A Simheuristic Approach to Optimize Energy Consumption in the Single-Machine Scheduling Problem with Stochastic Processing Times

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Abstract

This paper addresses a stochastic single-machine scheduling problem with energy consumption. In this problem, job processing times are random variables, and total energy consumption depends on job scheduling, as each job has its own energy use and each period follows a Time-Of-Use tariff policy. To solve the problem, we propose a simheuristic algorithm that combines the metaheuristics Simulated Annealing and Greedy Randomized Adaptive Search Procedure to explore the solution space, along with Monte Carlo Simulation to better evaluate the solutions during the search. The solutions obtained are compared with those derived from a deterministic approach, and the results show that the simheuristic outperforms the deterministic method in terms of Average, Value at Risk, and Conditional Value at Risk, emphasizing the importance of incorporating uncertainty into the solution methods.

Keywords: Green Scheduling, Time-Of-use, Stochastic Processing Time.

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1. Literature review

This document presents all the articles used in the three literature reviews conducted in the paper "Simheuristic Approach to the Single-Machine Scheduling Problem with Stochastic Processing Times and Energy-Efficient". This section aims to establish the review protocols, which specify the objectives, the questions to be answered, the databases to be consulted, the types of studies to be analyzed, the keywords to be searched, the languages, the years of publication, and the inclusion and exclusion criteria for the studies obtained. Thus, these protocols seek to provide a clear and pre-defined framework that outlines and guides the entire review process, describing in a transparent manner all the methodological aspects for the search and selection of articles, thereby ensuring the reproducibility of the study.

Therefore, we have three objectives, one for each review. For SSMSP, we aim to identify gaps and trends regarding this model. For SMGSP, to evaluate the state of the art. And for SGSP, to analyze the current landscape of research on this topic. The questions to be answered for each objective are presented in Table 1.

Table 1: Questions to be answered for each review

Review	Questions
SSMSP	(1) Which methods are used to solve this type of problem; (2) What are the most addressed stochastic parameters in the literature.
SMGSP	(1) Classification of models according to the number of objective functions; (2) Which objective function(s) is/are considered; (3) What are the main environmental considerations; (4) What methods are used to solve this type of problem.
SGSP	(1) Which methods are used to solve this type of problem; (2) What are the most addressed stochastic parameters in the literature; (3) What are the main environmental considerations.

The review was conducted exclusively using the Web of Science database as the source for the literature review. This choice was made because this database is recognized for its multidisciplinary scope and its extensive coverage of renowned international scientific journals. Additionally, the search was limited to only one type of document, which is articles, as they represent a primary and consolidated source of academic knowledge, typically subjected to a rigorous peer-review process, which ensures the credibility and reliability of the information contained in them.

Preliminarily, a search was conducted on Google Scholar to identify keywords present in existing works in the literature. This enabled the formulation of a search string that ensured both the breadth and accuracy of the review, aiming to avoid the exclusion of relevant studies and the inclusion of irrelevant ones. Furthermore, all searches for keywords were performed only in the titles (TI) and the abstract (AB) of the works, and the asterisk (“ * ”) was used as a truncation operator to find all research with the same root. Thus, the search strings adopted can be observed in Table 2.

Table 2: Search string adopted for each review

Review	**Search string**
SSMSP	TI=(*single machine*) AND TI=(*sched**) AND (TI=(*simheuristic*) OR TI=(*stoch**) OR TI=(*uncert**)) AND (AB=(*heuristi**) OR TI=(*simheuris**) OR TI=(*optimiz**))
SMGSP	TI=(*single machine*) AND TI=(*sched**) AND (TI=(*green*) OR TI=(*sustainab**) OR TI=(*energ**) OR TI=(*carbon**) OR TI=(*nois**) OR TI=(*pollut**) OR TI=(*tariff**) OR TI=(*Time Of Use*) OR TI=(*Energy-effici**)OR TI=(*Electricity prices**))
SGSP	TI=(*sched**) AND (TI=(*green*) OR TI=(*sustainab**) OR TI=(*energ**) OR TI=(*carbon**) OR TI=(*nois**) OR TI=(*pollut**)) AND (TI=(*simheuristic*) OR TI=(*stoch**) OR TI=(*uncert**)) AND (TI=(*single machine*) OR TI=(*parallel machines*) OR TI=(*flow shop*) OR TI=(*flow-shop*) OR TI=(*flowshop*) OR TI=(*jop shop*) OR TI=(*jop-shop*) OR TI=(*jopshop*) OR TI=(*open shop*) OR TI=(*open-shop*) OR TI=(*openshop*))

Therefore, as presented in Table 2, for the SSMSP review, the terms “simheuristic”, “stoch*”, “uncert*” were used to search for works that deal with random variables, and the terms “heuristi*”, “simheuris*”, and “optimiz*” were used to filter only approaches that use optimization methods. This search returned 23 results. However, 4 were excluded after reviewing the abstracts, resulting in a final selection of 19 papers.

Similarly, for the SMGSP review, the terms "green", "sustainab*", "energ*", "carbon*", "nois*", "pollut*", "tariff*", "Time of use", and "Energy-effici*" were adopted as filters to search for only works that have environmental considerations in their scope. The term "single machine*" was used to delimit the manufacturing environment, and the term "sched*" was adopted to specify the addressed problem. By using this search string, 48 works were retrieved. However, 7 were excluded after reviewing the abstracts, resulting in a final selection of 41 papers.

For the SGSP review, where the terms "single machine", "parallel machine", "flow shop", "job shop", "open shop", and their variants are adopted to represent all the manufacturing environments existing in the sequencing literature. This search returned 10 results. However, 2 were excluded after reviewing the abstracts, resulting in a final selection of 8 papers. All searches and article counting for each review were conducted on 15/05/2025.

The search was conducted without any time limitations or document publication type restrictions (i.e., conferences, symposia, and journals). All works were read in full, with only those that did not address the scheduling topic or were not fully available being excluded.

The tables provide a structured summary of the key aspects analyzed in the reviewed articles, offering a comprehensive overview of the state of the art in these areas. This mapping enables the identification of emerging trends and research gaps, providing insights for the development of new approaches and contributing to advancements in the field.

Table 3: Articles used for the SSMSP review

Ref.	Year	Objective Function	Stochastic parameter	Solution approach
[1]	1988	Inventory costs and setup cost	Demands	Heuristics with Simulation
[2]	1988	Inventory costs and setup cost	Demands	Heuristics with Simulation
[3]	1992	Reward	Release date	Heuristics with Simulation
[4]	1994	Inventory costs and setup cost	Demands	Heuristics with Simulation
[5]	1994	Earliness and tardiness costs	Processing times	Heuristics with Simulation
[6]	1997	Total tardiness	Processing times	Robust Programming
[7]	2002	Total tardiness	Processing times and due dates	Heuristics with Simulation
[8]	2007	Weighted total tardiness	Processing times and due dates	Heuristics with Simulation
[9]	2007	Net present value	Reward value	Branch-and-Bound
[10]	2009	Weighted total tardiness	Machine breakdown	Heuristics with Simulation
[11]	2013	Weighted total tardiness	Processing times	Heuristics with Simulation
[12]	2013	Makespan and Total completion time	Processing times	Branch-and-Bound
[13]	2014	Sum of completion times	Processing times	Robust Programming
[14]	2019	Total tardiness	Setups	Stochastic Programming
[15]	2018	Maximum tardiness	Release date	Robust Programming
[16]	2020	Maximum waiting time	Processing times	Robust Programming
[17]	2020	Makespan	Machine breakdown	Simheuristics
[18]	2022	Makespan	Processing times	Robust Programming
[19]	2024	Earliness and tardiness costs	Machine breakdown	Machine Learning

Table 4: Articles used for the SMGSP review

Ref.	Year	Objective Function	Environmental Characteristic	Solution approach
[20]	2014	Makespan and TEC	TOU	Exact Method
[21]	2014	TEC	Machine states and TOU	Metaheuristic
[22]	2015	Maximum tardiness and TEC	Speed adjustment	Exact Method
[23]	2016	TEC	TOU and Speed adjustment	Exact Method
[24]	2016	Makespan and TEC	TOU	Exact Method
[25]	2016	TEC	TOU	Exact Method
[26]	2016	Makespan and TEC	TOU	Heuristic
[27]	2016	TEC	TOU	Heuristic
[28]	2016	Total tardiness and TEC	Setups	Exact Method
[29]	2017	Maximum tardiness and TEC	Machine states	Exact Method
[30]	2017	Total earliness and TEC	Machine states and TOU	Exact Method and Heuristic
[31]	2017	TEC	Machine reliability	Exact Method and Metaheuristic
[32]	2017	Weighted total tardiness	Speed adjustment	Metaheuristic
[33]	2017	Makespan and TEC	Machine states and TOU	Heuristic
[34]	2018	Total flow time and CO_2 emission	CO_2 emission	Metaheuristic
[35]	2018	Total tardiness and TEC	TOU	Metaheuristic
[36]	2018	Makespan and TEC	TOU	Exact Method and Heuristic
[37]	2019	Weighted earliness/tardiness and TEC	TOU	Metaheuristic
[38]	2019	Total tardiness and TEC	Machine reliability	Metaheuristic
[39]	2019	TEC	Machine states and TOU	Exact Method
[40]	2019	TEC	Machine states and TOU	Exact Method
[41]	2019	Total tardiness and TEC	Machine states	Metaheuristic
[42]	2019	TEC	TOU	Exact Method
[43]	2019	Makespan and TEC	TOU	Metaheuristic
[44]	2019	Total tardiness and TEC	Energy storage	Machine Learning
[45]	2020	TEC	Machine states and TOU	Metaheuristic
[46]	2020	Makespan and TEC	TOU	Metaheuristic
[47]	2020	Weighted total tardiness and TEC	TOU	Metaheuristic
[48]	2021	Total tardiness and TEC	Speed adjustment	Metaheuristic
[49]	2021	Weighted cost and TEC	Machine reliability	Simulated Annealing
[50]	2021	TEC and Production cost	TOU	Heuristic
[51]	2022	TEC	TOU and Speed adjustment	Metaheuristic
[52]	2022	Makespan and TEC	Energy storage	Metaheuristic
[53]	2022	Total tardiness and TEC	Setups	Metaheuristic
[54]	2022	Tardiness and Noise pollution	Noise	Metaheuristic Algorithm
[55]	2022	Total tardiness and TEC	Machine states	Metaheuristic
[56]	2022	Total tardiness and TEC	TOU	Metaheuristic
[57]	2023	Makespan and TEC	TOU	Metaheuristic
[58]	2023	Cost	Machine states and Speed adjustment	Exact Method and Heuristic
[59]	2024	TEC	TOU	Exact Method
[60]	2025	TEC	TOU	Exact Method and Heuristic

Table 5: Articles used for the SGSP review

Ref.	Year	Objective Function	Stochastic parameter	Environmental Characteristic	Manuf. Env.	Solution approach
[61]	2016	CO_2 emission and Makespan	Amplitude and magnitude of energy	Sustainable energy storage	1	Interval number theory
[62]	2019	Makespan and TEC	Processing time	Speed adjustment	F	Heuristic
[63]	2020	Makespan and TEC	Processing time	Speed adjustment	F	Metaheuristics
[64]	2020	Makespan and TEC	Processing time	Sustainable energy storage	F	Heuristic
[65]	2021	TEC	Arrival and cancellation of orders	TOU	F	Metaheuristics
[66]	2023	Makespan and TEC	Processing time	Speed adjustment	Pm	Heuristic
[67]	2023	Profit	Processing time	CO_2 emission	1	Machine learning
[68]	2024	TEC	Amplitude and magnitude of renewable energy	TOU and Renewable energy	F	Stochastic Programming
[69]	2024	Minimize total delay and TEC	Processing time	Machine states	O	Heuristic

Note: 1: Single machine; F: Flow shop; Pm: Parallel machine; O: Open shop.

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