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Energy-Efficient Permutation Flow Shop Scheduling Problem: A Systematic Literature Review

Dana Marsetiya Utama, Meri Dines Primayesti, Sabila Zahra Umamy, Bunga Milenia Nur Kholifa

Department of Industrial Engineering, Universitas Muhammadiyah Malang, Indonesia
* Corresponding author: dana@umm.ac.id

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ABSTRACT

Energy-efficient scheduling is an important problem in the industrial world because improper scheduling can increase energy consumption. One of the production scheduling problems is the Permutation Flow Shop Scheduling Problem (PFSP). This article tries to review research on energy-efficient PFSP to provide a comprehensive review of trends and research gaps in energy-efficient PFSP. A systematic literature review (SLR) was used to conduct this research survey, and 123 articles were collected from 2011-2023. This SLR classifies articles based on publication year, type, objective function, and optimization method used. The results of the literature review analysis show a significant increase every year for energy-efficient PFSP, and multi-objective problems are the dominant problems studied. Based on the analysis of solutions to solve energy efficient PFSP, metaheuristic procedures are the procedures that contribute the largest to solving energy efficient PFSP, and the objective function that is popularly used is to minimize total energy consumption. In addition to this, this study presents a gap research analysis and future research directions for energy-efficient PFSP.

1. Introduction

Flow shop scheduling has gained significant attention from researchers in recent decades, particularly the Permutation Flow Shop Scheduling Problem (PFSP) [1] [2]. PFSP refers to a scheduling problem where a set of jobs with the same process sequence is processed on multiple machines in a specific permutation [3-5]. In the PFSP, the order of job execution on each machine has been determined based on the permutation sequence. PFSP goes beyond resource allocation and can also be a company performance evaluation [6, 7]. Due to its complexity, PFSP is categorized as a non-polynomial hard problem (NP-hard) [8] [8, 9]. Various forms of PFSP exist, such as the classical PFSP, no-idle flow shop scheduling, and no-wait flow shop scheduling [10]. When discussing PFSP, minimization turnaround time (makespan) [11] and tardiness [12] are commonly considered objective functions. The increasing concern over emissions and the depletion of fuel reserves has led industries to prioritize energy efficiency [13, 14]. Manufacturing contributes to high fuel and energy consumption, which has resulted in several attempts by researchers to solve this problem [15-18]. Implementing energy-efficient scheduling is one of the most effective approaches to reducing energy consumption [19, 20]. Therefore, there has been a growing

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interest among researchers in energy-efficient PFSP, leading to the development of various methods.

Several literature reviews on energy-efficient scheduling have been published, including one by Gahm, et al. [21] that discussed the three dimensions of energetic coverage, energy supply, and energy demand in manufacturing companies. Gao, et al. [22] reviewed energy-efficient production scheduling for intelligent manufacturing systems. They analyzed five indicators, including shop floor, models, approaches and algorithms, objectives, and aspects of energy consumption. Fernandes, et al. [23] recently examined a review of energy-efficient scheduling in job shop manufacturing systems. Furthermore, Biel and Glock [24] reviewed decision support models for energy-efficient production planning. The scope of this review is limited to the mid-term, including master production scheduling and capacity planning, and short-term planning, including lot-sizing and machine scheduling. Bänsch, et al. [25] conducted a systematic literature review to investigate recent literature focusing on integrating these options into industrial decision support models. They specifically identify relevant papers from machine scheduling, lot sizing, and other energy-intensive processes. Meanwhile, Li and Wang [26] reviewed green shop scheduling problems based on four aspects: shop scheduling environment, optimization objective, mathematical model, and solution method. Their study analyzed several variants of shop environment, including single machine, parallel machine, open shop, job shop, and flow shop. Most recently, Neufeld, et al. [27] provided reviews on hybrid multi-objective flow shop scheduling and distributed permutation flowshop scheduling problems, respectively. Unfortunately, based on previous literature reviews on energy-efficient scheduling, no review article focuses on the energy-efficient PFSP.

PFSP are widely applied in real-world production systems and service industries. Some applications of PFSP are in production systems [28], quality control processes [29], and human resource scheduling in manufacturing and service industries [30]. Even in recent years, the problem of PFSP has become the focus of research literature [31]. Researchers have published several comprehensive literature reviews on PFSP. Yenisey and Yagmahan [1] examined 86 articles on the multi-objective flow shop scheduling problem in 2014 and identified trends in the multi-objective flow shop scheduling problem as well as research gaps. In addition, Rossit, et al. [32] reviewed 72 articles on non-permutation flow-shop scheduling problems in 2018. According to the study, makespan is the most frequently studied objective function. Zaied, et al. [2] reviewed 102 papers on PFSP with the makespan criterion. According to their research findings, 81% of the methods used to minimization makespan are metaheuristics. Several published PFSP review articles described earlier show that PFSP issues have received attention from researchers. However, even though research in this field is increasing, we have yet to find a literature review that discusses the problem of energy-efficient PFSP.

The increasing research on energy-efficient PFSPs encourages us to thoroughly review published articles to identify trends and directions for future research. As stated in the preceding paragraph, no comprehensive study has discussed the energy-efficient PFSP. As a result, this article reviews energy-efficient FPSP research, with the method used in this study being a systematic literature review. This study examines several sections, including the type of problem, the objective function, the optimization method used, and the energy-efficient PFSP variant. The following research questions (RQ) are addressed in this study: (RQ1) What types of problems dominate energy-efficient PFSP research? (RQ2) What variant dominates the energy-efficient PFSP? (RQ3) What procedures dominate research on energy-efficient PFSP? (RQ4) What objective function is frequently used by researchers for research on energy-efficient PFSP? This article also discusses trends, gaps, and future research directions for energy-efficient PFSP. To make

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it easier for readers to understand the terms that often appear in this article, a list of abbreviations is presented in the Appendix.

To address these four research questions, this paper is organized as follows. Section 2 describes the methodology used to conduct a systematic literature review (SLR) and the proposed classification scheme for examining the energy-efficient PFSP. Section 3 examines the problem types, variants, optimization tools, and objective functions for energy-efficient PFSP. This section also summarizes and discusses the most important findings, as well as the identification of gaps and opportunities for future research. Finally, Section 4 concludes the literature review.

2. Methods

This literature review focuses on articles that discuss energy-efficient PFSP, hoping that the results can describe the map of energy-efficient PFSP research in the past. In addition, the findings of this literature review provide an analysis of trends, opportunities, and research gaps to provide further research guidelines for energy-efficient PFSP. A thorough literature review methodology is required to present a comprehensive literature review. Figure 1 depicts the stages of the literature review process for energy-efficient PFSP. This stage is based on the systematic review stage of Utama, et al. [33].

The first step in conducting a literature review is identifying relevant keywords for the energy-efficient PFSP. The next step is to collect articles from the chosen database, which are then filtered based on the inclusion criteria used in the energy-efficient PFSP. Stage 3 is to separate and tabulate the articles that have been filtered based on the classification scheme defined in the literature review. Finally, stage 4 presents the analysis of the article by presenting a literature review based on the classification and variants of the energy-efficient PFSP. This literature review article concludes with an analysis of trends, gaps, and recommendations for the following research guide on energy-efficient PFSP. In sections 2.1 and 2.2, the classification scheme and data collection methodology utilized for this article are described in depth.

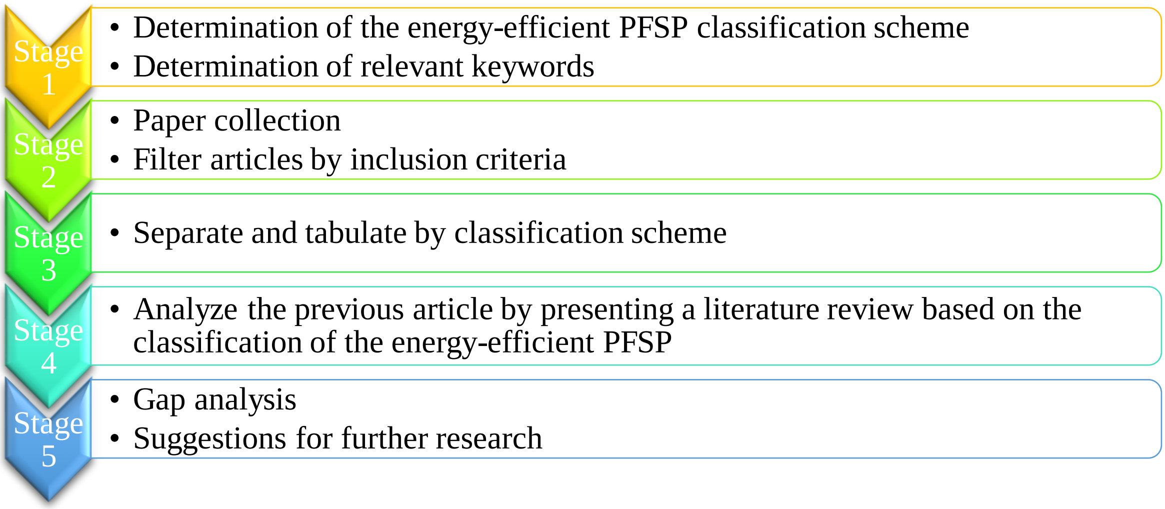

Figure 1. Stages of systematic literature review energy-efficient PFSP

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2.1 Classification Scheme

The literature review presented in this paper provides a comprehensive review of energy-efficient PFSP. The reviews are organized by country, year, publisher, journal or conference, type of optimization, objective function problems, variants, and optimization tools. Figure 2 depicts the classification scheme of the literature review of energy-efficient PFSP. This classification provides a comprehensive review of energy-efficient PFSP. In the type of optimization, energy-efficient PFSP are classified into single-objective and multi-objective. Single-objective optimization refers to the energy-efficient PFSP that optimizes a single objective. In contrast, in multi-objective problems, this optimization focuses on optimizing multiple objectives simultaneously. This optimization can provide a set of solutions that represent trade-offs between different objectives.

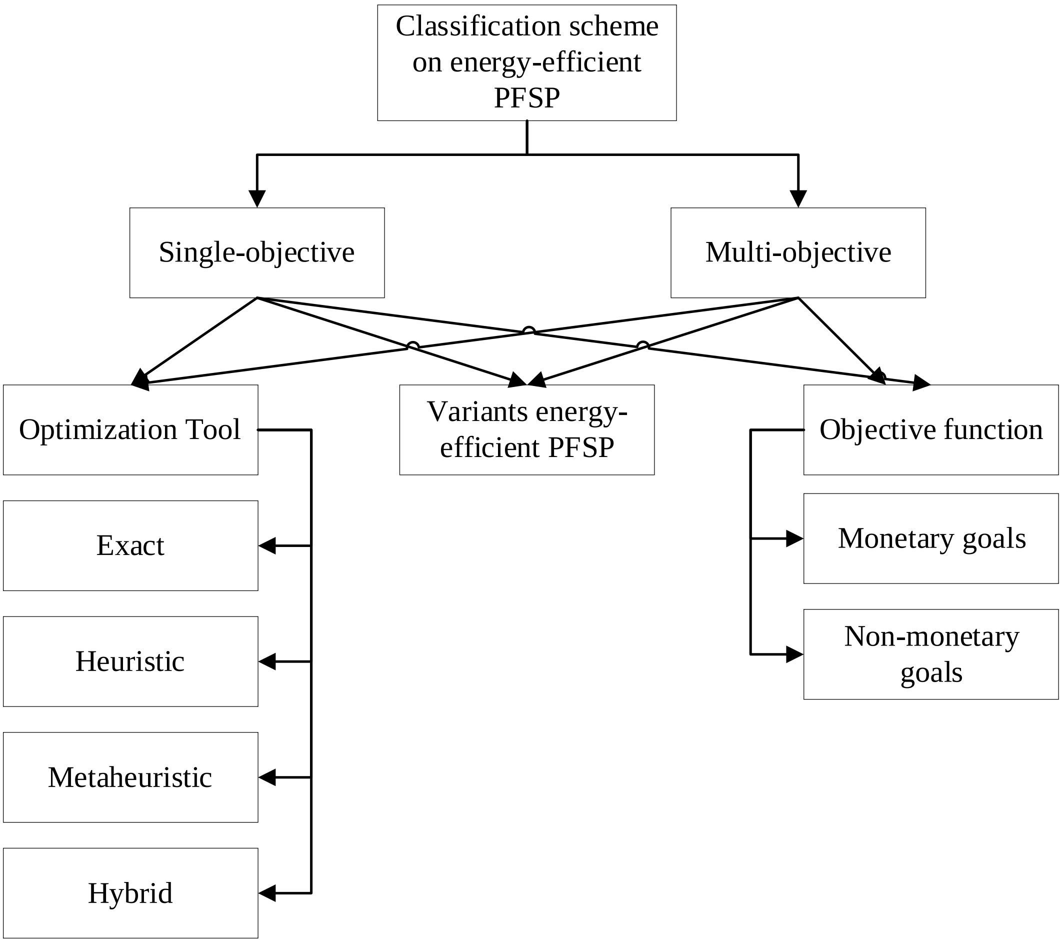

Figure 2. Classification scheme literature review energy-efficient PFSP.

In classifying objective function problems, these problems are categorized into two groups: monetary objective and non-monetary objective. Monetary objective functions focus on performance assessment from a financial point of view. This objective function has the main goal of optimizing factors that have a direct impact on financial gains or costs in scheduling. On the one hand, non-monetary objective functions are not directly related to financial aspects. This objective function focuses more on non-economic factors important in scheduling, such as time efficiency, energy, customer satisfaction, and improved product quality. Furthermore, the energy-efficient PFSP review is also analyzed based on variants. Variants of the energy-efficient PFSP refer to variations of the basic problem that involve changes in problem constraints, rule preferences, or other special conditions. In variant classification, each problem variant has different characteristics and can affect problem-solving complexity.

In the classification of optimization tools, energy-efficient PFSP are grouped into exact, heuristic, metaheuristic, and hybrid. The exact algorithm tries to find the optimal solution from all alternative solutions but requires high computation time. The heuristic algorithm uses rules of thumb to find a good solution quickly, but it does not guarantee optimality. Metaheuristic is a sophisticated solution-finding method to explore the solution space efficiently. It utilizes concepts such as exploration and exploitation mechanisms to explore different solution regions and achieve good solutions globally or locally. In contrast, hybrid approaches combine two or more optimization techniques, utilizing the advantages of each method to achieve better solutions efficiently.

2.2 Data Collection

This section discusses the data collection for articles on energy-efficient PFSP. In collecting papers for review, this literature search utilizes the procedure defined by Webster and Watson [34]. The search was based on backward and forward search procedures. The backward procedure is performed by querying academic databases with keywords based on relevant articles. Unlike the backward search, where the collection of articles is based on a keyword search, the forward search involves searching through other sources that have cited the articles found in the backward search procedure. Figure 3 depicts the process of searching for and evaluating articles for inclusion. The articles were screened using inclusion criteria, which included studies published in conference proceedings and journals (peer-reviewed articles) as well as full-text in English.

In the backward procedure, determining keywords is crucial in collecting articles in the database. The article search method employs the Boolean method. The keyword syntax used to search for articles in the Scopus database and the Google Scholar search engine is "Energy" AND "Efficient" OR "Aware" OR "Consumption" AND "Permutation" AND "Flow" AND "Shop" AND "Scheduling." The Scopus database was chosen because it has a good reputation for article indexing. Google Scholar was chosen because it searches for open-access articles. After removing duplicate articles, 336 articles were collected using the Scopus database and the Google Scholar search engine.

Publications that did not focus on energy-efficient PFSP were excluded from consideration. Sorting was done based on the title, abstract, and full text, as well as defined inclusion criteria. Based on these criteria, 95 articles were selected as relevant. After that, we performed a forward search based on the 95 selected articles by checking the citations of each selected article. The forward search was conducted manually by checking the Scopus database and Google Scholar citations. This search resulted in 28 new relevant articles. In total, 123 articles were found for review in this literature review.

Figure 4 depicts the classification of energy-efficient PFSP papers derived from collecting energy-efficient PFSP articles. It shows that number of journal papers; 96 (78%), and number of conference papers; 27 (22 %).

Table 1. Distribution of papers by journal. shows the distribution of papers based on the journal. The International Journal of Production Research and the Journal of Cleaner Production contributed the most articles with 8 and 7 papers, respectively. In addition, 4 papers were contributed by Swarm and Evolutionary Computation, and the Academic Journal of Manufacturing Engineering as well as IEEE transactions on cybernetics contributed 3 papers.

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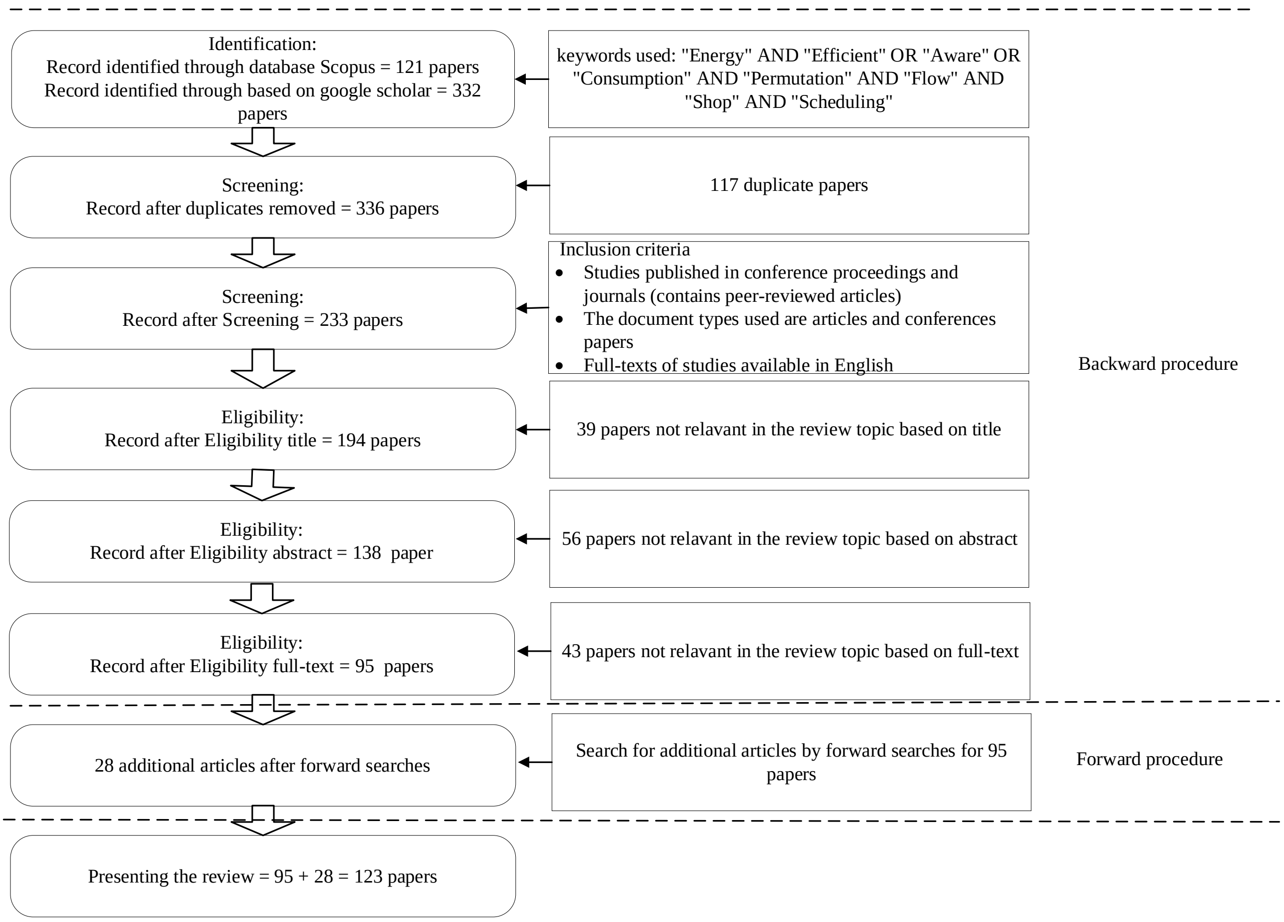

Figure 3. Literature search and evaluation for inclusion.

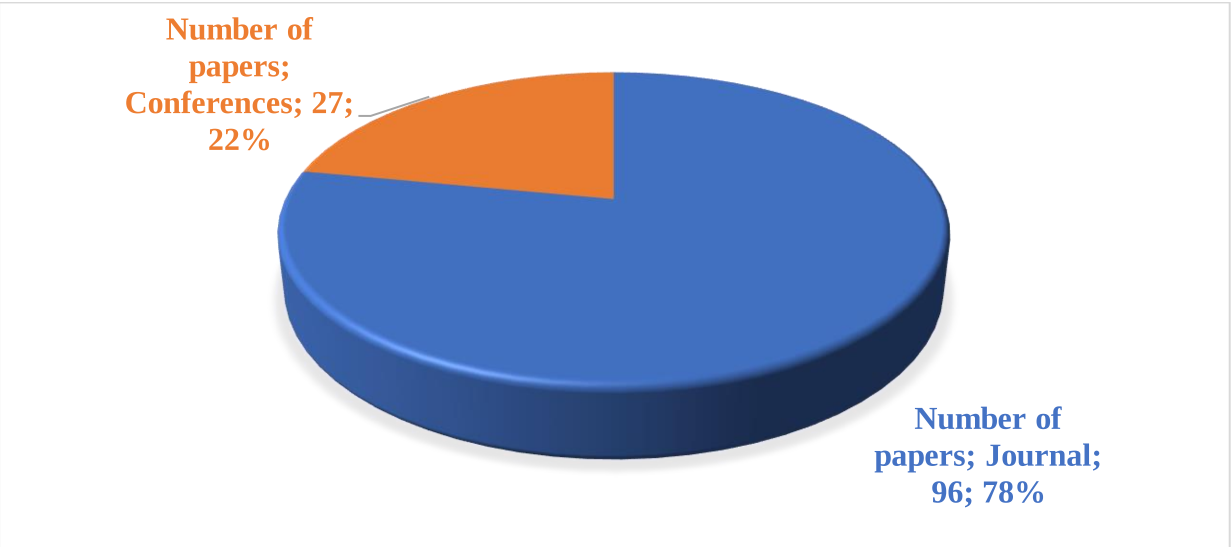

Figure 4. Classification of types of energy-efficient PFSP papers.

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Table 1. Distribution of papers by journal.

No.	Journal	Frequency
1	International Journal of Production Research	8
2	Journal of Cleaner Production	7
3	Swarm and Evolutionary Computation	4
4	Academic Journal of Manufacturing Engineering	3
5	IEEE transactions on cybernetics	3
6	Annals of Operations Research	2
7	Applied Soft Computing	2
8	European Journal of Operational Research	2
9	Advances in Mechanical Engineering	2
10	IEEE transactions on fuzzy systems	2
11	IET Collaborative Intelligent Manufacturing	2
12	Journal of Industrial Engineering and Management	2
13	Mathematical Problems in Engineering	2
14	Omega	2
15	Sustainability	2
16	The International Journal of Advanced Manufacturing Technology	2
17	Other	49

3. Results and Discussion

This section presents a review of energy-efficient PFSP articles presented based on paper distribution based on the year and country of publication (Subsection 3.1), a review of energy-efficient PFSP research based on single and multi-objective, energy-efficient PFSP variants (Subsection 3.2). This section ends with analysis, gaps identification, and further research (Subsection 3.3).

3.1 Paper Distribution Based on Year and Country of Publication

Energy-efficient PFSP has piqued the interest of researchers. Figure 5 shows the distribution of papers in this study from 2011-2023. Additionally, also articles and pre-print articles of early 2024 are covered. These results show that researchers' interest in the energy-efficient PFSP continues to increase every year. According to Figure 5, there is a significant increasing trend in the number of publications each year. At the beginning of the period, only one publication was recorded in 2011, but soon after, the number of publications steadily increased. There were no publications in 2012, but starting in 2013, a positive trend began with two publications, which continued to increase yearly. In 2018, there was a significant spike in the number of publications, with 13 growing rapidly. In 2023, the highest number in the data was recorded at 21 publications. This trend indicates a growing interest from researchers in understanding and solving energy-efficient permutation process flow scheduling problems. This increase in the number of publications may reflect the situation's complexity and the need of industry and society for more energy-efficient solutions. Thus, further research in this domain is very important and relevant to pursue, along with the increasing awareness of the importance of energy efficiency in production and manufacturing processes.

The energy-efficient PFSP has garnered attention from scientists worldwide. Various countries have contributed to addressing this issue, attesting to its global significance. Figure 6 illustrates the countries involved in research on energy-efficient

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PFSP from 2011 to 2023. Based on the data provided, it can be seen that most of the research related to the energy-efficient permutation workflow scheduling problem comes from China, with 69 papers or 56.10% of the total. Indonesia follows with 12 papers (9.76%), followed by Iran with 9 papers (7.32%). Other countries, such as the United States, France, and Turkey, contributed some papers, albeit in smaller numbers. From this distribution, it can be inferred that China is a major contributor to this research, showing a strong interest and commitment to solving energy-efficient permutation workflow scheduling problems. This also reflects the high global attention to energy and efficiency issues in manufacturing processes.

China is the largest contributor to the energy-efficient PFSP as it is one of the countries with very high energy consumption and has great challenges in dealing with environmental impacts and increasing greenhouse gas emissions in manufacturing. In 2015, energy consumed by the manufacturing sector accounted for 56.97% of China's overall energy consumption, while carbon dioxide emissions contributed to 54.90% of the country's total carbon emissions [35, 36]. Therefore, it is clear that many Chinese researchers are concerned about energy depletion and environmental issues. In addition, the Chinese government has been pushing initiatives and policies to reduce energy use and improve energy efficiency in various sectors, including the manufacturing industry [37]. Therefore, researchers from China are motivated to research energy-efficient PFSP to solve the problems of environmental impact and increasing greenhouse gas emissions.

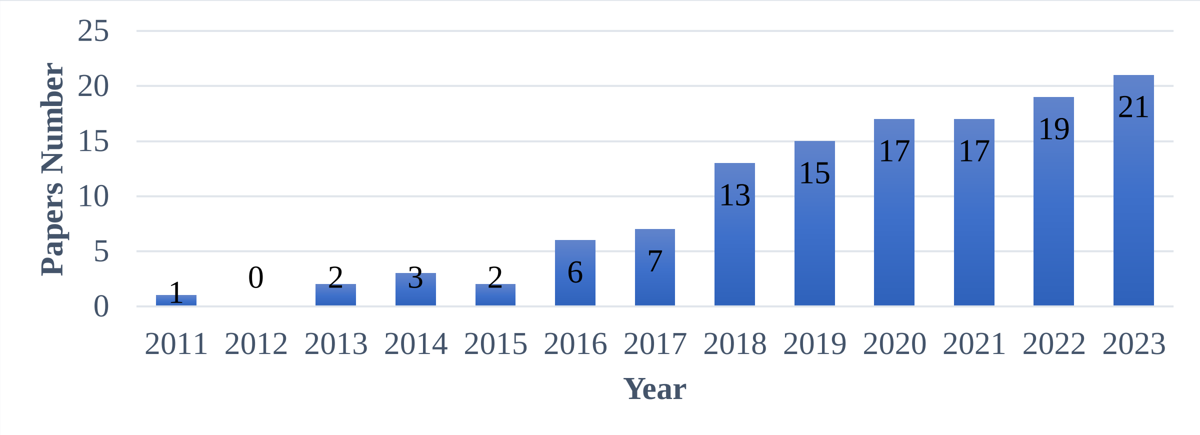

Figure 5. Distribution of papers by year

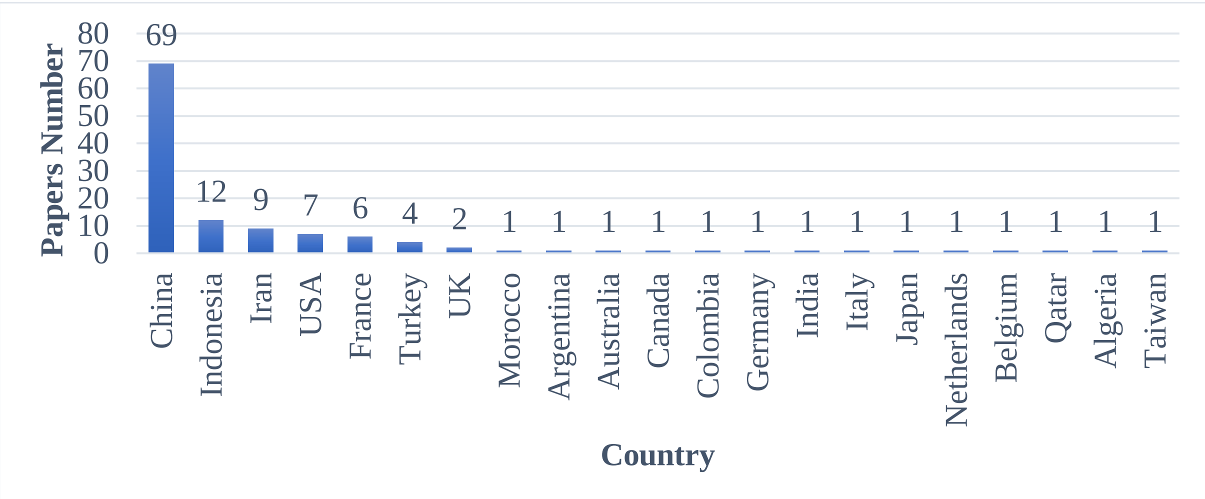

Figure 6. Distribution of articles by country

3.2 Literature Review

This study examined 108 articles that were classified using a predetermined classification scheme. Table 2 shows the classification of articles based on problems, variants, optimization tools, and objective functions. We successfully identified 11 variants of energy-efficient PFSP based on 108 articles. They are classical permutation flow shop scheduling problem (CPFSP), distributed permutation flow shop scheduling problem (DPFSP), no-wait permutation flow shop scheduling problem (NWPFSP), distributed no-wait permutation flow shop scheduling problem (DNWPFSP), blocking permutation flow shop scheduling problem (BPFSP), distributed no-idle permutation flow shop scheduling problem (DNIPFSP), mixed permutation flow shop scheduling problem (MPFSP), no-idle permutation flow shop scheduling problem (NIPFSP), reentrant permutation flow shop scheduling problems (RPFSP), distributed blocking permutation flow shop scheduling problem (DBPFSP), and distributed assembly no-wait permutation flow shop scheduling problem (DANWPFSP).

In the CPFSP, a set of jobs must be processed sequentially on several available machines in the same order, and each job can only be executed once on each machine [38]. Some of the assumptions of this problem are: (1) The permutation order has determined the order in which jobs are processed on each machine; (2) The entire set of jobs must be processed on multiple machines in the same processing order; (3) All jobs arrive and are ready to be processed at time 0; (4) Each machine can only process one job at a time, and each job can only be processed on one machine at a certain time; (5) When a job is processed, the process cannot be interrupted; and (6) The machine speed level for processing each job is the same. This problem can be applied to manufacturing, electronics, and automotive industries [39]. CPFSP is a classic flow shop problem that is further developed into various variants of the PFSP.

In solving the CPFSP, this review tries to present one of the mathematical models which modified by Öztop, et al. [40] to minimize total energy consumption (Min TEC). The following is the notation used in the CPFSP mathematical model:

Index:

i, k : Job index

j : Index for machines $j = 1, 2..M$

Parameters:

N : Number of jobs

M : Number of machines

D : A very large number

P_{ij} : Processing time in hour for job $i \in N$ on machine $j \in M$

φ_j : Machine power in kilowatt-hour (kWh) when idle at machine $j \in M$

τ_j : Machine power in kilowatt-hour (kWh)when process at machine $j \in M$

Positive variables:

C_{ij} : Completion time of the i-th job on the j-th machine

C_{im} : Completion time of the i-th job on the last machine (stage)

C_{max} : Makespan

θ_j : Idle time of j-th machine in hour

TEC : Total energy consumption in kilowatt-hour (kWh)

Binary variables:

γ_{ij} : 1, if job i is performed on machine j ; 0, otherwise

X_{ik} : 1, if job k is preceded by job i; 0, otherwise $(i \neq k)$

The MILP mathematical model for energy consumption minimization in the CPFSP is as follows:
Objective function:

$$Min\ TEC \quad (1)$$

Constraints:

$$P_{i1}\gamma_{i1} \leq C_{i1} \quad \forall i \in N \quad (2)$$

$$P_{ij}\gamma_{ij} \leq C_{ij} - C_{i,j-1} \quad \forall i \in N, \forall j \in M: J \geq 2 \quad (3)$$

$$P_{ij}\gamma_{ij} \leq C_{ij} - C_{kj} + D_{X_{ik}} \quad \forall i,\ k \in N: k \neq i, \forall j \in M \quad (4)$$

$$C_{ij} - C_{kj} + D_{X_{ik}} \leq D - P_{kj}\gamma_{kj} \quad \forall i,\ k \in N: k \neq i, \forall j \in M \quad (5)$$

$$C_{im} \leq C_{max} \quad \forall i \in N \quad (6)$$

$$\sum_i X_{ik} = 1; \quad \forall i \in N \mid i \neq k \quad (7)$$

$$\sum_k X_{ik} = 1; \quad \forall k \in N \mid i \neq k \quad (8)$$

$$\theta_j = C_{max} - \sum_{i \in N} P_{ij}\gamma_{ij} \quad \forall j \in M \quad (9)$$

$$TEC = \sum_{i \in N}\sum_{j \in M} P_{ij}\tau_j\gamma_{ij} + \sum_{j \epsilon M}\varphi_j\theta_j \quad (10)$$

$$\gamma_{ij}\ \epsilon\ \{0,1\} \quad \forall i \in N, \forall j \in M \quad (11)$$

$$X_{ik} \in \{0,1\} \quad \forall i, k \in N: k > i \quad C_{ij} \geq 0,\ \forall i \in N, \forall j \in M \quad (12)$$

Equation (1) is an objective function that aims to minimize energy consumption in kilowatt hour. Constraint (2) determines the completion time of the initial job on machine 1. Constraint (3) guarantees that the completion time of jobs on machine m must be greater than or equal to the previous machine's completion time plus the processing time on machine m. Constraints (4) and (5) serve the purpose of ensuring that there is no overlapping of two jobs on the same machine within the job permutation sequence. It should be noted that D represents a significantly large number, specifically when $D > \sum_{i \in N}\sum_{j \in M} P_{ij}$. Constraint (6) is responsible for calculating the makespan, which refers to the maximum completion time of all jobs on the last machine. This calculation is essential for the computation of the Total Energy Consumption (TEC). Constraints (7) and (8) produces a sequence of jobs, which keeps the feasibility of the sequence and maintains the feasibility of the sequence. Constraint (9) is used to calculate the idle time on each machine. Constraint (10) calculates the TEC, as suggested by Öztop, et al. [40] with considering processing and idle time in each machine. Finally, Equation (11) and (12) describes the decision variables in binary numbers.

Meanwhile, the abbreviations presented in this study are as follows:

BPFSP : Blocking Permutation Flow Shop Scheduling Problem
CPFSP : Classical Permutation Flow Shop Scheduling Problem
DANWPFSP : Distributed Assembly No-Wait Permutation Flow Shop Scheduling Problem
DBPFSP : Distributed Blocking Permutation Flow Shop Scheduling Problem
DNIPFSP : Distributed No-Idle Permutation Flow Shop Scheduling Problem
DNWPFSP : Distributed No-Wait Permutation Flow Shop Scheduling Problem
DPFSP : Distributed Permutation Flow Shop Scheduling Problem
Max QR : Maximization Quality Robustness
Max SR : Maximization Solution Robustness
MILP : Mixed Integer Linear Programming
Min Adj : Minimization adjustment
Min CF : Minimization Carbon Footprint
Min CE : Minimization Carbon Emission
Min FT : Minimization Flow Time
Min Maks : Minimization Makespan

Min NP	: Minimization Noise Pollution
Min NSI	: Minimization Negative Social Impact
Min PC	: Minimization Production Cost
Min PT	: Minimization Production Time
Min Tar	: Minimization Tardiness
Min TEC	: Minimization Total Energy Consumption
Min TECo	: Minimization Total Energy Cost
Min TC	: Minimization Tardiness Cost
Min TF	: Minimization Tardiness Fine
Min TIEC	: Minimization Total Idle Energy Consumption
NIPFSP	: No-Idle Permutation Flow Shop Scheduling Problem
NP-hard	: Non-Polynomial Hard Problem
NWPFSP	: No-Wait Permutation Flow Shop Scheduling Problem
PFSP	: Permutation Flow Shop Scheduling Problem
RPFSP	: Reentrant Permutation Flow Shop Scheduling Problems
SLR	: Systematic Literature Review

Furthermore, the DPFSP is an extension of the CPFS. The CPFSP considers processing to be done at a factory. However, in this DPFSP, PFSP schedule settings must be distributed to several factories to achieve optimal scheduling goals [41] [42]. This DPFSP is mostly applied in the automotive industry [43]. On the other hand, NWPFSP is a special variant of CPFSP that does not allow waiting time [44]. In this variant, each job can be processed on the next machine as soon as it is completed on the previous machine, so there is no waiting time between machines [45]. This problem has been applied to various pharmaceutical, chemical, steel, and just-in-time manufacturing processes in the pharmaceutical industry [46]. The DNWPFSP is a development of the NWPFSP where the schedule setting must be distributed to several factories [47]. In addition, the DNWPFSP is also developed in the DANWPFSP, which emphasizes the assembly process [48].

NIPFSP is an extension of CPFSP that does not allow idle machines between job processing [49]. NIPFSP has the characteristics of a machine that continues to process the first job to the last without any interruptions [50]. Industries that apply the characteristics of the problem are the ceramic industry, glass manufacturing companies, and fiberglass processing [51]. Furthermore, this problem is extended to the DNIPFSP. In the NIPFSP, this problem focuses on setting up a factory. However, in DNIPFSP, the NIPFSP schedule setting must be distributed to several factories [52]. On the other hand, a blocking Permutation Flow Shop Scheduling Problem (BPFSP) is a type of PFSP that allows jobs that have finished processing on a particular machine to wait until the next machine is available for processing [53]. This problem is applied to the cider industry [54]. On the other hand, the DBPFSP is developed from the BPFSP that must be distributed to several factories [55]. In this variant of RPFSP, jobs can return to the machine that has finished processing them for additional processing [56]. This problem is commonly applied to coating and printing processes in the tinplate printing industry [57]. The last variant is MPFSP which combines the PFSP with other variants because some of the operations applied have special characteristics [58].

Moreover, 17 objective functions were identified from the energy-efficient PFSP. Out of 17 objective functions, 3 objective functions are grouped into monetary objective functions, namely minimization total energy cost (Min TECo), minimization production cost (Min PC), and minimization tardiness cost (Min TC). The minimization total energy cost (Min TECo) objective function focuses on reducing energy consumption based on energy tariffs. In the meantime, minimization production cost (Min PC) is used to minimization production costs, including energy consumption and other operating costs.

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Furthermore, 14 objective functions are classified as non-monetary objective functions, such as minimization total energy consumption (Min TEC), minimization carbon footprint (Min CF), minimization carbon emission (Min CE), maximizing quality robustness (Max QR), minimization noise pollution (Min NP), minimization production time (Min PT), minimization flow time (Min FT), Maximization solution robustness (Max SR), minimization tardiness fine (Min TF), minimization total idle energy consumption (Min TIEC), minimization the negative social impact (Min NSI), minimization adjustment (Min Adj), minimization makespan (Min Maks), and minimization tardiness (Min Tar).

Some objective functions related to environmental aspects include minimization total energy consumption (Min TEC), minimization carbon footprint (Min CF), minimization carbon emission (Min CE), and minimization total idle energy consumption (Min TIEC). By minimization total energy consumption (Min TEC), this objective function minimizations energy for job completion. It addresses, in general, the energy required for job processing and idle machine energy caused by waiting machines. In contrast, an objective function that emphasizes reducing energy consumption from idle machines is the minimization of total idle energy consumption (Min TIEC). The minimization carbon emission (Min CE) objective function is an objective function that tries to minimization the amount of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, due to the manufacturing process. In contrast, minimization carbon footprint (Min CF) tries to minimization the number of greenhouse gases from the manufacturing process and other activities such as transportation and disposal of goods.

Time-related objective functions include minimization makespan (Min Maks), minimization flow time (Min FT), minimization tardiness (Min Tar), and minimization adjustment (Min Adj). The minimization adjustment (Min Adj) is an objective function that is used to minimize the total amount of changes time that all jobs take to process. In the meantime, 2 objective functions address social aspects, namely minimization noise pollution (Min NP) and minimization negative social impact (Min NSI). The review of Energy-Efficient PFSP paper based on single and multi-objective are presented in subsections 3.2.1 and 3.2.2.

3.2.1. Energy-Efficient Single-Objective PFSP

This section contains studies on single-objective optimization problems. Exact methods for solving this problem in the CPFSP variant have been proposed, including Branch and bound [59] [60] and mixed integer linear programming (MILP) [61] [62] [63] [64] [65] [66] [67]. To solve CPFSP, heuristic procedures such as bounds-based nested partition [68], novel NEH [69], greedy algorithm [70], decoding method [71], johnson's algorithm [72], q-learning algorithm [39], and fix-and-optimize [73] were proposed.

Ant colony optimization [74], genetic algorithm [75] [76] [38], immune clone [77], cross entropy-genetic algorithm-simulated annealing [78], decomposition-based algorithm [79], and memetic algorithm [80] [81] were also used to solve CPFSP variants. A hybrid procedure that combines heuristic and metaheuristic procedures is also proposed to solve the problem. Hybrid algorithms available include hybrid whale optimization [82], hybrid grasshopper algorithm optimization [83], hybrid harris hawk optimization [84], hybrid crow search algorithm [85], hybrid multi-verse optimizer algorithm [86], and hybrid gray wolf optimizer [87].

Zhong, et al. [49] addressed the problem of NIPFSP by proposing a metaheuristic procedure for the cuckoo search algorithm. On the same issue, Al-Imron, et al. [50] proposed grey wolf optimizer algorithm. Ferretti, et al. Ferretti and Zavanella [45] offered NWPFSP by utilizing the genetic algorithm metaheuristic procedure.

Recently, Kong, et al. [88] studied a BPFSP variant to minimize total energy consumption using a heuristic procedure. Utama and Sanafa [89] focus on the NIPFSP variant with the same purpose but using the Aquila Optimization Algorithm. Using the African Vultures Optimization Algorithm, Risma and Utama [90] also examined NIPFSP variants by minimizing total energy consumption. Meanwhile, Utama [91] examined NIPFSP variants by reducing total energy consumption using Beluga Whale Optimization. Ghorbanzadeh and Ranjbar [79] studied a variant of CPFSP to minimize total energy costs using a Heuristic approach. Finally, Wati and Amallynda [16] examined a variant of NIPFSP with the same objective but using the Fire Hawk Optimization Algorithm.

3.2.2 Energy-Efficient Multi-Objective PFSP

This section contains research on multi-objective optimization problems. The multi-objective MILP procedure is a popularly proposed procedure for the CPFSP [92] [93] [94] [95] [96] [97] [98]. Heuristic procedures by Xin, et al. Xin, et al. [99], local search & constructive heuristic [100], multi-objective iterated greedy [101] [102] [103] [40], and stochastic optimization [104] were used to solve this problem.

Many metaheuristic procedures have been proposed to solve the multi-objective CPFSP. The genetic algorithms [105] [106] [107] [108] [109] [110], estimation of distribution algorithm [111], particle swarm optimization [112], shuffle frog-leaping algorithm on cuckoo search [113], evolutionary algorithm [114] [115], brain storm optimization [116] were offered by researchers. Several other algorithms, including simulated annealing [117], estimation of distribution algorithm [118], non-dominated sorting genetic algorithm II [119] [120] [121] [122], and the optimal foraging algorithm [123], have been proposed. To solve this problem, whale optimization algorithms [124] [125] [126], swarm algorithms [127], and evolutionary algorithms based on decomposition [128] were also proposed.

Tirkolaee, et al. [129] proposed a hybrid procedure to solve the CPFSP that combines MILP and the self-adaptive artificial fish swarm algorithm. Other hybrid procedures, such as hybrid ant colony optimization [130] [131] [132], and hybrid backtracking search [133] [134], were proposed by combining heuristic-metaheuristic procedures. To solve this problem, the hybrid gray wolf optimization algorithm [135], the hybrid pathfinder Algorithm [136], and the hybrid cuckoo search algorithm [137] were also offered.

Several procedures are proposed to solve the DPFSP, including the exact procedure, which proposes multi-objective MILP [43]. To solve this problem, metaheuristic procedures such as knowledge-based cooperative [41], whale swarm optimization [42] [138], matrix cube-based estimation of distribution algorithm [139], and non-dominated sorting genetic algorithm II [140] were proposed. To address this issue, the knowledge-based multi-objective memetic optimization algorithm [141], co-evolutionary algorithm [142], and the collaborative algorithm [143] [144] were also developed.

Several metaheuristic procedures for the NWPFSP have been proposed, including adaptive multiobjective variable neighborhood search [145] [145], A discrete artificial bee colony [146] [44], and a cooperative evolutionary algorithm [147]. The DNWPFSP was investigated by Zhao, et al. [47] by proposing a reinforcement learning-driven cooperative algorithm procedure. Furthermore, this problem was extended by Zhao, et al. [48] to solve the DANWPFSP with a reinforcement learning-driven brain storm optimization procedure. Only two articles were published on the NIPFSP issue, proposing the greedy algorithm [148] and the cuckoo search algorithm [149]. The collaborative optimization algorithm [150] and the self-learning discrete Jaya algorithm [52] are proposed to solve the DNIPFSP.

Only two articles addressed the BPFSP by developing the parallel variable neighborhood search algorithm [151] and discrete evolutionary [53] procedures. The DBPFSP was studied by Zhao, et al. [55] by proposing a cooperative whale optimization algorithm procedure. Liu, et al. [56] proposed the non-dominated sorting genetic algorithm II procedure to solve the RPFSP. Peng, et al. [58] proposed an evolutionary algorithm to solve the MPFSP. Hyperheuristic with q-learning was proposed by Zhao, et al. [152] to solve DBFSP.

Most recently, Luo, et al. [153] studied a DPFSP variant to minimize makespan and total energy consumption using an evolutionary algorithm. Zhao, et al. [154] and Zhao, et al. [155] studied DANWPFSP and DBPFSP variants with the same objective function but used iterative and differential evolution approaches. Xue and Wang [156] and Wang, et al. [157] examined CPFSP variants to minimize total electricity cost and average delay using differential evolution and heuristic. In addition, Boufellouh and Belkaid [158] studied a BPFSP variant with a similar objective but using an ant algorithm. Zhang, et al. [159] also explored a variant of DPFSP by minimizing makespan and total energy consumption using particle swarm optimization. Finally, Bao, et al. [160] and Bao, et al. [161] examined variants of DBPFSP with the same objective function using a repeated greedy algorithm approach.

3.3 Analysis, gaps identification and further research

In this section, previous research on energy-efficient PFSP is analyzed. Then, research gaps are identified based on the classification of energy-efficient PFSP variants, problem types, objective functions, and optimization tools. The following sections provide details on the analysis (Subsections 3.3.1) as well as gaps identification and future directions (Subsections 3.3.2).

3.3.1 Analysis

This section provides an energy-efficient PFSP analysis in response to the RQ posed in the introduction section. Figure 7 depicts the classification of PFSP based on the type of problem based on RQ1, which is related to the type of energy-efficient PFSP. Based on the Figure 7, it can be concluded that most studies in the literature review articles on the Energy-efficient Permutation Flow Shop Scheduling Problem (EPFSP) focus more on multi-objective rather than single approaches. With 83 studies or 67.48% of the total, multi-objective approaches dominate in an attempt to minimize makespan and total energy consumption simultaneously. It shows that researchers tend to pay attention to more than one aspect of objectives in permutation workflow scheduling to achieve a more optimal solution overall. On the other hand, the single-objective approach still gains significant attention, with 40 studies or 32.52%, indicating that some researchers still focus on minimizing one single objective.

In addition, Figure 8 compares research on single-objective and multi-objective problems each year. The analysis results show that multi-objective research saw a significant increase from 2011 to 2023, with the number of studies steadily increasing from 1 in 2011 to 14 in 2023. In contrast, single-objective research showed a slower and more steady increase year-on-year, although it also saw a total increase from 0 in 2011 to 7 in 2023. It suggests that interest in the multi-objective approach is likely stronger than the single-objective approach in energy-efficient PFSP research over the given period. Multi-objective research may receive more attention due to its ability to consider more than one objective criterion, such as minimizing makespan and energy consumption simultaneously, which is relevant to real-world challenges in the manufacturing industry. Nonetheless, single-objective approaches also remain important as they provide more focused solutions on a single objective, which can suit the particular needs of some industrial applications.

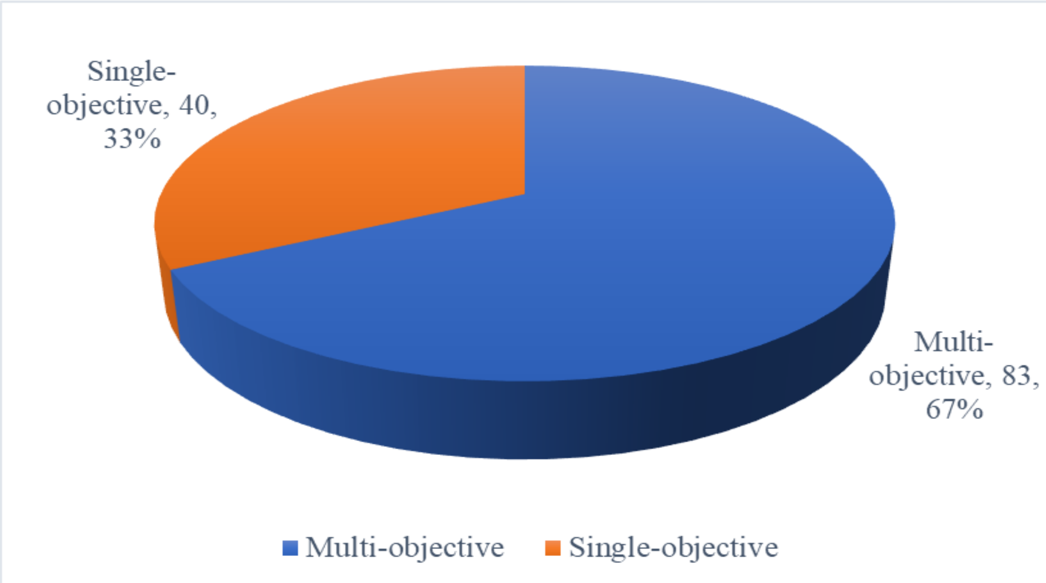

Figure 7. Distribute paper by problem type

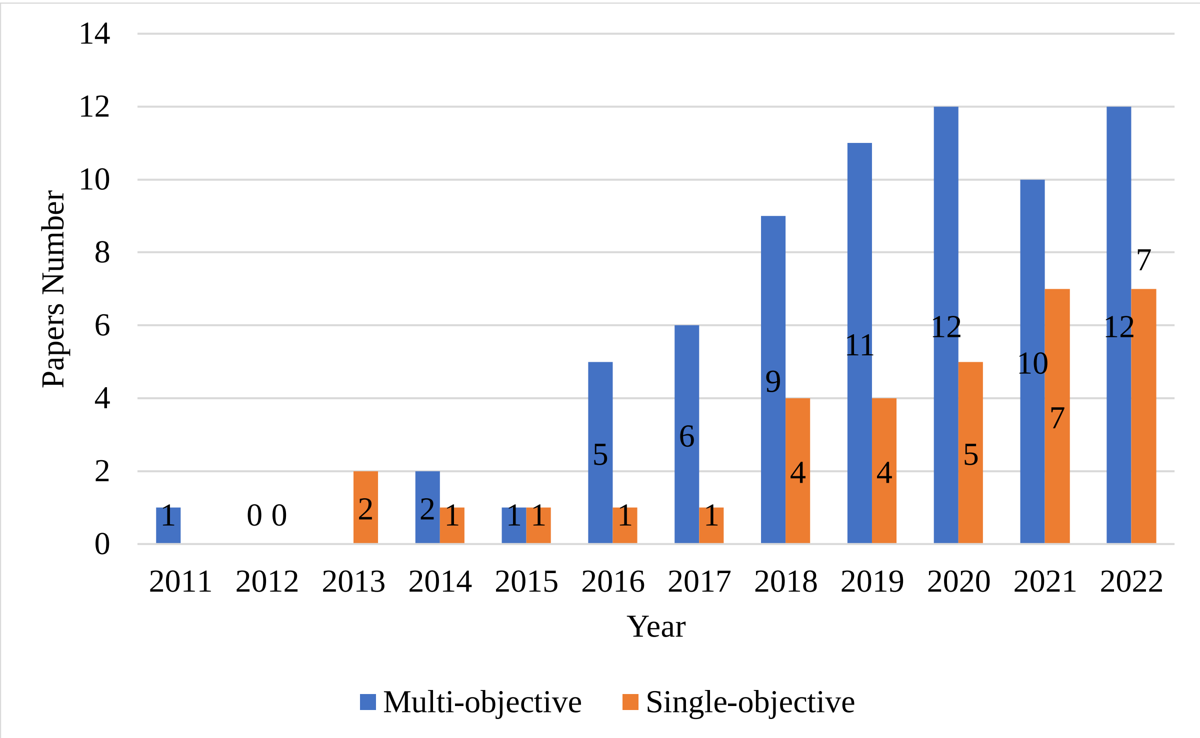

Figure 8. Research trends from year to year by type of problem

Jurnal Teknik Industri
Vol. 25, No. 1, February 2024, pp. 13-54

Table 2. Classification of articles by varians, type, objective function, and Optimization Tools

Author(s)	Variants PFSP	Type		Objective function																	Optimization tools
				Monetary			Non-monetary														
		Single	Multi	Min TECo	Min PC	Min TC	Min Maks	Min Tar	Min TEC	Min CF	Min CE	Max QR	Min NP	Min PT	Min FT	Max SR	Min TF	Min TIEC	Min NSI	Min Adj	
Fang, et al. [92]	CPFSP		√				√		√	√											Exact
Liu, et al. [59]	CPFSP	√							√												Exact
Fang, et al. [61]	CPFSP	√							√												Exact
Zhang, et al. [93]	CPFSP		√	√						√											Exact
Tuo, et al. [74]	CPFSP	√							√												Metaheuristic
Xin, et al. [99]	CPFSP		√				√		√												Heuristic
Liang, et al. [130]	CPFSP		√					√	√												Hybrid (heuristic-metaheuristic)
Masmoudi, et al. [62]	CPFSP	√		√																	Exact
Mansouri, et al. [100]	CPFSP		√				√		√												Heuristic
Afshin Mansouri and Aktas [105]	CPFSP		√				√		√												Metaheuristic
Masmoudi, et al. [63]	CPFSP	√							√												Exact
Ding, et al. [101]	CPFSP		√				√				√										Heuristic
Wang, et al. [111]	CPFSP		√				√		√												Metaheuristic
Huang, et al. [112]	CPFSP		√				√		√												Metaheuristic
Chen, et al. [133]	CPFSP		√				√		√												Hybrid (heuristic-metaheuristic)
Lu, et al. [134]	CPFSP		√				√		√												Hybrid (heuristic-metaheuristic)
Rahimi and Ziaee [106]	CPFSP		√				√		√												Metaheuristic
Masmoudi, et al. [75]	CPFSP	√		√																	Metaheuristic
Liu, et al. [56]	RPFSP		√	√			√														Metaheuristic
Liu, et al. [107]	CPFSP	√							√												Metaheuristic

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Author(s)	Variants PFSP	Type		Objective function																			Optimization tools
				Monetary			Non-monetary																
		Single	Multi	Min TECo	Min PC	Min TC	Min Maks	Min Tar	Min TEC	Min CF	Min CE	Max QR	Min NP	Min PT	Min FT	Max SR	Min TF	Min TIEC	Min NSI	Min Adj			
Nayak, et al. [108]	CPFSP		√			√			√														Metaheuristic
Wang and Wang [41]	DPFSP		√				√		√														Metaheuristic
Yang and Qi [77]	CPFSP	√							√														Metaheuristic
Lu, et al. [135]	CPFSP		√				√		√				√										Hybrid (heuristic-metaheuristic)
Wang, et al. [109]	CPFSP		√		√				√					√									Metaheuristic
Fazli Khalaf and Wang [64]	CPFSP	√		√																			Exact
Peng, et al. [58]	MPFSP		√						√								√						Metaheuristic
Liu, et al. [68]	CPFSP	√							√														Heuristic
Liu, et al. [69]	CPFSP		√						√									√					Heuristic
Wang, et al. [151]	BPFSP		√				√		√														Hybrid (heuristic-metaheuristic)
Zhong, et al. [113]	CPFSP		√				√		√														Metaheuristic
Pilerood, et al. [70]	CPFSP	√		√																			Heuristic
Öztop, et al. [102]	CPFSP		√						√						√								Heuristic
Ebrahimzadeh Pilerood, et al. [60]	CPFSP	√							√														Exact
Chen, et al. [150]	DNIPFSP		√				√		√														Heuristic
Liu, et al. [76]	CPFSP	√							√														Metaheuristic
Jiang and Wang [114]	CPFSP		√				√		√														Metaheuristic
Fallah, et al. [65]	CPFSP	√		√																			Exact
Wu and Che [145]	NWPFSP		√				√		√														Metaheuristic
Zheng, et al. [131]	CPFSP		√				√		√														Hybrid (heuristic-metaheuristic)
Ramezanian, et al. [103]	CPFSP		√				√		√														Heuristic

Jurnal Teknik Industri
Vol. 25, No. 1, February 2024, pp. 13-54

Author(s)	Variants PFSP	Type		Objective function																			Optimization tools
				Monetary			Non-monetary																
		Single	Multi	Min TECo	Min PC	Min TC	Min Maks	Min Tar	Min TEC	Min CF	Min CE	Max QR	Min NP	Min PT	Min FT	Max SR	Min TF	Min TIEC	Min NSI	Min Adj			
Wang, et al. [42]	DPFSP		√				√		√														Metaheuristic
Utama, et al. [78]	CPFSP	√							√														Metaheuristic
Fu, et al. [116]	CPFSP		√					√	√														Metaheuristic
Hosseini [94]	CPFSP		√	√			√																Exact
Tasgetiren, et al. [146]	NWPFSP		√						√						√								Metaheuristic
ZHANG and Jianwei [117]	CPFSP		√				√		√														Metaheuristic
Foumani and Smith-Miles [95]	CPFSP		√				√				√												Exact
Xiaowen, et al. [115]	CPFSP		√				√		√														Metaheuristic
Vallejos-Cifuentes, et al. [110]	CPFSP		√				√		√														Metaheuristic
Wang, et al. [71]	CPFSP	√							√														Heuristic
Öztop, et al. [40]	CPFSP		√						√						√								Heuristic
Assia, et al. [96]	CPFSP		√						√			√				√							Exact
Amiri and Behnamian [118]	CPFSP		√				√		√														Metaheuristic
Han, et al. [53]	BPFSP		√				√		√														Metaheuristic
Wang, et al. [138]	DPFSP		√				√		√														Metaheuristic
Yüksel, et al. [44]	NWPFSP		√					√	√														Metaheuristic
Wu and Che [145]	NWPFSP		√				√		√														Metaheuristic
Tirkolaee, et al. [129]	CPFSP		√		√				√														Hybrid (exact-metaheuristic)
Chen and Xu [132]	CPFSP		√				√		√														Hybrid (heuristic-metaheuristic)
Utama, et al. [82]	CPFSP	√							√														Hybrid (heuristic-metaheuristic)
Ho, et al. [72]	CPFSP	√							√														Heuristic
Wang, et al. [104]	CPFSP		√	√			√																Heuristic

Author(s)	Variants PFSP	Type		Objective function																	Optimization tools
				Monetary			Non-monetary														
		Single	Multi	Min TECo	Min PC	Min TC	Min Maks	Min Tar	Min TEC	Min CF	Min CE	Max QR	Min NP	Min PT	Min FT	Max SR	Min TF	Min TIEC	Min NSI	Min Adj	
Aghelinejad, et al. [66]	CPFSP	√		√																	Exact
Utama, et al. [83]	CPFSP	√							√												Hybrid (heuristic-metaheuristic)
Ferretti, et al. [45]	NWPFSP	√		√																	Metaheuristic
Aghelinejad, et al. [67]	CPFSP	√		√																	Exact
Cui, et al. [119]	CPFSP		√				√		√												Metaheuristic
Zhu, et al. [123]	CPFSP		√				√	√		√											Metaheuristic
Kurniawan and Fujimura [120]	CPFSP		√	√				√													Metaheuristic
Zhao, et al. [147]	NWPFSP		√				√		√												Metaheuristic
Lu, et al. [121]	CPFSP		√				√		√												Metaheuristic
Utama and Widodo [84]	CPFSP	√							√												Hybrid (heuristic-metaheuristic)
Li, et al. [140]	DPFSP		√						√						√						Metaheuristic
Zhong, et al. [49]	NIPFSP	√							√												Metaheuristic
Lu, et al. [141]	DPFSP		√				√		√										√		Metaheuristic
Utama [87]	CPFSP	√							√												Hybrid (heuristic-metaheuristic)
Xin, et al. [124]	CPFSP		√				√		√												Metaheuristic
Rong, et al. [136]	CPFSP		√				√		√												Hybrid (heuristic-metaheuristic)
Li, et al. [125]	CPFSP		√				√		√												Metaheuristic
Zhao, et al. [52]	DNIPFSP		√					√	√												Metaheuristic
Cheng, et al. [148]	NIPFSP	√							√												Heuristic
Wang, et al. [127]	CPFSP		√				√		√												Metaheuristic

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Jurnal Teknik Industri
Vol. 25, No. 1, February 2024, pp. 13-54

Author(s)	Variants PFSP	Type		Objective function																	Optimization tools
				Monetary			Non-monetary														
		Single	Multi	Min TECo	Min PC	Min TC	Min Maks	Min Tar	Min TEC	Min CF	Min CE	Max QR	Min NP	Min PT	Min FT	Max SR	Min TF	Min TIEC	Min NSI	Min Adj	
Badri, et al. [97]	CPFSP		√					√	√												Exact
D'Amico, et al. [98]	CPFSP		√				√		√												Exact
Gu, et al. [137]	CPFSP		√				√				√										Hybrid (heuristic-metaheuristic)
Gu, et al. [126]	CPFSP		√				√		√												Metaheuristic
Busse, et al. [73]	CPFSP	√		√																	Heuristic
Xin, et al. [122]	CPFSP		√				√		√												Metaheuristic
Wang, et al. [128]	CPFSP		√				√		√												Metaheuristic
Marichelvam, et al. [81]	CPFSP	√		√																	Metaheuristic
Fathollahi-Fard, et al. [43]	DPFSP		√				√		√												Exact
Zhong, et al. [149]	NIPFSP		√				√		√												Metaheuristic
Mou, et al. [143]	DPFSP		√						√											√	Metaheuristic
Lu, et al. [144]	DPFSP		√				√		√												Metaheuristic
Zhao, et al. [152]	DBFSP		√					√	√												Heuristic
Zhao, et al. [48]	DANWPFSP		√				√		√												Metaheuristic
Zhang, et al. [139]	DPFSP		√				√				√										Metaheuristic
Zhao, et al. [47]	DNWPFSP		√				√		√												Metaheuristic
Guo, et al. [38]	CPFSP	√							√												Metaheuristic
Utama [85]	CPFSP	√							√												Hybrid (heuristic-metaheuristic)
Peng, et al. [39]	CPFSP	√					√														Heuristic
Utama, et al. [86]	CPFSP	√							√												Hybrid (heuristic-metaheuristic)
Shen, et al. [80]	CPFSP	√		√																	Metaheuristic
Al-Imron, et al. [50]	NIPFSP	√							√												Metaheuristic

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Author(s)	Variants PFSP	Type		Objective function																	Optimization tools
				Monetary			Non-monetary														
		Single	Multi	Min TECo	Min PC	Min TC	Min Maks	Min Tar	Min TEC	Min CF	Min CE	Max QR	Min NP	Min PT	Min FT	Max SR	Min TF	Min TIEC	Min NSI	Min Adj	
Huang, et al. [142]	DPFSP		√				√		√												Metaheuristic
Ghorbanzadeh and Ranjbar [79]	CPFSP	√		√																	Metaheuristic
Zhao, et al. [55]	DBPFSP		√				√	√	√												Metaheuristic
Kong, et al. [88]	BPFSP	√							√												Heuristic
Utama and Sanafa [89]	NIPFSP	√							√												Metaheuristic
Luo, et al. [153]	DPFSP		√				√		√												Metaheuristic
Risma and Utama [90]	NIPFSP	√							√												Metaheuristic
Zhao, et al. [154]	DANWPFSP		√				√		√												Heuristic
Zhao, et al. [155]	DBPFSP		√				√		√												Metaheuristic
Utama [91]	NIPFSP	√							√												Metaheuristic
Ghorbanzadeh and Ranjbar [79]	CPFSP	√		√																	Heuristic
Xue and Wang [156]	CPFSP		√	√				√													Metaheuristic
Boufellouh and Belkaid [158]	BPFSP		√				√		√												Metaheuristic
Zhang, et al. [159]	DPFSP		√				√		√												Metaheuristic
Bao, et al. [160]	DBPFSP		√				√		√												Heuristic
Wang, et al. [157]	CPFSP		√	√				√													Heuristic
Bao, et al. [161]	DBPFSP		√				√		√												Heuristic
Wati and Amallynda [16]	NIPFSP	√							√												Metaheuristic

Referring to RQ2, which aims to determine the variant of the energy-efficient PFSP, Figure 9 depicts a distribution based on the variant energy-efficient PFSP. It demonstrates that in the single-objective approach, the CPFSP variant dominates with 32 studies, followed by NIPFSP with 6 studies. On the other hand, for the multi-objective approach, the CPFSP variant also dominates with 49 studies, followed by DPFSP with 12 studies. It shows that research on the CPFSP variant attracts significant interest, both in the single-objective and multi-objective approaches. In addition, other variants have also received attention, albeit in smaller numbers, such as the BPFSP and DBPFSP variants for the single-objective approach and NWPFSP and DANWPFSP for the multi-objective approach.

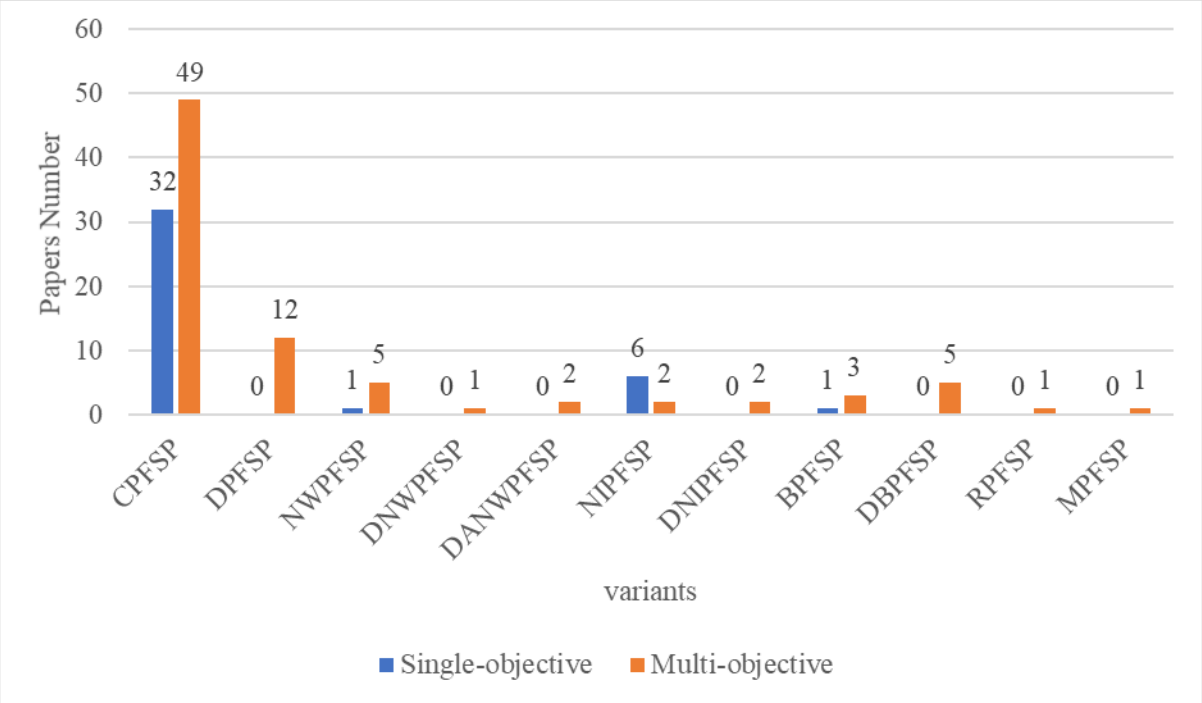

Figure 9. Distribution paper based on variant energy-efficient PFSP

Figure 10 depicts the distribution of research on procedures for solving energy-efficient PFSP based on RQ3, which aims to synthesize energy-efficient PFSP research procedures. In the single-objective approach, the most commonly used optimization tool is metaheuristics, with 16 studies, followed by heuristic algorithms with 9 studies. In the multi-objective approach, metaheuristics are much more dominant, with 51 studies, followed by heuristic algorithms, with 14 studies. It shows that metaheuristics are much more preferred in multi-objective research than single-objective due to their ability to handle complex problems better and search for more optimal solutions in a large search space. In addition, some studies use hybrid approaches, which combine different optimization algorithms, single-objective or multi-objective.

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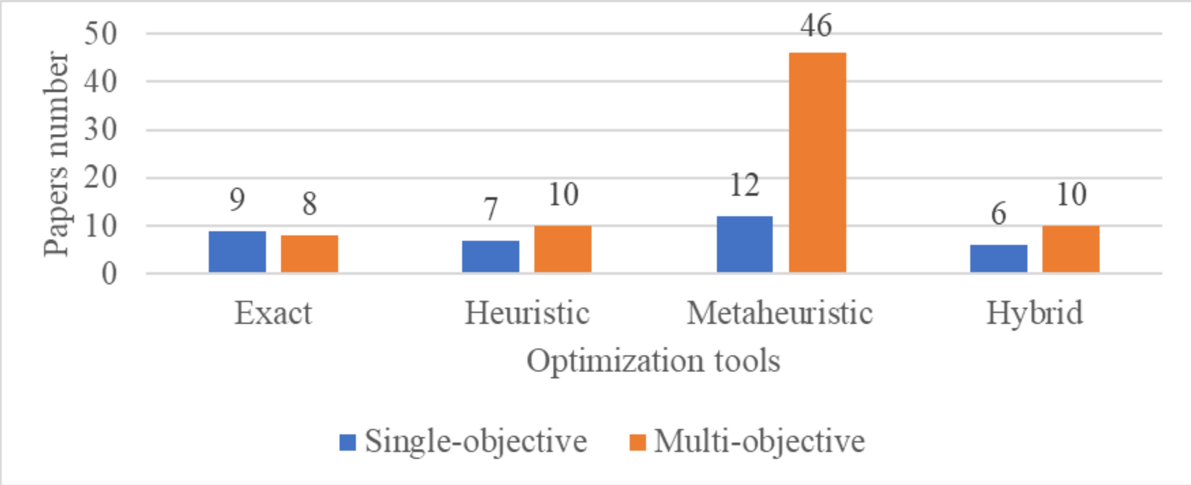

Figure 10. Distribution of research on optimization tools for energy-efficient PFSP

Referring to RQ4, which is related to the objective function used in energy-efficient PFSP, Figure 11 depicts the distribution of the objective functions used in the single objective problem of the energy-efficient PFSP. In the single objective function, of the 40 papers analyzed, 27 papers (67.50%) aimed to minimize total energy consumption, while another 12 papers (30.00%) sought to reduce total energy cost. Only 1 paper (2.50%) aimed to minimize makespan. It shows that energy-efficient permutation flow shop scheduling problems are often viewed from the point of view of decreasing energy consumption or energy cost, which is consistent with the global attention to energy efficiency issues and reducing carbon emissions in the industry.

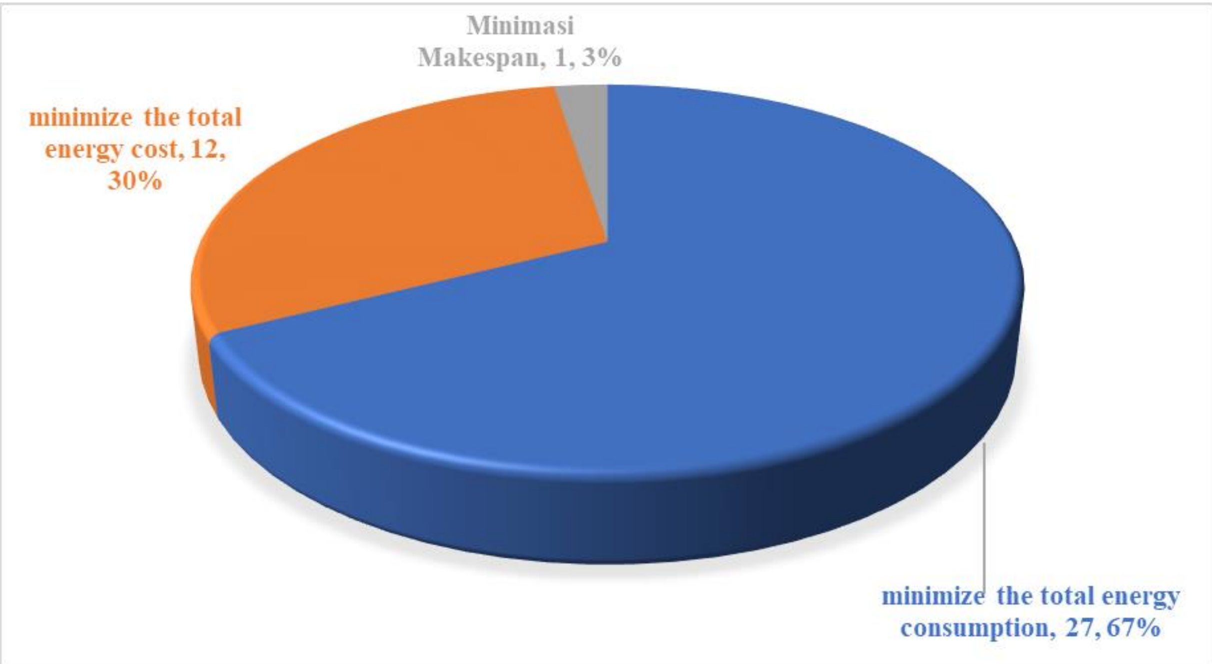

Figure 11. Distribution objective function on the single-objective problem of the energy-efficient PFSP

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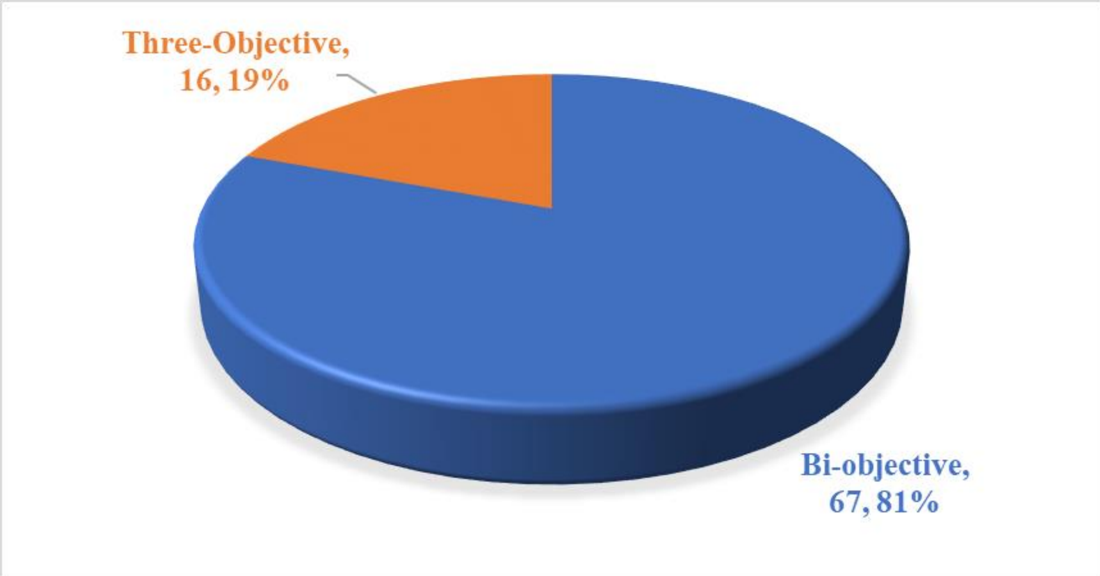

Figure 12. Distribution objective function on the energy-efficient PFSP's multi-objective problem.

Meanwhile, the distribution of the objective functions used in the multi-objective of the energy-efficient PFSP can be seen in Table 3. In the multi-objective case, the synthesis results show that most of the commonly used objective functions are the minimization of makespan and total energy consumption. The distribution of the categorization objective function on the multi-objective problem is shown in Figure 12. In the multi-objective approach, most of the research leads to bi-objective goals. Of the total 83 papers analyzed, 67 (80.72%) aim to solve problems by simultaneously considering two objectives. This approach allows researchers to search for an optimal solution that simultaneously minimizes more than one objective criterion, such as makespan and total energy consumption. In addition, a number of studies (16 papers or 19.28%) took a three-objective approach, indicating a slightly smaller interest in this more complex approach.

3.3.2 Gaps and Future directions

This section examines the research gaps and future directions for energy-efficient PFSPs. Table 4 maps energy-efficient PFSP based on variants, problem types, and optimization tools. It demonstrates that the metaheuristic method is researchers' most commonly used procedure in solving energy-efficient PFSP, particularly multi-objective problems.

Researchers are currently focusing on PFSP issues related to energy-efficient. However, further review and explanation of the research on this topic is required. Therefore, gap analysis and possible future research are presented in the following:

(1) The CPFSP dominates the energy-efficient PFSP and Other variants have been offered, such as DPFSP, NWPFSP, NIPFSP, DNIPFSP, BPFSP, RPFSP, MPFSP, DNWFSP, DANWFSP, and DBPFSP. These results show that a more modern PFSP environment can be investigated. The manufacturing environment has also changed in the context of PFSP. Large-scale distributed production models are becoming increasingly popular, and PFSP will become increasingly important to solve.

(2) Currently, energy-efficient PFSP models processing time and idle time as one of the energy-affecting parameters. In order to model an energy-efficient PFSP, all aspects

that affect energy consumption in production, such as setup and removal time, should be considered. As a result, the aspects influencing energy consumption reduction should be modeled in the energy-efficient PFSP scheduling. The greater the number of aspects modeled in the energy-efficient PFSP, the greater the possibility of improving energy efficiency and lowering energy consumption.

(3) Deterministic processing time dominates the problem of energy-efficient PFSP. The direction of further research that needs to be explored is problems with fuzzy and stochastic time characteristics.

(4) The issue of sustainability encourages researchers to employ objective functions that consider economic, social, and environmental factors. For example, the energy-efficient PFSP aims to minimization total energy consumption (environmental aspect) and completion time (economic aspect). However, in solving energy-efficient PFSP, social aspects are rarely considered. The current production characteristics of the chemical, steel, electronics, and automotive industries hurt social aspects such as workers and communities. The negative impacts are noise pollution and other negative social impacts that can affect workers and communitie long term. As a result, future research must consider three aspects of sustainability (economic, social, and environmental) and PFSP.

(5) The majority of researchers provide multi-objective problems. Researchers have paid less attention to the issue of single-objective energy-efficient PFSP. Although single-objective problems are less appealing, several objective functions from economic aspects such as minimization completion time, tardiness, and idle time as well as environmental aspects such as energy and emission minimization can be combined in the cost objective. Decision makers can easily use the single-objective solution to determine the optimal solution to the PFSP without finding a non-dominant solution.

(6) Multi-objective problems dominate energy-efficient PFSP scheduling. The most dominant objective functions used in energy-efficient PFSP are those related to minimization total energy consumption and the makespan. Traditional objective functions, such as tardiness, flow time, etc., receive less attention in multi-objective problems. Furthermore, the relationship between energy-related goals and other goals related to multi-objective problems was not examined. Instead, most researchers concentrated on developing more effective procedures for solving energy-efficient PFSP. As a result, the relationship between objective functions in multi-objective problems must be investigated and analyzed in greater depth. A critical question is the extent to which the relationships between the objective functions are inconsistent.

(7) The analysis in the preceding section shows that the metaheuristic procedure is an efficient method for solving energy efficiency scheduling problems. This procedure is effective and efficient for dealing with large-scale problems. As a result, developing high-quality advanced metaheuristic algorithms for single-objective and multi-objective problems must be improved, particularly for finding non-dominant solutions. To solve the energy-efficient PFSP, some local search operators and heuristic procedures can be used to improve the algorithm's quality. To solve the energy-efficient PFSP, a hybrid procedure that combines heuristic and metaheuristic procedures must be developed.

(8) Energy-efficiency research PFSP is dominated by research that takes job arrivals into account simultaneously. However, there has not been much research into dynamic job arrivals. As a result, more research is required to investigate the energy-efficient PFSP for dynamic job arrivals.

Several industries have unique characteristics that distinguish them from general PFSP. Furthermore, decision-makers are more concerned with using practical models and simple algorithms to solve problems. Because several articles have been published discussing complexity and multi-constraints, research focusing on specific industries with the practicality of models and algorithms is essential.

Table 3. Distribution objective function on the multi-objective problem of the energy-efficient PFSP

Objective Functions	Frequency	Category
Min Maks-Min TEC	50	Bi-objective
Min Tar-Min TEC	8	Bi-objective
Min Maks-Min CE	4	Bi-objective
Min TEC-Min FT	4	Bi-objective
Min Maks-Min TE cost	3	Bi-objective
Min CF-Min TE cost	1	Bi-objective
Min Maks-Min Tar-Min CF	1	Three-Objective
Min Maks-Min Tar-Min TEC	1	Three-Objective
Min Maks-Min TEC-Min CF	1	Three-Objective
Min Maks-Min TEC-Min NP	1	Three-Objective
Min Maks-Min TEC-Min NSI	1	Three-Objective
Min Tar-Min TE cost	1	Bi-objective
Min TEC-Min TF	1	Bi-objective
Min TEC-Max QR-Max SR	1	Three-Objective
Min TEC-Min Adj	1	Bi-objective
Min TEC-Min PC	1	Bi-objective
Min TEC-Min PC-Min PT	1	Three-Objective
Min TEC-Min TC	1	Bi-objective
Min TEC-Min TIEC	1	Bi-objective

Several questions are open for future research in Energy-efficient EPFSP based on the given gap analysis:

1) What is the role and influence of other PFSP variations, such as DPFSP, NWPFSP, and DBPFSP, in increasingly modern and complex manufacturing environments?
2) How do we model all aspects that affect energy consumption in production, such as setup and removal times, to create a more energy-efficient PFSP model?
3) What are the challenges and solutions in handling fuzzy and stochastic time characteristics in EPFSP problems to account for uncertainty?
4) Given the negative impacts of production on communities and workers, how can social aspects be incorporated into a sustainable PFSP model?
5) How does the performance compare between multi-objective and single-objective approaches in EPFSP, especially regarding ease of use and efficiency of optimal solutions?
6) What is the relationship between energy-related objectives and other objectives in the multi-objective approach of EPFSP, and what are the implications for overall problem-solving?
7) How can we improve the quality of metaheuristic algorithms for solving EPFSP problems, especially in finding non-dominant solutions and optimizing local search results?
8) How do we adapt EPFSP algorithms and models to handle dynamic job arrivals in a changing production environment?

9) How can we develop more practical and effective PFSP models and algorithms, especially for industries with unique characteristics and simpler decision-making needs?

Table 4. Mapping energy-efficient PFSP based on variants, problem types, and optimization tools

Variants	Single-Objective				Multi-Objective			
	Heuristic	Meta-heuristic	Hybrid	Exact	Heuristic	Meta-heuristic	Hybrid	Exact
CPFSP	[68] [69] [70] [71] [72] [73] [39] (7 papers)	[74] [75] [77] [76] [78] [81] [79] [80] [38] (9 papers)	[82] [83] [84] [87] [86] [85] (4 papers)	[59] [61] [62] [63] [64] [60] [65] [66] [67] (9 papers)	[99] [100] [101] [102] [103] [40] [104] (7 papers)	[105] [111] [112] [106] [107] [108] [109] [113] [114] [116] [117] [115] [110] [118] [119] [123] [120] [121] [124] [125] [127] [126] [122] [128] (24 papers)	[130] [133] [134] [135] [131] [129] [132] [136] [137] (9 papers)	[92] [93] [94] [95] [96] [97] [98] (7 papers)
DPFSP						[41] [42] [138] [140] [143] [144] [142] [139] (8 papers)		[43] (1 paper)
NWPFSP		[45] (1 paper)				[145] [146] [44] [145] [147] (5 paper)		
NIPFSP		[49] [50] (2 paper)			[148] (1 paper)	[149] (1 paper)		
DNI-PFSP					[150] (1 paper)	[52] (1 paper)		
BPFSP						[53] (1 paper)	[151] (1 paper)	
RPFSP						[56] (1 paper)		
MPFSP						[58] (1 paper)		
DNW-FSP						[47] (1 paper)		
DAN-WFSP						[48] (1 paper)		
DBPFSP					[152] (1 paper)	[55] (1 paper)		

(white) shows the number of researchers
(grey) shows limited studies
(black) shows a lack of research

4. Conclusion

This article provides an overview of PFSP that try to solve the energy-efficient PFSP. In this study, the authors conducted a literature review of 123 articles using PFSP variants classified into problem types, problem variants, optimization procedures, and objective functions. Based on the problem type classification, the findings show that the multi-objective problem is the most investigated problem type in energy-efficient PFSP. On the other hand, in the classification of energy-efficient PFSP variants, the CPFSP variant is a variant that researchers widely study. In addition, metaheuristic procedures have been widely applied as a method to handle the energy-efficient PFSP. Genetic Algorithm is the most widely used method to solve the energy-efficient PFSP. Furthermore, based on the classification of the objective function, many researchers use the objective function to reduce the total energy consumption in single-objective problems. On the other hand, in multi-objective problems, the objective functions of minimization makespan and total energy consumed are the popular objective functions applied by researchers.

This paper also discusses potential avenues for further studies on energy-efficient PFSP. The following are some suggestions regarding future research directions: (1) as the change of PFSP manufacturing environment enables a more modern PFSP environment, distributed scheduling problems are increasingly popular and interesting to investigate; (2) sustainability issues require more in-depth investigation in energy-efficient PFSP by considering the objective function on social aspects; (3) the characteristics of fuzzy and stochastic data should be taken into account in energy-efficient PFSP; (4) research on objective functions of more than two objective functions is needed for multi-objective problems; (5) researchers are encouraged to develop computational technology to solve the energy-efficient PFSP by developing advanced metaheuristic procedures; (6) cost functions such as energy cost, penalty cost, delay cost, and wastage cost need to be considered in the single-objective energy-efficient PFSP; and (7) energy-efficient PFSP research investigating dynamic job arrival also needs to be conducted.

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