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Review

A Keyword, Taxonomy and Cartographic Research Review of Sustainability Concepts for Production Scheduling in Manufacturing Systems

Massimo Bertolini *, Francesco Leali, Davide Mezzogori and Cristina Renzi

"Enzo Ferrari" Engineering Department, University of Modena and Reggio Emilia, 41121 Modena, Italy; francesco.leali@unimore.it (F.L.); davide.mezzogori@unimore.it (D.M.); cristina.renzi@unimore.it (C.R.)
* Correspondence: massimo.bertolini@unimore.it

Abstract: The concept of sustainability is defined as composed of three pillars: social, environmental, and economic. Social sustainability implies a commitment to equity in terms of several "interrelated and mutually supportive" principles of a "sustainable society"; this concept includes attitude change, the Earth's vitality and diversity conservation, and a global alliance to achieve sustainability. The social and environmental aspects of sustainability are related in the way sustainability indicators are related to "quality of life" and "ecological sustainability". The increasing interest in green and sustainable products and production has influenced research interests regarding sustainable scheduling problems in manufacturing systems. This study is aimed both at reducing pollutant emissions and increasing production efficiency: this topic is known as Green Scheduling. Existing literature research reviews on Green Scheduling Problems have pointed out both theoretical and practical aspects of this topic. The proposed work is a critical review of the scientific literature with a three-pronged approach based on keywords, taxonomy analysis, and research mapping. Specific research questions have been proposed to highlight the benefits and related objectives of this review: to discover the most widely used methodologies for solving SPGs in manufacturing and identify interesting development models, as well as the least studied domains and algorithms. The literature was analysed in order to define a map of the main research fields on SPG, highlight mainstream SPG research, propose an efficient view of emerging research areas, propose a taxonomy of SPG by collecting multiple keywords into semantic clusters, and analyse the literature according to a semantic knowledge approach. At the same time, GSP researchers are provided with an efficient view of emerging research areas, allowing them to avoid missing key research areas and focus on emerging ones.

Keywords: scheduling; sustainable manufacturing; taxonomy; persistence; dominance

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1. Introduction

The aim of the paper is to critically review the literature related to manufacturing scheduling and its applications in manufacturing systems in term of sustainability; this is often approached as Green Scheduling Problems (GSP). Due to the current quest for sustainability in manufacturing systems, this could be considered a poignant topic in the field of green and sustainable production as well as sustainable development.

Sustainable development is one of the pillars of the United Nations' Agenda 2030 [1], in which 17 goals have been defined to improve the social and economic growth of the global community. Goal 7 aims to "Ensure access to affordable, reliable, sustainable, and modern energy for all." The concept of sustainability has been defined as made of three pillars: social, environmental, and economic.

The social pillar of sustainability involves commitment to equity in terms of nine 'interrelated and mutually supporting principles of a sustainable society. This concept includes attitude change, the Earth's vitality and diversity conservation, and a global alliance for attaining sustainability. Social and environmental aspects of sustainability are correlated with indicators for sustainability presented as: quality of life, and ecological sustainability [2].

From the economic viewpoint, sustainability in manufacturing in industrial contexts is aimed at reducing total setup times and energy consumption [3]. This is achieved through efficiently scheduled manufacturing operations, optimal jobs machine allocation, and job sequencing, which ensures optimal product quality. According to this viewpoint, manufacturing industries have become increasingly attracted to green manufacturing due to the recent huge increase in global energy consumption as well as the variations in energy costs [4].

The meaning of sustainable production issues are well reported by Machado et al. [5], who recalled that the high level of digitization that has characterized industrial production systems in recent years has been defined as the fourth industrial revolution, commonly known as Industry 4.0. The sustainability concepts applied to industrial manufacturing have been considered widely in the literature. As a recent example, Danish et al. [6] proposed a relationship between technological, economic, and sustainability measures in the machining of Inconel 718. They considered machining costs and productivity as economical aspects, energy consumption as an environmental aspect, and technological aspects as including cutting forces, surface roughness, and tool wear.

Camarinha-Matos et al. [7] remarked that sustainable manufacturing represents the "integration of processes and systems capable to produce high-quality products and services using less and more sustainable resources (energy and materials), being safer for employees, customers and communities surrounding, and being able to mitigate environmental and social impacts throughout its whole life cycle". Moreover, in OCDE [8] the economical soundness of sustainable manufacturing was highlighted. Nevertheless, Beltrami et al. [9] provided a critical literature review, intending to clearly define the relationship between Industry 4.0 and sustainability; this relationship still seems unclear today.

Hence, the quest for the reduction in the environmental degradation effects becomes as fundamental as the optimization of industrial production efficiency [10,11]. In the context of Industry 4.0, smart manufacturing changes the traditional job shop scheduling problems into smart distributed scheduling problems. This shift provides increased flexibility, higher product quality, reduced lead times, and customized production (Liaqait et al., [12]).

Existing research reviews regarding GSP have been found in the literature; some recent ones have been listed in Table 1. They have been analysed according to their objectives, the time interval covered by the research, and the kind of analysis carried out, namely: keyword-based, taxonomy-based, and research map-based literature reviews.

We defined the keyword-based literature review approach as a review based on the analysis of the literature based on specific indicators of the number of keywords related to a specific topic. A taxonomy-based literature review approach evaluates research works on a specific topic and places them into a sub-topic in which the main problem is subdivided. The research map-based literature review approach investigates the main streams of the research topic and evaluates its evolution over the years; it also forecasts its future development.

Fernandes et al. [13] reviewed GSP-related papers ranging from 2013 and 2022, adopting a keyword-based approach with multiple aims, namely: the analysis of the kind of shop floor, the energy-efficiency strategy, the objective function, and the related specific problem and solution approach. Akbar and Irohara [14] proposed keyword-based review research aimed at defining sustainability indicators. Gahm et al. [15] proposed keyword-based energy-efficient scheduling techniques to be analysed in 3 dimensions: (i) energetic coverage; (ii) energy supply; and (iii) energy demand.

Khaled et al. [16] and Para et al. [17] proposed a taxonomy-based research review to analyse the first ten years of GSP literature, according to the sustainability pillars and relative indicators; the second review was related to the use of metaheuristics for solving GSP.

Li and Wang [18] proposed a research map for the GSP, enlightening related problem mathematical modelling and solving algorithms. Alvarez-Meaza et al. [19] proposed a research mapping review in which the academic sources, as well as GSP main topics, are analysed.

Table 1. Analysed GSP-related reviews.

Reference	Year	Analysed Research Time Interval	Objectives of the Review	Taxonomy Based	Keyword Based	Research Map
Authors'	2022	Before September 2022	Mapping research on GSP; finding research mainstream. Guide the researcher through emerging/trendy topics	✓	✓	✓
[13]	2022	2013–2022	Shop floor type Energy-efficiency strategy Objective function Newly added problem feature Problem-based solution approach	✗	✓	✗
[18]	2022	2000–2022	Steps of the GSP and related problem mathematical modelling and solving algorithms	✗	✗	✓
[16]	2022	2011–2021	Sustainability pillars and relative indicators	✓	✗	✗
[17]	2022	2010–2020	Multi-objective job shop scheduling optimization with metaheuristics	✓	✗	✗
[19]	2021	10 most cited publications	Who is researching/publishing journals/ Main topics	✗	✗	✓
[14]	2018	2008–2018	Map of sustainable manufacturing indicators	✗	✓	✗
[15]	2016	1990–2014	Energy-efficient scheduling techniques are analysed in 3 dimensions: - energetic coverage - energy supply - energy demand	✗	✓	✗

Other review works are related to the techniques applied to increase efficiency in specific environments, such as robotic-based [20] and machinery-based flow shops [21].

Several reviews produced a single-way viewpoint on the use of GSP in manufacturing. Both works are related to the keywords or the research maps without providing a quick and full view of the GSPs in the manufacturing field. Conversely, our research review is a three-objectives-based review (keyword-based, taxonomy-based and, mapping research-based review). Our research proposes a well-defined map of the research main streams of GSP based on two past studies [22,23], providing the researcher with a view of the emerging areas of research, as well as the vanishing ones. Moreover, the proposed review is not time-limited, providing a more comprehensive view of the evolution of the GSP over the years, as well as proposing a forecast of future GSP streams for the researchers. Therefore, this approach also delivers a taxonomy of GSPs main problems and streams. Furthermore, this review guides both industrial and academic research to trendy topics to better assess I4.0 problems related to sustainability.

Research Questions

The following research questions (Rq) have been proposed to highlight the advantages and the related objectives of the present review:

Rq. 1—Which are the most popular methodologies used to solve GSPs in manufacturing?

Rq. 2—Is it possible to identify interesting development patterns?

Rq. 3—Which are the least studied domains and algorithms?

To answer the above-mentioned research questions, the related publications domain was investigated, delivering the following objectives to the research community:

1. Defining a map of the research main fields on GSP, according to both the indexed and the authors' keywords;
2. Enlightening the mainstream of GSP research through an ordered list of keywords defining the "core" research stream;
3. Providing the academics or industry researchers work on GSPs with an efficient view of the emerging areas of research, allowing them to avoid vanishing research areas and focusing on trendy/core ones;
4. Proposing a taxonomy of GSPs by gathering multiple keywords into semantic clusters, hence analysing the literature under a semantic knowledge approach.

To the authors' best knowledge, the proposed review approach is novel in the field of GSP; thus, it proposes to enhance the prediction of further interventions in the GSP research field and cover recent emerging fields of research. Moreover, from an industrial viewpoint, the approach enlightens trendy research fields to be investigated by practitioners. This would provide a further step in applied research concerning existing literature review works.

This manuscript is organized as follows: Section 2 proposes the essential theoretical background on GSPs; Section 3 describes the research methodology in depth; Section 4 presents the review results; and Section 5 is dedicated to discussing the results. A short conclusion section concludes the paper.

2. Green Scheduling Problems in Manufacturing Systems

GSP could be defined as the problem of assigning multiple jobs to a given machine, which are to be processed at specific times, and gaining optimization of a given objective function. The GSP is an extension of the traditional Job Shop Scheduling Problem (JSSP), belonging to the family of NP-hard problems. The main characteristic of a traditional JSSP is an increased makespan, despite a high TEC, as well as the neglection of optimized resource allocation, operation methods, and job sequences.

On the contrary, GSPs are aimed at lowering the cost of operations and reducing energy consumption. Moreover, in this kind of problem, resource allocation and operations sequence optimization are aimed to reduce pollutant emissions. Since they are NP-hard problems, they can rarely be solved by exact algorithms. More generally, metaheuristics and memetic algorithms are used. In particular, several examples cover the use of evolutionary algorithms coupled with local search techniques [24], which is aimed at enhancing efficiency in the calculation [25].

Green Scheduling Problems Application Areas

To answer the first research question (Rq1) regarding the most popular methodologies used to solve GSPs in manufacturing, we identified typical problems related to the GSP. These problems were defined as modifying of the traditional flow shop scheduling problem to achieve opposite objectives, such as economic efficiency and sustainable efficiency. Some typical GSPs existing in the current industrial contexts and retrieved by the literature were derivations of the distributed flow shop GSP, known as the Distributed Permutation Flowshop Scheduling Problem (DPFSP) (e.g., [10,26–56]).

In Li et al. [27], a two-stage knowledge-driven evolutionary algorithm was proposed to solve a multi-objective distributed green flexible job shop scheduling problem. In the first stage, five heuristics were applied to improve the initial population quality. In the second stage, the same number of problem-specific neighbourhood structures were implemented to find out non-dominated solutions.

Lu et al. [30] proposed a Pareto-based multi-objective hybrid iterated greedy algorithm to solve a Distributed Hybrid Flowshop Scheduling Problem (DHFSP) by minimizing makespan and TEC.

The energy-efficient hybrid flow shop scheduling problems were tackled using artificial bee colony algorithms (e.g., [31,34]).

Xin et al. [32] proposed a modified whale swarm optimization algorithm for improving efficiency in a permutation flow shop scheduling problem with variable transportation time. Afsar et al. [35] proposed an enhanced memetic algorithm combining a multi-objective evolutionary algorithm with three procedures exploiting the problem-related available knowledge. They use fuzzy numbers to manage processing time uncertainties. Gong et al. [37] proposed a hybrid evolutionary algorithm to solve an energy-efficient flexible flow shop scheduling with worker flexibility. Cota et al. [38] proposed an extension of the adaptive large neighbourhood search metaheuristic with learning automata to the multi-objective problem to improve the efficiency of the search process and extend to problems related to large-scale instances.

In Han et al. [40], a mathematical model of a distributed blocking flowshop scheduling problem with a balanced energy costs criterion was formulated. Moreover, an efficient heuristic was proposed to generate a high-quality initial solution, followed by two local searches based on the characteristics of the proposed problem.

Zhu et al. [46] proposed a distributed no-wait flow shop scheduling problem with due windows, with an efficient discrete knowledge-guided learning fruit fly optimization algorithm. Similarly, Guo et al. [49] proposed a discrete fruit fly optimization algorithm based on a differential flight strategy to solve a DPFSP. Iterated greedy algorithms are used [50,52,56] to efficiently solve the DPFSP and enhance local search. Publications regarding the application of Non-Dominated Sorting Genetic Algorithms (NSGA) (alone or combined with other algorithms) in green scheduling manufacturing problems range in the years 2013–2022. Most of them were published in the years 2018–2022. Among them, several articles [32,57–73] were dedicated to the application of NSGA and its variations to the DFSP in green scheduling manufacturing. Optimization objectives are the minimization of the makespan and the Total Energy Consumption (TEC) and/or carbon emissions [12]. A recent study [57] uses NSGA-II to solve a Multi-Objective Distributed Permutation Flowshop Scheduling Problem (MO-DFSP) by minimizing the makespan and carbon emissions, considering production and transportation constraints. Dong and Ye [59] propose a combined hybrid salp swarm and NSGA-III algorithm to solve a two-stage re-entrant hybrid flow shop, considering energy resources and energy storage system constraints. In another study [60], an improved NSGA-II with some optimization strategies was proposed to solve a hybrid flow shop scheduling issue under a time-of-use and ladder electricity price system. The aim of that study was to reduce the TEC without compromising maximum completion time. Li et al. [54] used NSGA-II to solve an Energy-Efficient Distributed Permutation Flowshop Scheduling Problem (EEDPFSP) by minimize the total flow time and TEC. In Huo et al. [66], the optimization of a multi-objective energy-saving job-shop scheduling process was proposed to minimize the maximum makespan, total carbon emissions, and total tardiness. An improved NSGA-II was proven to efficiently solve the proposed energy-saving job-shop scheduling manufacturing problem. A combined NSGA-II and Simulated Annealing (SA) were applied in another study [72] to minimize the total carbon emission and maximum completion time in a Permutation Flowshop Scheduling Problem with Constrained Tool (PFS-CT) re-placement activities. Previously, Mi et al. [73] proposed an improved NSGA-II to solve green scheduling of predictive maintenance for complex equipment-related problems. Moreover, in Wen et al. [74] NSGA-II was improved to find the non-dominated scheduling plans and efficiently applied to an industrial context case concerning a battery packaging machinery workshop in China. In another study [75], a green scheduling algorithm was proposed based on an improved NSGA-II, considering makespan and energy consumption simultaneously. In Sang et al. [76], a novel disruption management was proposed that comprehensively measured the deviation of disturbances, including behavioural agents and physical entities in the system. The NSGA-III-based proposed algorithm was efficiently used to optimize the disruption management model. In Zhang et al. [77], a mathematical model for multi-objective optimization to minimize TEC, makespan, and peak power of the job shop was proposed, which used an integrated process planning and scheduling approach. The problem was efficiently solved by employing a hierarchical multi-strategy genetic algorithm based on a non-dominated sorting strategy.

3. Research Methodology

The literature analysis proposed in this work has been carried out, taking two variables into account: persistence and dominance [22,23]. Persistence was defined as the number of years in which a concept has been present in the research field, counting from the first time it appeared. It measures the presence of a given concept over time. Dominance was defined as the measure of the occurrence of the concept in the documents of the specific research field.

If a keyword has a high dominance, it is considered an important concept in a high number of documents. If a keyword has a high persistence, it means that it has been used for a long time in academic work and may either take a long time to disappear or be disappearing currently.

The analysis of the persistence and dominance of keywords is aimed at providing a useful indication for the researcher of which research stream is:

- ✓ consolidated or core (high persistence, high dominance)
- ✓ trendy (low persistence high dominance)
- ✓ intermittent (high persistence, low dominance)
- ✓ emerging (low persistence, low dominance).

Concepts generally start as emerging. Hence, in case the concept is no longer used in the literature, it is defined as the phantom. Otherwise, if a concept overcomes the phantom phase, it shifts to the low persistence and high dominance quadrant. In this case, it becomes trendy. Trendy concepts are an object of several publications; however, these studies cover a limited time interval. Nevertheless, an emergent concept could also enter the high persistence, low dominance quadrant and become an intermittent keyword. Intermittent keywords are concepts which are only discussed at small intervals in an on-off way. More specifically, intermittent concepts have not become established as a consolidated pillar of the research and could become phantoms at a certain moment. Finally, concepts that are discussed in several articles and persist continuously over the years considered represent fundamental or core concepts.

Associating the values of persistence and dominance variables to each keyword allows for the building of a map of research based on the distribution of keywords on a two-dimensional plane, as depicted in Figure 1. The four quadrants have been identified utilizing the Average Dominance Count (ADC) and Average Persistence Count (APC) methods; these methods use the mathematical average values of the dominance and the persistence counts of each keyword.

Once the quadrants have been defined and the concepts are allocated within the specific quadrant, a picture of the actual literature review on GSPs in manufacturing is delivered to the reader. Hence, at the time the picture is taken, the present trend of the research in this research field is easily mapped and shown to the researcher. Moreover, a more general trend of research has been proposed by grouping keywords belonging to the same thematic area into clusters within each quadrant. This method is intended to deliver a visual research map as a quick guide for both academics and practitioners to a more precise selection of trendy research areas. According to the keyword-based review approach, the analysis of the keywords related to the GSPs research could be carried out by considering the covering time and occurrence of GSP-correlated concepts. Hence, the Scopus database has been investigated to retrieve information by application of a specific query.

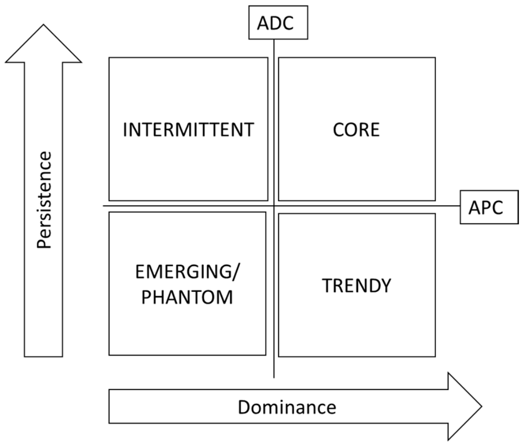

Figure 1. Keywords-based classification methodology according to Fadlalla and Amani [22].

Initial Query-Based Search

The search was limited to journal articles. The search query was intended to include concepts related to energy-efficiency and its control, as well as to include green scheduling concepts. More than 12,000 documents were retrieved after the first research step. Hence, as reported in Figure 2, some limitations have been considered useful to ease up the management of the bibliographic data, while focusing the research on main applications in the engineering-related field.

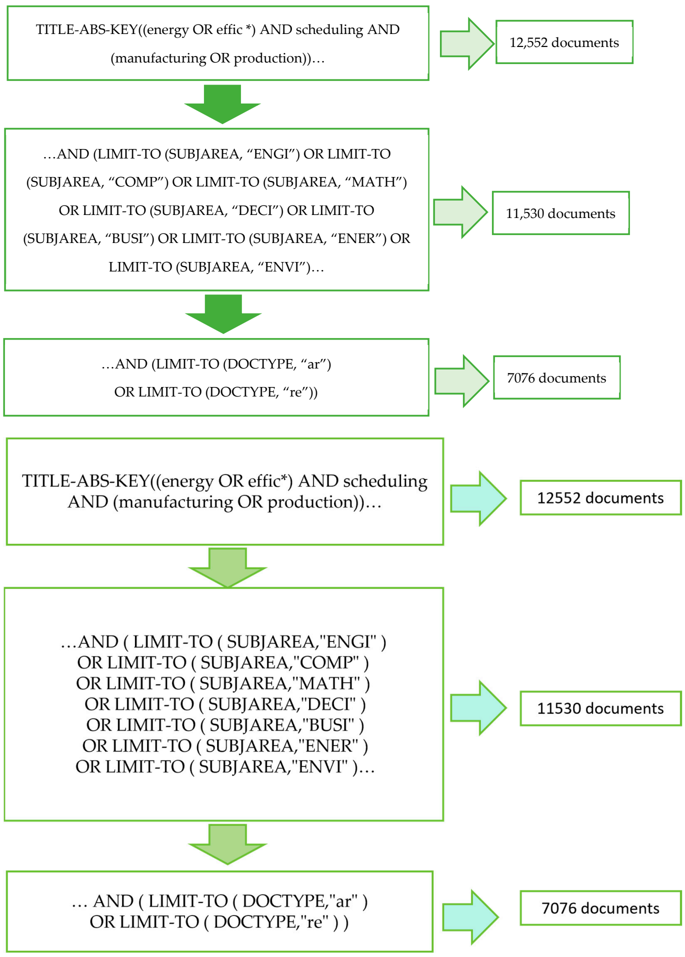

Figure 2. Query carried out on the Scopus advanced search engine and the amount of related retrieved documents.

The first restriction to the search field was related to the subject areas of engineering, computation, mathematics, decision science, business management and accounting, energy, and environmental science.

A second filter was applied that limited the search to academic (scholar) articles only. This research supplied 7076 articles (research was carried out in September 2022). In Figure 2, the asterisk "*" is used in the search query to broaden the search by finding words that start with the same letters.

4. Persistence and Dominance

Dominance and persistence counts have been found for each keyword, as reported by Fadlalla and Amani [22]; they developed a map of keywords in the two-dimensional graph. The highest persistence keyword was Scheduling (persistence count 4731), which was excluded from the graphic representation for the sake of clarity. Core, intermittent, emerging, and trendy keywords have been identified for the GSPs research field using the APC and the ADC indexes.

4.1. GSPs Keyword Terms Positions in the Persistence-Dominance Plane

Reading the persistence–dominance map reported in Figure 3, according to the definition of ADC and APC, four quadrants could be defined. In the first quadrant, the core keywords are grouped; in the second quadrant, the intermittent keywords are mapped; in the third quadrant, the emerging keywords are shown, and in the fourth quadrant, the trendy keywords are depicted.

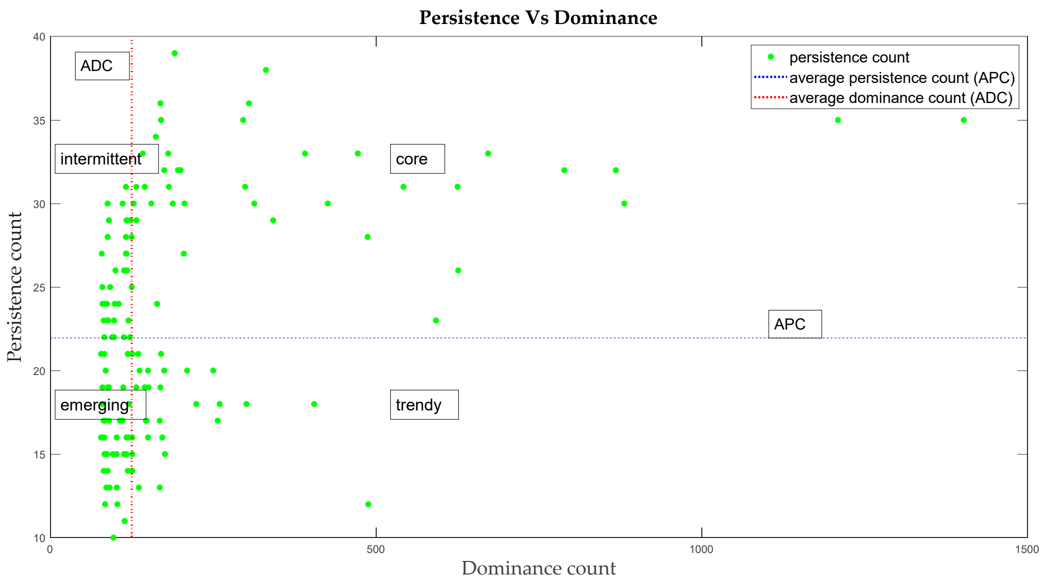

Figure 3. Core–intermittent–emerging–trendy keywords map.

Accordingly, the following "core" keywords were found in the first quadrant. The numbers in parenthesis were referred to keywords' persistence count: scheduling (4371), optimization (1402), production control (1209), manufacture (868), genetic algorithm/s (804), integer programming (789), scheduling algorithm/s (626), job shop scheduling (625), energy utilization (592), algorithm/s (587) heuristic methods (542) problem solving (487), production scheduling (472), decision making (426), mathematical models (391), flexible manufacturing systems (331), heuristic algorithm/s (325), production engineering (313), planning (305), efficiency (299), computer simulation (296), resource allocation (206), makespan (205), production planning (200), machinery (196), operations research (191), computational complexity (188), dynamic programming (182), linear programming (181), maintenance (175), heuristics (170), inventory control (170), production (169), energy conservation (164), simulation (162), constraint theory (155), assembly (145), computer aided manufacturing (142), artificial intelligence (132), decision support systems (132), and just in time production (128).

Likewise, "intermittent" keywords were listed as follows: combinatorial optimization (125), electric power generation (125), production system (123), cost effectiveness (120), tabu search (118), petri nets (117), real-time systems (117), materials handling (116), non-linear programming (116), semiconductor device manufacture (116), manufacturing (113), industrial management (111), dynamic scheduling (105), automation (100), supply chain management (99), preventive maintenance (98), multi-agent systems (92), process planning (90), competition (89), cellular manufacturing (88), job analysis (88), neural networks (88), computer programming (87), job shop (83), information management (82), customer satisfaction (80), machine tools (80), and computer software (79).

"Emerging/phantom" keywords were listed as follows: computational methods (122), optimal scheduling (121), computational results (120), electric utilities (119), energy storage (119), learning algorithm/s (117), optimisations (117), mixed integer linear programming model (114), flexible job-shop scheduling problem (113), mathematical programming (113), uncertainty (112), manufacturing industries (111), stochastic models (110), mixed integer (or (mixed-integer)), linear programming (107), renewable energies (103), cost reduction (102), multi objective (102), power markets (102), economics (98), demand response (97), job shop scheduling problems (96), optimal systems (95), electric energy storage (91), profitability (90), stochastic programming (90), np-hard (88), sensitivity analysis (88), manufacturing process (87), optimization problems (86), process engineering (85), energy (84), optimization algorithms (84), total energy consumption (84), computer integrated manufacturing (83), flexible job-shop scheduling (83), objective functions (83), semiconductor manufacturing (83), optimal solutions (82), production process (82), flow-shop scheduling (80), performance (80), sequence-dependent setup time (79), ant colony optimization (78), and batch data processing (78).

Finally, a list of "trendy" keywords were reported as follows: costs (488), energy-efficiency (405), multi-objective optimization (301), machine shop practice (260), stochastic systems (257), scheduling problem (250), process control (247), computational efficiency (224), simulated annealing (209), electric load dispatching (176), evolutionary algorithm/s (175), productivity (173), particle swarm optimization (pso) (172), benchmarking (170), industrial research (169), electric power transmission networks (168), renewable energy resources (168), multi-objective optimization (151), computational experiment (150), production efficiency (150), uncertainty analysis (148), strategic planning (147), supply chains (145), steelmaking (137), sustainable development (136), iterative methods (135), energy management (132), commerce (126), economic and social effects (126), energy consumption (126), and forecasting (126).

4.2. Semantic Clusters: A Map-Based Review Approach

In the proposed keyword classification, each keyword was mapped into the persistence and dominance planes. Nevertheless, further classification could be carried out to gather keywords belonging to the same thematic area in clusters. This further map-based classification was intended to provide the reader with a quick look at the ongoing research on GSPs, as well as the evolution of the GSPs' thematic areas in the research environment.

To this end, authors have gathered keywords belonging to the same thematic and semantic areas. As a result, the following clusters have been reported:

(A). Algorithms
(B). Computer simulation and optimization
(C). Economics
(D). Energy
(E). Manufacturing
(F). Problem modelling
(G). Problems
(H). Production

(I). Resources allocation
(J). Scheduling

A short description of the clusters could be made hereafter:

(A). The algorithm cluster includes keywords related to the algorithms used in the solution of GSPs problems, namely: genetic algorithm/s, algorithm/s, heuristic algorithm/, heuristic methods, heuristics, constraint theory, tabu search, petri nets, neural networks, learning algorithm/s, np-hard, sensitivity analysis, ant colony optimization, simulated annealing, evolutionary algorithm/s, particle swarm optimization (PSO). The computer simulation and optimization cluster includes the following keywords, which are related to the applications of optimization techniques and computer simulations to solve GSPs in manufacturing:: optimization, computer simulation, operations research, computational complexity, combinatorial optimization, computer software, multi-objective optimization, stochastic systems, and computational efficiency.
(B). The economics cluster includes keywords related to cost and customers' needs have been gathered, namely: cost effectiveness, customer satisfaction, costs, benchmarking, industrial research, sustainable development, commerce, economic and social effects, and forecasting.
(C). The energy cluster includes keywords related to the use/transformation of energy, such as: energy utilization, energy conservation, efficiency, electric power generation, energy-efficiency, electric load dispatching, electric power transmission networks, renewable energy resources, energy management, energy consumption, energy storage, electric utilities, renewable energies, electric energy storage, energy utilization, energy conservation, and efficiency.
(D). The manufacturing cluster includes keyword terms related to the manufacturing operations, as well as systems used in manufacturing, such as: manufacture, flexible manufacturing systems, machinery, computer aided manufacturing, materials handling, semiconductor device manufacture, manufacturing, cellular manufacturing, machine tools, manufacturing, machine shop practice, and steelmaking.
(E). The problem modelling cluster includes grouped terms describing mathematical problem modelling and programming techniques, such as: integer programming, dynamic programming, linear programming, mathematical models, nonlinear programming, computer programming, mixed integer linear programming model, and mathematical programming.
(F). The problems cluster includes terms related to the decision support area, namely: problem-solving, decision making, decision support systems, uncertainty, uncertainty analysis, and iterative methods.
(G). The production cluster includes key terms related to the production systems, namely: production control, production engineering, planning, production planning, production, production system, preventive maintenance, process planning, process control, productivity, sustainable development, and supply chains.
(H). The resources allocation cluster includes terms related to the management of resources during production operations, such as: makespan, maintenance, efficiency, resource allocation, makespan, inventory control, assembly, industrial management, automation, supply chain management, multi-agent systems, competition, information management, performance, sequence-dependent setup time, and supply chains.
(I). The scheduling cluster includes terms related to the scheduling of production operations are gathered, such as: scheduling, scheduling algorithm/s, job shop scheduling, optimal scheduling, flexible job-shop scheduling problem, job shop scheduling problems, flow-shop scheduling, and scheduling problem.

This map-based approach, with the use of clusters, provides interesting information on the main research stream of GSPs. Persistence counts relative to clustered keywords are reported in Tables 2–5. In Table 2, representations of the clusters relative to the core keywords are reported. For clarity, the prefix "C-" has been added to each term in the set. In order of decrescent persistence, core clusters are "C-Scheduling", "C-Algorithms", "C-Production", "C-Computer simulation/optimization", "C-Problem modelling", "C-Manufacturing", and "C-Resources allocation".

Table 2. Distribution of core keywords into clusters according to their persistence count.

Core Keywords	Persistence Count		% Persistence Count
C-Scheduling	5622		29%
Scheduling		4371	
Scheduling algorithm(s)		626	
Job shop scheduling		625	
C-Algorithms	2583		13%
Genetic algorithm(s)		804	
Algorithm(s)		587	
Heuristic algorithm(s)		325	
Heuristic methods		542	
Heuristics		170	
Constraint theory		155	
C-Production	2196		11%
Production control		1209	
Production engineering		313	
Planning		305	
Production planning		200	
Production		169	
C-Computer simulation and optimization	2077		11%
Optimization		1402	
Computer simulation		296	
Operations research		191	
Computational complexity		188	
C-Problem modelling	1543		8%
Integer programming		789	
Dynamic programming		182	
Linear programming		181	
Mathematical models		391	
C-Manufacturing	1537		8%
Manufacture		868	
Flexible manufacturing systems		331	
Machinery		196	
Computer aided manufacturing		142	
C-Resources allocation	1405		7%
Makespan		205	
Maintenance		175	
Efficiency		299	
Resource allocation		206	
Makespan		205	
Inventory control		170	
Assembly		145	
C-Energy	1055		6%
Energy utilization		592	
Energy conservation		164	
Efficiency		299	
C-Problems	1045		5%
Problem-solving		487	
Decision making		426	
Decision support systems		132	

Table 3. Persistence count of intermittent keywords.

Intermittent Keywords	Persistence Count		% Persistence Count
I-Resources allocation	806		46%
Real-time systems		117	
Materials handling		116	
Industrial management		111	
Automation		100	
Supply chain management		99	
Multi-agent systems		92	
Competition		89	
Information management		82	
I-Manufacturing	397		22%
Semiconductor device manufacture		116	
Manufacturing		113	
Cellular manufacturing		88	
Machine tools		80	
I-Algorithms	323		18%
Tabu search		118	
Petri nets		117	
Neural networks		88	
I-Production	311		18%
Production system		123	
Preventive maintenance		98	
Process planning		90	
I-Economics	205		12%
Cost effectiveness		125	
Customer satisfaction		80	
I-Computer simulation and optimization	204		12%
Combinatorial optimization		125	
Computer software		79	
I-Problem modelling	203		11%
Nonlinear programming		116	
Computer programming		87	
I-Energy	125		7%
Electric power generation		125	

Table 4. Distribution of trendy keywords into clusters according to their persistence count.

Trendy Keywords	Persistence Count		% Persistence Count
T-Economics	1341		24%
Costs		488	
Benchmarking		170	
Industrial research		169	
Sustainable development		136	
Commerce		126	
Economic and social effects		126	
Forecasting		126	
T-Energy	1175		21%
Energy-Efficiency		405	
Electric load dispatching		176	
Electric power transmission Networks		168	
Renewable energy resources		168	

Table 4. *Cont.*

Trendy Keywords	Persistence Count		% Persistence Count
Energy management		132	
Energy consumption		126	
T-Computer simulation and optimization	782		14%
Multi-objective optimization		301	
Stochastic systems		257	
Computational efficiency		224	
T-Production	701		12%
Process control		247	
Productivity		173	
Sustainable development		136	
Supply chains		145	
T-Algorithms	556		10%
Simulated annealing		209	
Evolutionary algorithm(s)		175	
Particle swarm optimization (PSO)		172	
T-Manufacturing	397		7%
Machine shop practice		260	
Steelmaking		137	
T-Problems	283		5%
Uncertainty analysis		148	
Iterative methods		135	
T-Scheduling	250		4%
Scheduling problem		250	
T-Resources allocation	145		3%
Supply chains		145	

Table 5. Distribution of emerging keywords into clusters according to their persistence count.

Emerging Keywords	Persistence Count		% Persistence Count
E-Computer simulation and optimization	1079		32%
Computational methods		122	
Computational results		120	
Optimizations		117	
Stochastic models		110	
Multi-objective		102	
Optimal systems		95	
Optimization problems		86	
Optimization algorithms		84	
Objective functions		83	
Optimal solutions		82	
Batch Data processing		78	
E-Economics	489		14%
Cost reduction		102	
Power markets		102	
Economics		98	
Demand response		97	
Profitability		90	

Table 5. *Cont.*

Emerging Keywords	Persistence Count		% Persistence Count
E-Energy	432		13%
Energy storage		119	
Electric utilities		119	
Renewable energies		103	
Electric energy storage		91	
E-Scheduling	410		12%
Optimal scheduling		121	
Flexible job-shop scheduling Problem		113	
Job shop scheduling problems		96	
Flow-shop scheduling		80	
E-Algorithms	371		11%
Learning algorithm(s)		117	
NP-hard		88	
Sensitivity analysis		88	
Ant colony optimization		78	
E-Problem modelling	227		7%
Mixed integer linear programming model		114	
Mathematical programming		113	
E-Resources allocation	159		5%
Performance		80	
sequence-dependent setup time		79	
E-Problems	112		3%
Uncertainty		112	
E-Manufacturing	111		3%
Manufacturing industries		111	

Limiting the description to the core cluster, a brief explanation of the core keywords was provided as follows:

- ✓ The C-Scheduling cluster included the keywords “scheduling algorithms” and “job shop scheduling”. Related problems represent the principal core of the GSPs;
- ✓ The C-Algorithms cluster included keywords such as “genetic algorithms”, “heuristics”, and “constraint theory”;
- ✓ The C-Production cluster included information on the strategic planning and control of production in GSPs.
- ✓ The C-Computer Simulation and Optimization keyword cluster included “optimization”, “computer simulation”, “operations research”, and “computational complexity”.

Clusters such as C-Problem modelling, C-Manufacturing, C-Resources allocation, C-Energy, and C-Problems gained less than 8% persistence count on the total core cluster.

In Table 3, intermittent keywords were clustered in a specific set. For intermittent keywords, a prefix “I-” was added at each term of the set. In the case of intermittent keywords, the most persistent cluster was “I-Resources allocation”. This cluster was followed by “I-Manufacturing”, “I-Algorithms”, “I-Production”, “I-Economics”, “I-Computer Simulation and Optimization”, “I-Problem modelling”, and “I-Energy”. It is also noticeable that the “Economics” cluster appeared here for the first time.

Trendy keywords were clustered as reported in Table 4. In the case of trendy keywords, a prefix “T-” was added at each term of the set. In this set, the most persistent cluster was “T-Economics”. This cluster was followed by “T-Energy”, “T-Computer Simulation and Optimization”, “T-Production”, “T-Algorithms”, “T-Manufacturing”, “T-Problems”, “T-Scheduling”, and “T-Resources Allocation”. In the trendy group of keywords, the "T-Economics" cluster significantly increased its persistence count relative to the intermittent group.

In Table 5, emerging keywords were clustered. In this case, the prefix "E-" was added at each term of the set. Hence, the most persistent cluster was "E-Computer Simulation and Optimization". This emerging (or phantom) cluster was followed by "E-Economics", "E-Energy", "E-Scheduling", "E-Algorithms", "E-Problem modelling", "E-Resources Allocation", "E-Problems", and "E-Manufacturing".

5. Discussion

All keywords were classified according to the persistence continuity. As described in a prior study [22], persistence is defined as continuous when it is present for some contiguous years greater than the average of the total years of its presence in the literature; otherwise, it is defined as intermittent persistence.

Intermittent persistence keywords were found in this study (see Table 6). As an example, the "NP-hard" keyword had a persistence count of 88; it appeared in the literature in 2003 before being intermittently present, with negligible contribution until 2020 when it started to be widely used.

Table 6. Phantom, intermittent persistence keyword classification.

Intermittent Persistence Keywords	Keyword Classification
Computational methods, process engineering, and computer integrated manufacturing	Phantom
Decision making, machinery, operations research, benchmarking, computer aided manufacturing, cost effectiveness, semiconductor device, manufacture, process planning, sensitivity analysis, NP-hard, energy, customer satisfaction, machine tools; computer software, cost, and decision support	Intermittent persistence

In the third graph quadrant, which was related to low persistence and low dominance keywords, both emerging and phantom keywords were included. A keyword considered emerging could become a phantom or core keyword in the future. Hence, further specific analysis of the continuous or intermittent persistence must be provided in future research reviews. Regarding phantom keywords, the "computational methods" keyword first appeared in 1993 and was almost continuous until 2010. It then appeared discontinuously until 2019, after which point it was no present longer and was considered a phantom. Another example of a phantom keyword is "process engineering". It first appeared in 1992 and was almost continuously present until 2009. It then re-emerged in 2019 and 2020 before disappearing again. "Computer integrated manufacturing" appeared in 1984 and was continuous until 2006. It appeared again in 2010 and 2011 before disappearing until 2020 and 2021, with only one contribution per year. It could now be considered a phantom.

At this point, the authors propose an answer to the research questions (Rq2 and Rq3) included in the introduction section. To identify interesting development patterns (Rq2), as well as the least studied research topics in GSPs (Rq3), a further taxonomy representation and classification of the GSP research space is proposed hereafter. To this end, the persistence count of each cluster is depicted in pie charts shown in Figure 4. In particular, clusters of keywords are ordered according to descendant persistence count for each quadrant (core–intermittent–emerging–trendy).

In the "core" quadrant, clusters with the highest persistence count are: C-Scheduling; C-Algorithm; and C-Production. Hence, according to the previous considerations and considering the clusters definitions, consolidated and core research arguments in GSPs seem to follow the topics of scheduling, the use of mathematical algorithms, (in terms of Genetic Algorithm/s, heuristics and constraint theory), and the production research topics, as production planning, control, and engineering.

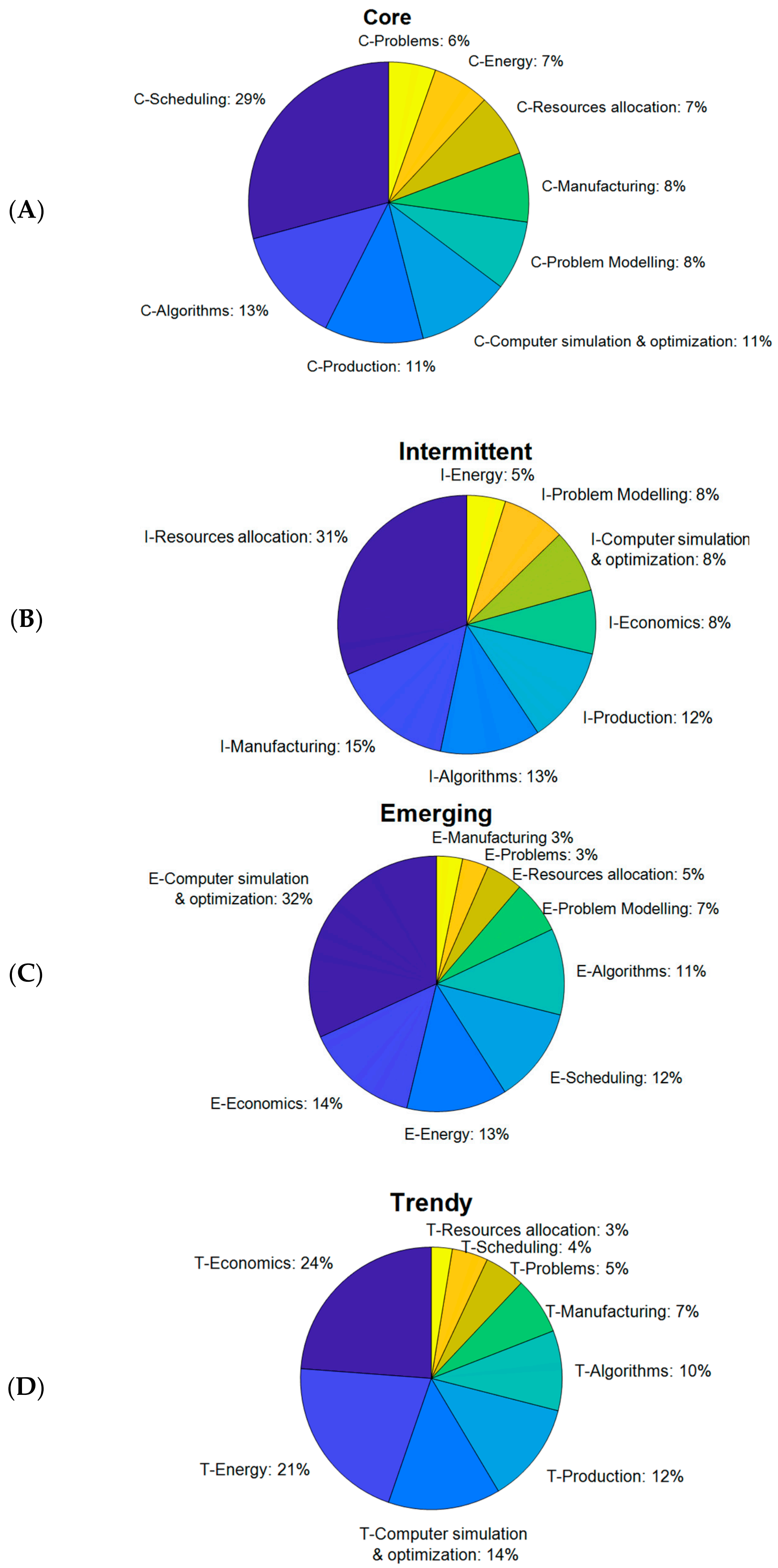

Figure 4. Taxonomy distribution of core (**A**), intermittent (**B**), emerging (**C**), and trendy (**D**) keywords into clusters according to their persistence count.

Concerning the "intermittent" persistence quadrant, clusters characterised by the highest persistence count are: I-Resources Allocation (real-time systems, materials handling, industrial management, automation, supply chain management, multi-agent systems, competition, information management); I-Manufacturing, (semiconductor device manufacture, cellular manufacturing, machine tools); and I-Algorithm (tabu search, petri nets, neural networks). Since these keywords are present in the research topics in a non-continuous way, they could disappear or emerge in the next few years.

Regarding the "emerging" keywords, clusters with the highest persistence counts are: E-Computer simulation and optimization; (computational methods, computational results, optimisations, stochastic models, multi-objective, optimal systems, optimization problems, optimization algorithms, objective functions, optimal solutions, batch data processing); E-Economics (cost reduction, power markets, economics, demand response, profitability); and E-Energy (energy storage, electric utilities, renewable energies, electric energy storage). These keywords may emerge and become core or trendy in GSPs in the next few years' research.

Finally, for "trendy" keywords clusters showing the highest persistence count are T-Economics (costs, benchmarking, industrial research, sustainable development, commerce, economic and social effects, forecasting); T-Energy (energy-efficiency, electric load dispatching, electric power transmission networks, renewable energy resources, energy management, energy consumption); and T-Computer simulation and optimization (multi-objective optimization, stochastic systems, computational efficiency).

6. Conclusions

The recent need for a compromise between production and energy-efficiency has led ever- more manufacturing industries to tackle the issues of sustainability linked to green manufacturing. The proposed review approach has advantages and limitations that should be clarified. One benefit is that it provides a well-defined map for GSP research, using the data available in the Scopus database. One limitation is that only scholarly publications were analysed, while conference works were not included. The use of a taxonomy of GS problems by collecting keywords in semantic clusters allows analysis of the literature with a semantic knowledge approach, providing a quick evaluation of the ongoing research on GSP. At the same time, phantom or emerging research areas are also shown, allowing researchers in GSPs to avoid focusing efforts on endangered research areas. Another advantage is that the mainstream of GSP research is clearly defined by core clusters of keywords. Hence, according to the definition of clusters, the following conclusions could be reported.

- ✓ Keywords grouped in the Algorithm cluster were present in all quadrants, with different meanings. Core concepts related to Algorithm clusters were mostly correlated to genetic algorithms, heuristics, and constraint theory;
- ✓ Computer simulation and optimization had a main percentage of persistence count in the emerging declination of keywords (32%). This is reasonable because it is strictly correlated to the scheduling problem solution concepts;
- ✓ Production was present in the core declination keywords and in the intermittent declination keywords for 12%. It was also present as a trendy concept for 11%. It was not present in the emerging or phantom quadrant as it had already been consolidated;
- ✓ Problem modelling, including mathematical models related to keywords for modelling the GSP problems, was not considered a trendy concept as it mainly belonged to the core concepts and was present in intermittent and emerging ones;
- ✓ Problems cluster gathered concepts related to decision making and supported problems. It was considered a core, trendy, and emerging concept.
- ✓ Resources allocations were positioned in the core quadrant and with the least persistence count. This was likely because some concepts were born late and were still trendy or emerging.
- ✓ Economics was not considered a core concept in GSP. It was, nonetheless, a trendy concept with the highest persistence. It was also present in the emerging and intermittent quadrants according to specific related keywords.

In the proposed literature review approach in the field of GSP, the authors aimed to share the main themes of the GSP with emerging fields, as well as themes on the verge of extinction. Themes of costs, energy-efficiency, multi-objective optimization, and process control were trendy topics in GSP in manufacturing. Themes related to computational methods, cost reduction, energy storage, and optimal scheduling were emerging topics in the same field. Other topics such as computational methods, process engineering, and computer integrated manufacturing were phantom topics in the field and have not been followed by recent researchers.

This finding allows the development of further interventions in the field of GSP research. It also covers and develops recent emerging research fields with a view to sustainable development and profit.

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Abbreviations

Acronym	Definition
ADC	Average Dominance Count
APC	Average Persistence Count
DFSP	Distributed Permutation Flowshop Scheduling Problem
DHFSP	Distributed Hybrid Flowshop Scheduling Problem
EEDPFSP	Energy-Efficient Distributed Permutation Flowshop Scheduling Problem
GSP	Green Scheduling Problem
JSSP	Job Shop Scheduling Problem
MO-DFSP	Multi-Objective Distributed Permutation Flowshop Scheduling Problem
NSGA	Non-Dominated Sorting Genetic Algorithms
PFS-CT	Permutation Flowshop Scheduling Problem with Constrained Tool
SA	Simulated Annealing
TEC	Total Energy Consumption

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