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Contributions to new variants of the open shop scheduling problem: modeling and solution methods

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RESUMO

Esta tese de doutorado teve como objetivo estudar o problema de programação open shop com aplicações em setores industriais e de serviços. Foram observadas restrições essenciais, que se tornaram novas variantes para o problema, como o estudo de reprocessamento ou repetição de operações no processo produtivo e a entrega de produtos por meio de roteamento de veículos. O objetivo foi a minimização do makespan. Foram propostos métodos heurísticos para resolver esses problemas, como técnicas construtivas, meta-heurísticas bioinspiradas e métodos de programação matemática, como programação linear inteira e por restrições e mateheurísticas. Para os testes computacionais, os métodos foram executados com dados robustos de instâncias clássicas da literatura adaptadas nas restrições dos problemas em consideração e novas instâncias propostas durante o estudo. Os resultados mostraram que os métodos exatos e aproximados propostos forneceram soluções de qualidade com eficiência computacional e foram competitivos em comparação com os métodos da literatura.

PALAVRAS CHAVE. Modelagem matemática. Algoritmos de aproximação. Algoritmos populacionais.

Tópicos: PM - Programação Matemática; MH - Metaheurísticas; POI - PO na Indústria.

ABSTRACT

This doctoral dissertation aimed to study the open shop scheduling problem with many applications in the industrial and services areas. We observed essential constraints for the described environment, which became new variants for the problem as the study of reprocessing or repetition of operations in the production process and the delivery of products through vehicle routing. The objective was the makespan minimization. We proposed heuristic methods for modeling and solving these problems, such as constructive techniques, bio-inspired meta-heuristics, and mathematical programming methods, such as integer linear programming and constraint programming models and matheuristics. For the computational tests, we ran the methods with robust data from classical literature instances adapted to the constraints of the problems under consideration and new instances proposed during the study. The results showed that the proposed exact and approximate methods provided quality solutions with computational efficiency and were competitive compared to the literature methods.

KEYWORDS. Mathematical modeling. Approximation algorithms. Population algorithms.

Paper topics: PM - Mathematical Programming; MH - Metaheuristics; POI - OR in Industry.

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1. Introduction

The industrial environment is developing at a fast rate. Such changes are represented by the increasing levels of production provided by the constant technological advancement of methods and processes related to operations management. The production processes are becoming more specific and detailed, which allows them to operate on a large scale with personalized demands or demands with more flexibility [Framinan et al., 2014].

In order to maintain the required production level in the industry, quantitative methods should be created and applied to support decision-making processes to achieve greater effectiveness of production systems, hence ensuring that the demands required of industry are delivered in the best possible way.

This doctoral dissertation aimed at proposing models and solution approaches for new emergent variants of the open shop scheduling problem (OSSP). The problem is not so covered in the literature of scheduling when compared to other classical problems in the area [Ahmadian et al., 2021]. The objective is to minimize the total scheduling duration (makespan), using for solving the problem: exact methods, such as mixed-integer linear and constraint programming models (MILP and CP models), and approximate methods, such as constructive heuristics, metaheuristics, and matheuristics.

Despite the theoretical and practical importance of the open shop, contributions in the literature to new variants of the problem are limited. These limitations are highlighted in some recent literature reviews on production scheduling problems with setup costs [Allahverdi, 2015], blocking constraints [Hall and Sriskandarajah, 1996; Miyata and Nagano, 2019], integrated scheduling and distribution problems [Wang et al., 2015] and on open shop problems [Adak et al., 2020; Ahmadian et al., 2021]. These are the most recent gaps in the open shop literature.

In summary, the main motivation for this study was that there are few studies in the open shop problem literature with different industrial applications, such as machine blocking and operations repetitions characteristics. In addition, the need for more efficient methods for solving the open shop in the current literature was also a research motivation, as shown in the most recent open shop literature reviews [Adak et al., 2020; Ahmadian et al., 2021].

The doctoral dissertation aimed to study the open shop production scheduling problem, considering its classical structure, together with emerging variants, based on characteristics of production scheduling in complex industrial environments, such as explicit and sequence-dependent setup times; repetition of operations; zero buffer or machine blocking constraints and job delivery by vehicle routing. In each variant, the objective was to minimize the makespan.

Each of the following five objective/section in this summary document corresponds to a new study or variant of the open shop explored, which is equivalent to a chapter in the doctoral dissertation and a published article.

1. Implementation of new constructive heuristics to solve the classical open shop problem, comparing it with seminal heuristics such as priority rules and constructive heuristics presented in the literature;

2. Proposition of matheuristic techniques with the proposed constructive heuristics, mixed-integer linear programming, and constraint programming to solve the variant of the problem with setup times, considering randomly generated instances from the literature. Comparing the algorithms with the main state-of-the-art solving methods;

3. Proposition of a formal definition for the open shop problem with machine blocking and develop mathematical models of integer and constrained programming and hybrid exact methods to solve the problem.

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4. Study the open shop scheduling problem, considering the possibility of repetition of operations, demonstrating properties of the problem, and developing exact and approximate solving methods;

5. Study the open shop problem, integrating the scheduling and distribution of orders by capacitated single vehicle and using exact methods and bio-inspired metaheuristics for the problem's solution;

2. New efficient heuristics for scheduling open shops with makespan minimization

In this chapter, several efficient constructive heuristics that exploit some specific properties of the OSSP, such as operations idleness and lower bound, were proposed. An extensive computational experience using problem instances taken from the related literature was conducted to assess the performance of the proposed algorithms compared to existing ones with respect to the quality of the solutions and the CPU time required.

In summary, a new beam search and cheapest insertion procedures hybridized with new constructive heuristics were developed. Finally, an efficient local search algorithm (LS) that leads to excellent results within an admissible computational effort was proposed. The extensive computational tests show the excellent performance of the heuristics proposed, resulting in the one of best heuristics for the classic problem.

3. A new hybridization of adaptive large neighborhood search (ALNS) with constraint programming for open shop scheduling with sequence-dependent setup times

In this chapter, a new hybridization of an ALNS with a CP model as a local search phase was presented to solve the open shop scheduling with non-anticipatory sequence-dependent setup time. ALNS-CP used an heuristic based in operations idleness proposed in the classic OSSP study as initial solution. An MILP model is also presented based on the classic open shop model, and a new CP model was proposed considering proprieties of the non-anticipatory setup times.

The proposed CP model has not been addressed in the revised literature and outperforms all other exact methods. Many approximations and exact algorithms to obtain high-quality solutions in acceptable computational times were tested. The extensive computational experience shows that the proposed hybridization of metaheuristic and constraint programming as a matheuristic approach with improvement heuristics type is promising for solving large-sized instances.

4. A new two-stage constraint programming approach for open shop scheduling problem with machine blocking

In this chapter, a variant of the open shop scheduling problem is considered in which the intermediate storage is forbidden among two adjacent production stages (zero buffer or machine blocking constraint). Since this is an NP-hard problem, a two-stage constraint programming approach was proposed as a new exact method.

Computational results point to the ability of the proposed method to solve large-sized instances in comparison with the developed MILP model and a simple CP model, both with user cuts. In all set of instances, the proposed two-stage with CP method performed better than benchmarking methods and a two-stage integer programming model implemented for comparisons purposes.

5. A new variable neighborhood search (VNS) with constraint programming search strategy for open shop scheduling problem with operation repetitions

In this chapter, a new variant for the open shop scheduling problem, the open shop scheduling problem with repetitions (OSSPR), where the jobs can be processed on any machine more than once (operation by operation) was presented. Thereby, all the jobs can be scheduled in

an unconstrained way, substantially increasing the number of feasible solutions in comparison with the classical open shop. The OSSPR has many applications in automotive and maintenance actives.

To solve the problem, a MILP model was presented and a new CP model was proposed. A new efficient VNS is also proposed using variable search strategies through the proposed constraint programming model. Computational results show very good performance of the proposed metaheuristic on the instances tested.

6. A new efficient biased random key genetic algorithm (BRKGA) for open shop scheduling with routing by capacitated single vehicle and makespan minimization

In this chapter, the open shop scheduling problem with routing by a capacitated single vehicle (OSSP-VRP) was proposed in attention to scheduling problems integrating production environments and distribution systems to adopt more realistic assumptions. The study presented a MILP model and a new BRKGA with an Iterated Greedy (IG) local search procedure to solve the problem.

BRKGA-IG has a new decoding scheme for OSSP-VRP solutions, an intensive exploitation mechanism with an iterated greedy local search procedure, and a restart mechanism to reduce premature population convergence. With these new mechanisms, the extensive computational experience carried out showed that the proposed metaheuristic BRKGA-IG was promising in solving large-sized instances for the new proposed problem, outperforming all other tested methods.

7. Summary, main results, publications and awards of the doctoral dissertation

In summary, Figure 1 illustrates the integration between the doctoral dissertation's five objectives (each one of five papers illustrated in previous sections), the articles, and the methodologies and tools used in each article. In addition, Figure 1 shows the contributions of each article and what methods were used to achieve the main objectives of the doctoral dissertation.

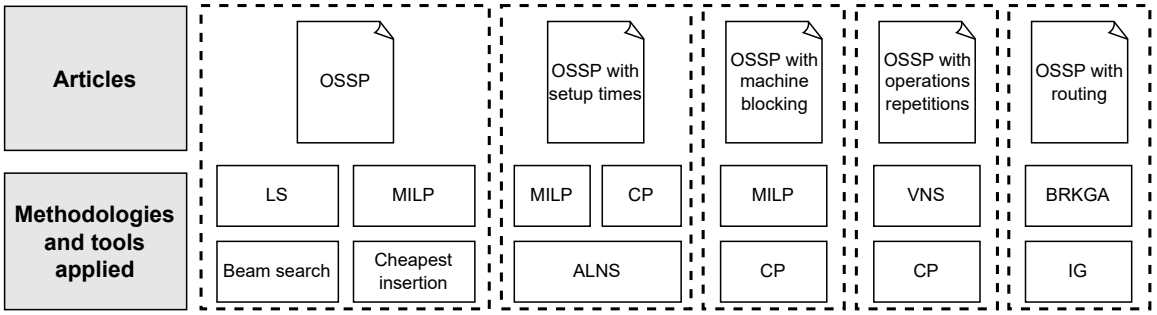


Figure 1: Summary of proposed article-based doctoral dissertation.

The doctoral dissertation resulted in thirteen sub-products, all already published as articles in high-impact international journals, national and international conferences, software registrations, and awards at international and national conferences.

The following subtopics describe each sub-products developed. We obtained the Qualis Capes metrics from `https://sucupira.capes.gov.br/sucupira/`. We reached the Journal Citation Report (JCR) indicators from `https://jcr.clarivate.com/jcr/home`. We collected the number of papers' citations of each article from the Google Scholar database up to May 6th, 2024.

In summary, the sub-products of the doctoral dissertation are:

- Six publications as first author in Qualis A1 international journals.
- One publication as first author in an international Qualis A2 journal.

- One publication as first author in a national conference.
- One publication as first author in an international conference.
- Two certificates of computer software registration (computer software patent) by developing visual and iterative solvers for production scheduling problems in the open shop environment.
- One award for best paper (honorable mention) at an international conference.
- One award for best doctoral dissertation at a conference given by a national association of industrial engineering.

7.1. Publications in international journals

Qualis A1 - JCR 8.0 - Engineering Applications of Artificial Intelligence (2021) - Citations: 33

Abreu, L. R., Tavares-Neto, R. F., & Nagano, M. S. (2021). A new efficient biased random key genetic algorithm for open shop scheduling with routing by capacitated single vehicle and makespan minimization. *Engineering Applications of Artificial Intelligence*, 104, 104373. Link: https://doi.org/10.1016/j.engappai.2021.104373.

This article refers to chapter three of the doctoral dissertation and proposes a new two-stage method for solving the open shop scheduling problem with machine blocking. The classic open shop problem (without blocking constraint) is solved in the first stage using the MILP model solver. In the second stage, the result is used as an initial and partial solution for the complete CP model solver (with blocking constraint), which is then solved.

Qualis A1 - JCR 9.2 - International Journal of Production Research (2022) - Citations: 2

Abreu, L. R., Nagano, M. S., & Prata, B. A. (2022). A new two-stage constraint programming approach for open shop scheduling problem with machine blocking. *International Journal of Production Research*, 61(24), 8560-8579. Link: https://doi.org/10.1080/00207543.2022.2154404.

This article refers to chapter three of the doctoral dissertation and proposes a new two-stage method for solving the open shop scheduling problem with machine blocking. The classic open shop problem (without blocking constraint) is solved in the first stage using a basic CP model solver. In the second stage, the result is used as an initial and partial solution for the complete CP model solver (with blocking constraint), which is then solved.

Qualis A1 - JCR 7.9 - Computers & Industrial Engineering (2022) - Citations: 16

Abreu, L. R., & Nagano, M. S. (2022). A new hybridization of adaptive large neighborhood search with constraint programming for open shop scheduling with sequence-dependent setup times. *Computers & Industrial Engineering*, 168, 108128. Link: https://doi.org/10.1016/j.cie.2022.108128.

This article refers to chapter two of the doctoral dissertation, which develops a new competitive ALNS method hybridized with a CP model for solving the open shop problem with sequence-dependent setup times. The new CP model improves in solving time and quality compared to the CP models already presented in the literature.

Qualis A1 - JCR 4.6 - Computers & Operations Research (2022) - Citations: 16

Abreu, L. R., Prata, B. A., Framinan, J. M., & Nagano, M. S. (2022). New efficient heuristics for scheduling open shops with makespan minimization. *Computers & Operations Research*, 142, 105744. Link: https://doi.org/10.1016/j.cor.2022.105744.

This article corresponds to chapter one of the doctoral dissertation and proposes new constructive and improvement heuristics for solving the classic open shop problem with makespan minimization. An extensive computational analysis was carried out, and several of the proposed

heuristics outperformed the traditional ones in the literature. In addition, the new heuristics proposed served as a competitive initial solution for the resolution methods proposed for the other open shop variants in the doctoral dissertation.

Qualis A1 - JCR 10.0 - Swarm and Evolutionary Computation (2022) - Citations: 3

de Abreu, L. R., de Athayde Prata, B., Gomes, A. C., Braga-Santos, S. A., & Nagano, M. S. (2022). A novel BRKGA for the customer order scheduling with missing operations to minimize total tardiness. *Swarm and Evolutionary Computation*, 75, 101149. Link: `https://doi.org/10.1016/j.swevo.2022.101149`.

The article implements an adaptation of the BRKGA proposed in chapter five of the doctoral dissertation in a new order scheduling problem with missing operations to minimize total tardiness. The problem is based on the real-world industrial problem of physical-chemical analysis scheduling for product release in pharmaceutical quality control laboratories. In addition, the order scheduling problem is a special case of the open shop, in which the same job (product samples) can be processed at the same time on different machines [Lee, 2013].

Qualis A1 - JCR 4.6 - Computers & Operations Research (2023) - Citations: 3

Abreu, L. R., Prata, B. A., Nagano, M. S., & Framinan, J. M. (2023). A constraint programming-based iterated greedy algorithm for the open shop with sequence-dependent processing times and makespan minimization. *Computers & Operations Research*, 160, 106386. Link: `https://doi.org/10.1016/j.cor.2023.106386`.

The article introduces a new IGA hybridized with the CP model proposed in chapter two of the doctoral dissertation in a new variant of the open shop, considering sequence-dependent processing times. The method developed achieved competitive performance when compared to the traditional IGA.

Qualis A2 - JCR 2.7 - Engineering Optimization (2021) - Citations: 19

de Abreu, L. R., Araújo, K. A. G., de Athayde Prata, B., Nagano, M. S., & Moccellin, J. V. (2021). A new variable neighbourhood search with a constraint programming search strategy for the open shop scheduling problem with operation repetitions. *Engineering Optimization*, 54(9), 1563-1582. Link: `https://doi.org/10.1080/0305215X.2021.1957101`.

This article refers to chapter four of the doctoral dissertation, which deals with developing a VNS hybridized with a CP model designed for the new variant of the open shop, considering the repetition of operations. The problem is based on the real-world problem of scheduling maintenance in automotive garages, where vehicles can carry out different operations in the same space (repetition of operations on the same machine or resource).

7.2. Publications in international conference proceedings

ICPR 2022 - 11th International Conference on Production Research Americas (2022)

Abreu, L. R., Prata, B. A., Framinan, J. M., & Nagano, M. S. (2022, November). Integer and Constraint Programming Formulations for the Open Shop Scheduling Problem with Sequence-Dependent Processing Times. *In 11th International Conference on Production Research* (pp. 76-83). Cham: Springer Nature Switzerland. Link: `https://doi.org/10.1007/978-3-031-36121-0_9`.

7.3. Publications in national conference proceedings

SIMPEP 2021 - XXVIII Simpósio de Engenharia de Produção (2021)

Abreu, L. R., & Nagano, M. S. (2021, Novembro). Novas heurísticas construtivas para o Problema de programação da produção Em ambiente open shop. *No XXVIII Simpósio de Engenharia de Produção: Como preparar as novas gerações para os desafios do século XXI*. UNESP-Câmpus de Bauru. Link: `https://www.simpep.feb.unesp.br/abrir_arquivo_pdf.php?tipo=artigo&evento=16&art=226&cad=27165&opcao=com_id`.

7.4. Certificates of computer software registration

Registered computer software - Registration number: BR512024000879-9 - Registration date: 18/03/2024

Patente: Programa de Computador. Número do registro: BR512024000879-9, data de registro: 18/03/2024, título: "Sistema de apoio à decisão baseado em heurísticas construtivas para a programação da produção em ambiente open shop com minimização da duração total da programação" , Instituição de registro: INPI - Instituto Nacional da Propriedade Industrial. Link: https://ufcbr-my.sharepoint.com/:b:/g/personal/levi_abreu_ufc_br/EZh-sjSLUcRKjH63LYIRfioBLNpF-pFGHRjbSlwMy-Hakw?e=egmzeo.

- GitHub project page: https://github.com/levirabreu/DSS_ConstructiveHeuristics_OSSP.
- Download link: https://github.com/levirabreu/DSS_ConstructiveHeuristics_OSSP/releases/tag/Latest.

The software is an open shop scheduling problem solver for makespan minimization with an automatic Gantt chart illustration of the solution. The algorithm used to solve the problem is the Minimal Idleness Heuristic with cheap InSerTion procedure [MIH-IST] (see the article by Abreu et al. [2022]). Some features of the decision support system are the selection of the time horizon in numerical or date and time format and the possibility to edit the processing times for each machine-job operation in the processing time matrix. The new processing times must be integers with a single space delimiter.

Registered computer software - Registration number: BR512024000925-6 - Registration date: 21/03/2024

Patente: Programa de Computador. Número do registro: BR512024000925-6, data de registro: 21/03/2024, título: "Sistema de apoio à decisão baseado em algoritmos genéticos para a programação da produção em ambiente open shop com roteirização de veículos e minimização da duração total da programação" , Instituição de registro: INPI - Instituto Nacional da Propriedade Industrial. Link: https://ufcbr-my.sharepoint.com/:b:/g/personal/levi_abreu_ufc_br/EXmqiKVwnLNFgOQX7fe26cAB3u6GOnClErUiIXAfTr6YDg?e=yTqJF5.

- GitHub project page: https://github.com/levirabreu/DSS_GeneticAlgorithm_OSSP_with_routing.
- Download link: https://github.com/levirabreu/DSS_GeneticAlgorithm_OSSP_with_routing/releases/tag/Latest.

The software is an open shop scheduling problem with routing by a capacitated single vehicle comand line solver for makespan minimization. The algorithm used to solve the problem is the BRKGA (see the article by Abreu et al. [2021]).

7.5. Awards won in conferences

International Congress Award - ICPR 2022 - 11th International Conference on Production Research Americas (2022) - BEST PAPER AWARD Special Mention

Best Paper Award ICPR Americas 2022 (Special Mention) with the paper "Integer and constraint programming formulations for the open shop scheduling problem with sequence-dependent processing times", Research Award Committee ICPR Americas. Link: https://ufcbr-m

y.sharepoint.com/:b:/g/personal/levi_abreu_ufc_br/Efct73nwUUtMp1bJJe-pGucBUjRmmvbbUC4ATay2DRobwA?e=ly7k9N.

National Congress Award - ENEGEP 2023 - XLIII Encontro Nacional de Engenharia de Produção (2023) - Prêmio ABEPRO Tese de Doutorado

Prêmio ABEPRO de melhor tese de doutorado com o trabalho ”Contributions to new variants of the open shop scheduling problem: modeling and solution methods”, Comitê Científico - Associação Brasileira de Engenharia de Produção. Link: https://ufcbr-my.sharepoint.com/:b:/g/personal/levi_abreu_ufc_br/EUuffFzkd_pJqwdjtVyKtAwBXA69GHt25zDx41WC3WUFwA?e=E7OFdS.

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