since 2019. Furthermore, recent years have seen a shift toward considering supply chains, as evidenced by the emergence of the indicator “Supplier selection based on environmental criteria”.

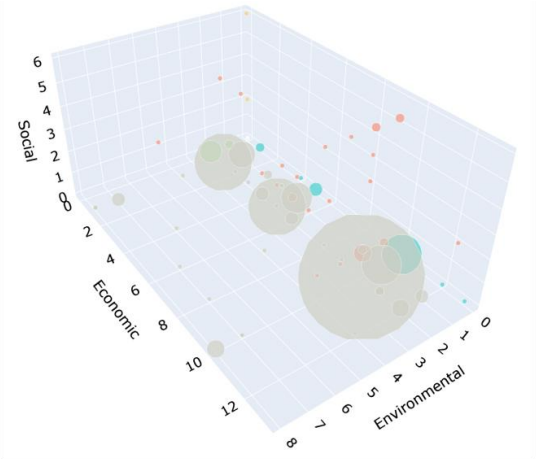
Turning to the social aspect, it is still in the early stages of exploration. Before 2018, no social indicators were considered. The first social indicator, "Working hours/Productivity" was introduced and has remained relevant until 2023. However, in 2019, a broader range of social indicators began to be considered, indicating an increasing interest in this dimension. In 2019, indicators such as "Working conditions" and “Customer complaints and returns” emerged. Although the focus on employee well-being is gradually increasing, it has not yet gained significant momentum, with indicators like “Skills and training” mentioned only once in 2020 and again in 2023, and “Social benefits” and “Lost workday injury and illness case rate” each appearing once in 2021.

4.2.2 Integration of Sustainability Indicators in Scheduling Problems

Although the use of indicators is important to analyse, when it comes to analysing sustainability, the focus should be placed on the integration of indicators. To gather this information, a 3D Bubble Chart was created (see Figure 11). Each bubble within the figure signifies a unique combination of indicators employed across all the studies, with the size of the bubble denoting the frequency of its utilization. The indicators themselves are marked with numbers, and a color-coded system has been implemented to enhance clarity in discerning these combinations.

Specifically, bubbles in orange, green, and blue correspond to the exclusive utilization of social, environmental, and economic indicators, respectively. Meanwhile, the grey ones signify a fusion of environmental and economic indicators, and the red bubbles denote the holistic incorporation of all three aspects.

Notably, the prevalence of studies solely addressing one facet of sustainability is relatively low. This observation underscores the importance of adopting a multifaceted approach when addressing sustainability concerns. Regarding the combinations of indicators, it becomes evident that the grey spheres



Economic indicators	
1	Operating cost
2	Total load transport distance
3	Set up cost
4	Productivity
5	Tardiness
6	Labor cost
7	Idle time
8	Maintenance cost
9	Profit
10	Makespan
11	Quality
12	Workload/Capacity utilization
13	Delivery cost
14	Inventory cost

Environmental indicators	
1	GHG emissions
2	Energy consumption
3	Fresh water consumption
4	Waste
5	Supplier selection based on environmental performance
6	LCA
7	Material used
8	Power consumption
9	Recycling cost

Social indicators	
1	Working hours/Productivity
2	Skills and training
3	Customer complaints and returns
4	Social benefits
5	Lost workday injury and illness case rate
6	Working conditions

Social dimension
Environmental dimension
Economic dimension
Social, Economic and Environmental dimension
Economic and Environmental dimension

Figure 11: Integration of sustainability indicators.

dominate both in terms of abundance and size. This suggests that the most advanced and thoroughly integrated aspects of sustainability often pertain to economic and environmental considerations. More specifically, the most frequently employed combination of indicators comprises "Energy consumption" and "Makespan." Additionally, "Energy consumption" is commonly paired with "Operating cost" and "Tardiness." In contrast, the red bubbles, symbolizing the integration of all three sustainability aspects, are noticeably smaller in size when compared to their grey counterparts. This distinction underscores the relative infrequency of such comprehensive sustainability approaches within the analysed studies. The largest among the red bubbles signifies the integration of "Makespan", "Energy consumption" and "Working hours/productivity." Furthermore, "Makespan"

appears in three out of the four subsequent red bubbles in terms of size. Turning our attention to the realm of social indicators, the ones most frequently employed are "Working hours/productivity" and "Working conditions". These indicators are pivotal in shaping the holistic perspective of sustainability adopted within the analysed studies.

5 DISCUSSIONS

In this section, a discussion of the results is undertaken. Firstly, the integration of sustainability indicators into production scheduling is explored. Following that, insights into the prevalent resolution methods are provided. Finally, drawing from our analysis of 120 articles, we deliberate on potential directions for future research.

5.1 Sustainability Indicators

Sustainability indicators are being actively integrated into scheduling problems, driven by the overarching goal of enhancing the sustainability of production processes. The subsequent subsections delve into a detailed examination of the incorporation of the social pillar, evaluate opportunities for enhancements in economic and environmental indicators, and scrutinize how studied with real-life applications consider and select sustainability indicators.

5.1.1 Emerging Social Sustainability Concerns

The diversity of indicators used to assess sustainability in production planning underscores the multifaceted nature of this field. While economic and environmental indicators continue to play a central role, the exploration of social indicators is still in its early stages. Although the focus on employee well-being is gradually gaining momentum, it has not yet achieved widespread adoption, as indicated by the limited utilization of indicators like “Skills and training”, “Social benefits” and “Lost workday injury and illness case rate”. These results are in line with the revision conducted by Akbar & Irohara (2018) five years ago, who identified that only one (out of 50 considered articles) included minimizing noise level as an objective function, and another one included accident rate as a constraint. Khaled et al. (2022) also highlight that the social pillar is the least addressed pillar and mention that indicators such as customer satisfaction and employee health and safety are suitable indicators to incorporate into scheduling problems (although customer satisfaction can be considered also an economic indicator). In the articles analysed, the growing awareness of the need to address social aspects within production scheduling has been highlighted by five authors. Out of these studies, only the first one proposes a specific social indicator to consider in future work: “balance of workers’ workload”, meanwhile the others just mention the need to incorporate the social pillar but do not address how. This reflects that although the direction is known, the path is not clear.

5.1.2 Improvement in Economic and Environmental Indicators

There are mainly two types of indicators that are well integrated into most of the scheduling problems, which are “Makespan” and “Energy consumption”. Although energy-related indicators are widely used, An et al. (2020) and other eight articles mention the need to go deeper into the calculation of the energy consumed, either by including the time of use (TOU) electricity price policy or similar schemes, by including machine operating modes or speeds or by refining the relationship between energy consumption and CO_2 emissions. However, the appearance of other environmental indicators related to water consumption, material consumption, and waste generated shows that only including aspects of energy consumption is not enough to evaluate the environmental sustainability of production processes. In particular, Piroozfard et al. (2018) mention that future research lines should incorporate indicators related to the use of water, meanwhile, Feng et al. (2020) mention contemplating material consumption and waste generation. Regarding the indicator “Supplier selection based on environmental performance”, although it has only been used once, the literature reveals a trend in including similar indicators. Six articles point out the possibility of considering transportation by measuring fuel consumption or including additional time. Moreover, more and more authors are realizing the importance of considering factors of the supply chain that affect production scheduling. In particular, Fülöp et al. (2022) mention the need to incorporate aspects from the whole production line into the problem and Feng et al. (2020) go for a further approach, wanting to include aspects from the whole supply chain into its problem.

5.1.3 Real-Life Applications

Out of the 120 articles included in this analysis, only 20 of them provide a real-life application in a

manufacturing company. Through the analysis of these studies, some insights about the selection of sustainability indicators and their alignment with a company's unique needs and objectives emerge.

One notable finding is that several studies lack clear justification for their choice of sustainability indicators. Seven studies provide general sustainability-related reasons to justify their selection. Eight studies justify their indicator selection by referencing the energy-intensive nature of the sector under study. While sector-specific considerations are important, they should be complemented by a deeper understanding of each company's distinct requirements and sustainability objectives. Finally, only a small number of studies, five in our analysis, consider the specific needs, preferences, or goals of the companies they investigate when selecting sustainability indicators. Specifically, Coca et al. (2019) evaluated all the inputs of the production process to find which aspects they should consider. This gap indicates that a significant portion of the research may not be effectively aligned with what would truly enhance a company's sustainability profile. Instead, many studies tend to rely on typical or conventional energy-related indicators, overlooking the unique circumstances of each company.

Also, the studies showcase a significant absence of standardized sets of indicators from which researchers could choose to evaluate sustainability comprehensively. Only Coca et al. (2019) and Fathollahi-Fard et al. (2021) mention the use of ISO guidelines to choose the indicators they consider in their scheduling problem, but these guidelines are specific to energy efficiency or workers conditions. The use of a guideline that covers all sustainability aspects and that permits a holistic understanding of it is lacking in the studies analysed. This absence of a standardized framework for indicator selection means that the choice of indicators used is often not made critically and deliberately, and there is limited understanding of their potential impact on various aspects of the company.

Regarding an evaluation of the companies' sustainability performance, there is a lack of evaluation of how the chosen sustainability indicators may impact other critical aspects of the company. This absence of holistic assessment means that potential trade-offs or synergies between sustainability goals and broader business objectives are often not considered.

5.2 Resolution Methods

Regarding the resolution methods, heuristic and metaheuristic methods are the most used to reach solutions to scheduling problems, regardless of the number of objectives considered. In the short-listed studies, these methods were used 105 times since as the problem becomes more complex and objectives are added, these resolution methods can provide solutions in reasonable computational time. Indeed, these resolution approaches are the main ones used in those studies that consider all three sustainability objectives. Within this group, the most used method is the Genetic Algorithm and its variants. In addition, swarm-based methods are widely used. The use of hybrid methods, which combine at least two methods from the categories analysed, is also abundant (Zhang, 2017).

Although there is a great diversity of algorithms that have been used, many of them are used only once or twice. As attempts are made to introduce additional constraints, conflicting objectives, and multi-dimensional goals, the necessity to formulate more robust resolution methods emerges (Giret et al., 2015). Based on the analysis of articles, there was a general trend to use a resolution method as a basis and improve it to obtain better results quickly. Forty-nine articles mention that the resolution algorithm needs improvement, which highlights the direction that future research is taking. The improvements they mention are related to improving the efficiency of the resolution method to be able to analyse a more complex problem (Fu et al., 2019; Lu et al., 2021). Other studies mention the importance of comparing the resolution algorithms with other existing ones for benchmarking (Gao et al., 2021; Marimin & Farhan, 2020).

5.3 Future Research Lines

Finally, adding up to the future lines already mentioned, some other ones have been identified in this research. Introducing dynamic and uncertain events was mentioned by thirty-five studies. Related to practical applications, Feng et al. (2020) mention that it is limited and that some advanced theories have not been verified in real cases. Y. Z. Li et al. (2021) and Jiang et al. (2019) consider that further studies should include more practical constraints and restrictions that meet the actual industrial conditions. Uncertain events like machine failure, the arrival of new jobs, cancellation of jobs, and rush orders are aspects that should be considered (Cui & Lu, 2021). Dynamic scheduling has also been addressed by authors for future research accompanied using real-time data (Fülöp et al., 2022), among others.

6 CONCLUSIONS

The main goal of this systematic review was to fill the knowledge gap about integrating sustainability into manufacturing scheduling. The analysis of 120 studies in this area contributes to the understanding of the current state of research in this field and provides insights for future research and practice, guiding manufacturing companies towards a proactive stance in embracing sustainable production practices. Three main conclusions can be drawn from this study, which are explained below.

First, the review underscores the need for integrating economic, environmental, and social indicators in production scheduling. While economic and environmental metrics like "Makespan" and "Energy consumption" are common, social indicators, including employee well-being and safety, are less integrated. The analysis reveals gaps in real-life applications, indicator justifications, standardization, and holistic assessments, highlighting the need for practical and strategic sustainability management aligned with companies' unique goals.

Second, resolution methods for scheduling problems are predominantly dominated by heuristic and metaheuristic techniques, with Genetic Algorithms being a prevailing choice. Regarding the industrial sectors, sustainable production research has been prominently centred on the metal and engineering sectors. However, to ensure the continued relevance of future research, it is imperative to validate advanced theories through real-world industrial applications and incorporate practical constraints.

The final insight that this study provides is regarding future research. It should prioritize the effective integration of sustainability indicators into the objective functions of scheduling models. This integration should be based on holistic sustainability frameworks that encompass all three sustainability dimensions. Studying the alignment of sustainability indicators with a company's specific needs and objectives is crucial.

Nevertheless, it's important to acknowledge the limitations of this review. The reliance on published articles may have overlooked valuable insights from other document types and real-world software applications.

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APPENDIX

The categorization of the revised indicators can be seen in the following link: Appendix 1. The full list of revised articles can be seen in the following link: Appendix 2.