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JOURNAL INDUSTRIAL SERVICESS

journal homepage: http://jurnal.untirta.ac.id/index.php/jiss

eISSN 2461-0631

Review article

A review of energy-aware multi-objective hybrid flow shop scheduling with parallel machines in manufacturing systems

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ARTICLE INFO

Article history:
Received 20 September 2024
Received in revised form 13 December 2024
Accepted 30 December 2024
Published online 15 January 2025

Keywords:
Energy-conscious scheduling
Hybrid flow shop
Parallel machine
Multi-objective

Editor:
Akbar Gunawan

Publisher's note:
The publisher remains neutral concerning jurisdictional claims in published maps and institutional affiliations.

ABSTRACT

Hybrid flow shop scheduling (HFSS) with parallel machines has gained attention among researchers in manufacturing systems because of its critical role in enhancing production efficiency. This type of production system is widely implemented in modern factories today. This production system combines the characteristics of a job shop and flow shop, with each stage having more than one machine capable of processing all jobs. This review provides a comprehensive analysis of HFSS, focusing on the integration of parallel machines to address real-world manufacturing complexities. Key topics covered include problem formulations, mathematical models, heuristic and metaheuristic approaches, and recent advancements in solution techniques. The study highlights the advantages and limitations of various methodologies, emphasizing their applicability in diverse industrial contexts. Furthermore, the review identifies current trends, such as the incorporation of artificial intelligence and Industry 4.0 technologies, as well as gaps in the literature that require further exploration. By synthesizing existing research, this paper aims to guide future studies and offer practical insights for practitioners aiming to enhance scheduling performance in dynamic manufacturing environments.

1. Introduction

Energy is a vital component of everyday human life. Its utilization extends beyond daily needs and plays a pivotal role in various sectors, including the economy. The manufacturing industry is particularly energy dependent. As a major player in the global economy, the manufacturing sector consumes a significant portion of the world's energy, exceeding 50% [1]. The situation is growing more urgent as most energy sources, particularly fossil fuels, are finite and non-renewable. This creates concerns about the long-term sustainability of energy supplies and highlights the need for stronger efforts in energy conservation. [2].

To lower energy consumption and improve efficiency, many research efforts have focused on finding solutions for the manufacturing industry. One promising approach is energy conservation through environmentally conscious scheduling, which prioritizes energy use alongside traditional goals like reducing production costs and lead times. [3]. Integrating energy consumption into production scheduling often conflicts with economic goals like reducing operational costs and speeding up delivery. This creates a challenge because energy-efficient solutions can sometimes result in higher costs or longer processing times. As a result, energy-aware scheduling is seen as a complex task that involves balancing multiple, often conflicting, objectives.

Hybrid flow shop scheduling is a type of scheduling used in manufacturing that combines elements of job shop, flow shop, and parallel scheduling [3], [4], [5]. It offers flexibility by supporting various production processes and configurations. However, it's more complex than other scheduling types due to its multiple production stages and more intricate resource allocation [6], [7], [8]. This added complexity creates significant opportunities for optimization, especially when it comes to improving energy efficiency while still maintaining production effectiveness. By factoring in energy consumption during scheduling, it's possible to reduce overall energy use without compromising productivity or profitability [9], [10], [11].

This research aims to review studies on multi-objective scheduling in hybrid flow shops (MOHFS), with a particular focus on minimizing energy

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http://dx.doi.org/10.62870/jiss.v10i2.30920

consumption. By analyzing existing literature and methodologies, the review seeks to provide a thorough understanding of the current state of research, highlight key developments, and identify emerging trends in the field. The goal is to offer valuable insights to researchers and practitioners in scheduling, helping them understand the progress made so far and uncover opportunities for future research to enhance the effectiveness and efficiency of sustainable production scheduling.

As the manufacturing sector grows and faces greater pressure to reduce its environmental impact, understanding the challenges and solutions related to energy-efficient scheduling is becoming increasingly important [12], [13]. Future research needs to explore new ways to integrate energy conservation with other key factors, such as cost optimization and process reliability [14], [15]. The ongoing development of scheduling methodologies will be essential in driving more sustainable manufacturing practices in the years ahead [16], [17], [18].

This paper is organized as follows: Section 2 describes the materials and methods used in this review. Section 3 offers an analysis and discussion of the key findings. The paper concludes with a summary and recommendations for future research.

2. Material and method

2.1. Multi-objective hybrid flow shop scheduling problem

We can formulate the multi-objective hybrid flow shop scheduling problem (MOHFS) as follows: A manufacturing facility has N jobs that must be processed through M stages, where each stage t ($t = 1,2,\ldots,M$) has m_t machines operating in parallel. Each job has a different processing time depending on the machine it's processed on at each stage. The scheduling decision involves determining the order in which jobs are processed at each stage, with the goal of minimizing multiple objectives, one of which is reducing energy consumption.

2.2. Literature search method

The method used to search for literature is explained in this section. The first step is to determine the search engine or article database. This study uses article databases with primary sources from Google Scholar, Scopus, and Web of Science. These three databases cover more than 80% of scholarly article databases worldwide. The next step is to determine the keywords. The keywords used in this study are "hybrid flow shop," "multi-objective," "energy-aware," and "energy-conscious." These keywords are then used either individually or in combinations as defined.

After that, we determine the publication time filter and the place of publication. The publication time is filtered between 2015 and 2023. As for the place of publication, it is limited to articles published in journals or proceedings; books are not included.

3. Results and discussions

3.1. Research trend

Fig. 1 shows the research trend in multi-objective hybrid flow shop from 2015 to 2023, published in Scopus-indexed journals [19], [20]. From Fig. 1, it can be seen that this topic has a positive trend. From 2015 to 2023, there has been a consistent increase in the number of publications each year. The total number of publications significantly increased from 18 articles in 2015 to 56 articles in 2023, with an average increase of about 4-6 articles per year. When analyzed by periods, the growth from 2015 to 2017 was moderate, with an average of 22 articles per year. From 2018 to 2020, there was a more significant increase, with an average of 36 articles per year. Meanwhile, the period from 2021 to 2023 became the most productive, with an average of 52 articles per year. Overall, the total number of publications from 2015 to 2023 reached 329 articles, with nearly 47% of the total publications coming from the period of 2021 to 2023.

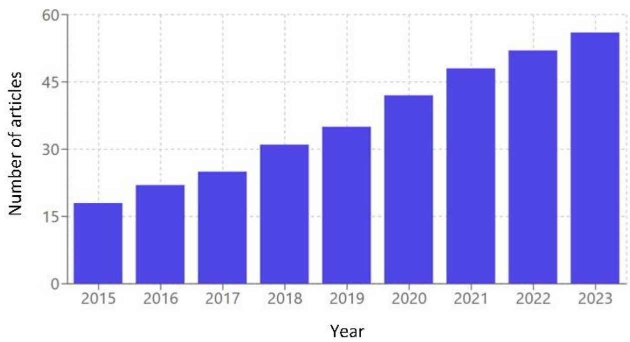

Figure 1. Research trend in multi-objective hybrid flow shop

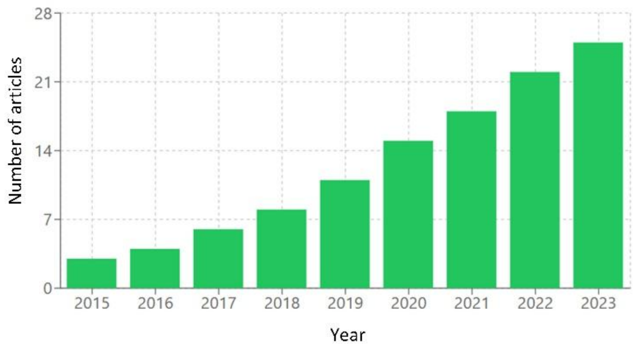

Figure 2. Research trend in energy-conscious multi-objective hybrid flow shop

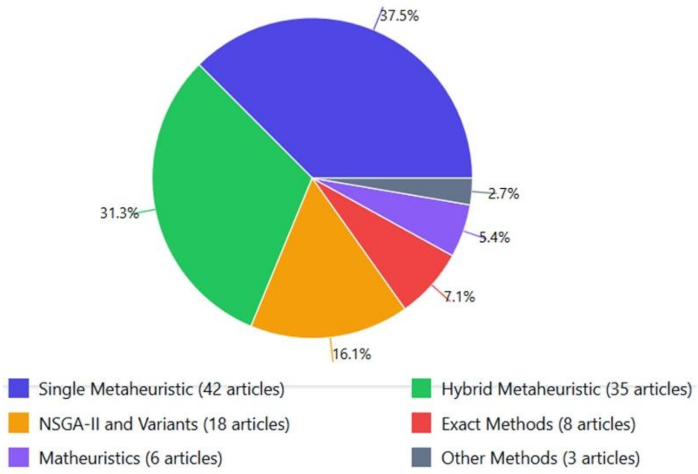

Figure 3. Solution method to energy-conscious multi-objective hybrid flow shop

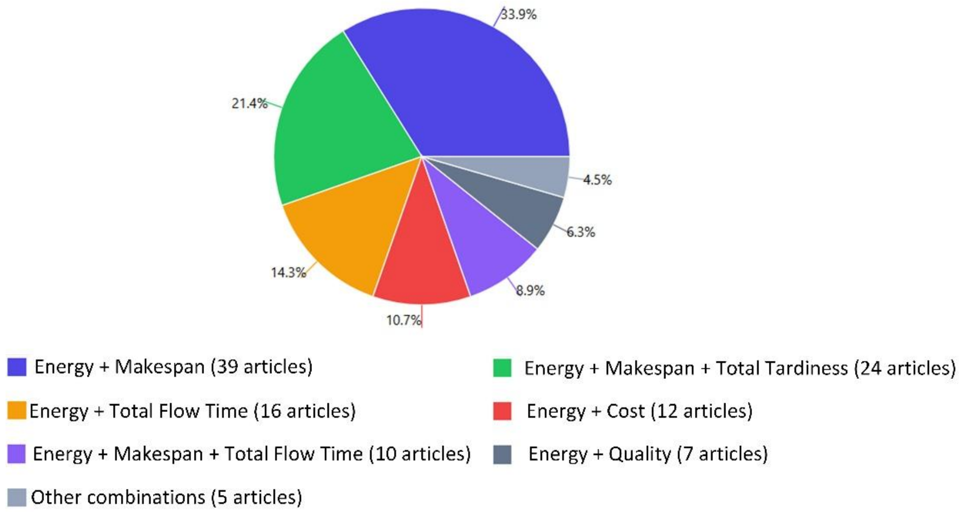

Figure 4. The objective functions used in energy-conscious multi-objective hybrid flow shop

For the keyword "energy-conscious multi-objective hybrid flow shop," the resulting trend is similar to that of multi-objective hybrid flow shop, as shown in Fig. 2. There has been a significant increase in publications on this topic, from 3 articles in 2015 to 25 articles in 2023. The most rapid growth occurred after 2019, with an average increase of about 2-4 articles per year. When analyzed by periods, the years 2015 to 2017 represent the early phase with a limited number of publications, ranging from 3 to 6 articles per year.

From 2018 to 2020, the growth began to rise, with publications ranging from 8 to 15 articles per year. Meanwhile, the period from 2021 to 2023 became the most productive, with publications ranging from 18 to 25 articles per year. Overall, the total number of publications on this topic reached 112 articles, with nearly 58% of the total publications being produced in the last 3 years (2021-2023). Key driving factors behind this increase include the rising awareness of sustainability in manufacturing [21], [22], stricter regulations on energy use [23], [24], the development of more effective multi-objective optimization methods [25], [26], [27] and industry demands for environmentally friendly scheduling solutions [28], [29].

3.2. Distribution of solution methods

Fig. 3 shows solutions methods used by researchers to solve the energy-conscious hybrid flow shop scheduling problem. We can extract a few significant conclusions. Single metaheuristics dominate with 42 articles (37.5%), while hybrid metaheuristics rank second with 35 articles (31.3%), making the total use of metaheuristics (single + hybrid) reach 68.8%. Articles that employed NSGA-II and its variants are 18 (16.1%), which is comparatively more than other algorithms developed for multi-objective problems. Other categories including Exact methods were published only in 8 articles (7.1%), while matheuristics had 6 articles (5.4%), both of which had low occurrences because the problems were too intricate. In terms of

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http://dx.doi.org/10.62870/jiss.v10i2.30920

usage trends, hybrid methods have increased over the years, exact methods remain common, especially for small sized problems and are providing Matheuristics a chance to prove their worth.

3.3. Objective functions

Fig. 4 illustrates the objective functions used in energy-conscious multi-objective hybrid flow shop studies. The most frequently used combination is Energy + Makespan, which appears in 38 articles (33.9%). This is followed by the combination of Energy + Makespan + Total Tardiness, found in 24 articles (21.4%), and Energy + Total Flow Time, which appears in 16 articles (14.3%). Bi-objective problems (Energy + a single objective) make up about 65% of the articles, while three-objective problems account for around 30%. More complex combinations are less common. The Energy + Cost combination appears in 12 articles (10.7%), reflecting a growing interest in the economic aspects of energy optimization. Additionally, the Energy + Quality combination, featured in 7 articles (6.3%), indicates an emerging focus on the trade-offs between quality and energy. Finally, various other combinations, including those involving noise, reliability, and other specific objectives, are found in 5 articles (4.5%).

3.4. Research opportunities

The research landscape in energy-conscious multi-objective hybrid flow shop scheduling still has plenty of untapped potential. Looking at the current trends, one big opportunity lies in connecting real-time energy pricing and dynamic electricity tariffs with production scheduling. This is becoming increasingly relevant as more industries adopt smart grid tech and renewable energy. Think about it - we could create scheduling systems that actually adapt on the fly to changing energy prices and availability, all while keeping production running smoothly. The really exciting part is bringing in AI and machine learning to figure out energy usage patterns and make smarter scheduling decisions, especially when you're dealing with complex setups where machines have different configurations and processing needs.

When we look deeper, there's also this fascinating challenge of developing better multi-objective models that juggle everything at once - energy use, traditional goals like makespan and tardiness, and newer sustainability metrics. We need to really understand how pushing for energy efficiency might affect product quality, how machine wear and tear plays into all this, and how to deal with all the uncertainties in both production and energy availability. The real kicker is making all this work in actual factories - we need practical solutions that can handle real-world problems like machine restrictions, setup times that depend on the sequence, and coordinating workers, all while keeping energy efficiency in mind.

4. Conclusions

We have reviewed several articles on energy-conscious multi-objective hybrid flow shop scheduling, and research in this area has steadily increased over the past 10 years (2015-2023). Heuristic methods continue to be the preferred approach for solving these problems, with NSGA-II being especially popular. Additionally, energy considerations are frequently combined with makespan in the objective functions.

Looking ahead, the future of this research lies in applying AI to scheduling systems to monitor energy consumption while maintaining efficiency and productivity. Another area of focus is the use of time-of-use (TOU) tariff schemes to optimize energy costs.

Declaration statement

Arif Saptiyadi: **Conceptualization, Methodology, Writing-Original Draft**. Faula Arina: **Collecting data.** Bobby Kurniawan: **Writing-Review & Editing.**

Acknowledgement

The acknowledgement was given to anonymous refrees for constructive feedback.

Disclosure statement

The author declares that this manuscript is free from conflict of interest and is processed by applicable journal provisions and policies to avoid deviations from publication ethics in various forms.

Funding statement

The authors received no funding for this research.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

AI usage statement

Generative AI and AI-assisted tools were used to enhance the language and readability of this manuscript. The authors have reviewed and revised all AI-generated content to ensure its accuracy and alignment with the research. The authors remain fully responsible for the work's scientific content, conclusions, and integrity, and disclose the use of AI to ensure transparency and adherence to publisher guidelines.

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