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Modeling a Flexible Flow Shop Scheduling Problem without Unemployment by Considering Sequence-Dependent Preparation Times and Solving it with a Meta-Heuristic Algorithm

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ABSTRACT

In this paper, the scheduling of the flexible flow shop scheduling problem without unemployment is considered by considering the sequence-dependent preparation times with parallel and identical machines in each workstation in order to minimize the maximum completion time that has been done so far. The assumption of the existence of sequence-dependent preparation times has not been observed in the literature on the issue of flexible workflow without unemployment. In this study, a mixed integer programming model for the problem is first developed. Since the problem under study is one of the NP-hard problems and the mathematical model solving software is not able to obtain the optimal solution of relatively large problems at a reasonable time, to provide a meta-heuristic method of genetic algorithm to obtain optimal solutions or close to optimal for the problem. The computational results show the relatively good performance of the genetic algorithm for solving problems in less time than the mathematical programming model.

Keywords: Flexible Flow Shop, Sequence-Dependent Preparation, Genetic Algorithm, Programming Model

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1. INTRODUCTION

Production scheduling focuses on the allocation of limited resources over time to carry out a group of different activities. In the scheduling theory, resources and tasks are often known as machines and jobs, respectively (Ab Yajid, 2020; Thanh *et al.*, 2021; Jalil *et al.*, 2020; Matthews and Mokoena, 2020). Some of the most important objectives of scheduling problems include the efficient use of resources, quick response to demand and accurate compliance of delivery times with the specified delivery date (Qazani *et al.*, 2021; Shamsipur *et al.*, 2012; Tirkolaee *et al.*, 2020). A flexible flow shop scheduling problem is a developed form of general flow shop environments and parallel machines, where C stations are arranged in series instead of m machines, such that m_1 equal machines are parallel to each other in each station of $(L = 1, 2, \dots, c)L$. Each task must be performed by one machine (one of the parallel machines) in each station, even though all machines can carry out the process (Barzamini and Ghassemian, 2019; Johar and Alkawaz, 2018; Alhodiry *et al.*, 2021). In other words, each job is performed by one of the parallel machines in station 1, and then by one of the equal parallel machines in station 2 and ultimately by one of the equal machines in the last station. In some machine environments in operating environments, unemployment of a machine between the processing operations of two jobs makes that machine environment or manufacturing industry unfeasible and uneconomical. This is one of the important aspects of industries such as fiberglass manufacturing, casting, production of integrated circuits, steel manufacturing industries, dairy industries, textile industries, paint industries, among others (Dahmardeh *et al.*, 2013; Sholpanbaeva *et al.*, 2021; Nursalim, 2021). This is known as a non-permutation flowshop scheduling problem (NPFSP), where the unemployment of machines is not allowed from the beginning of the first job to the end of the last job. Therefore, delay in the commence of jobs must occur in a way that the constraints related to the unemployment of each machine (i.e., idle time) are guaranteed to be zero. Two preparation processes are carried in scheduling problems to prepare the machines for jobs. In the first mode, preparation time is sequence-independent, meaning that preparation time is considered during the processing of the work by the machine. In the second mode, however, machine preparation time depends on the task that has been already processed by the machine (Fofack *et al.*, 2020; Jaapar *et al.*, 2020; Wafa, 2021; Alwreikat and Rjoub, 2020). Observed in most machine environments, the second preparation mode is recognized as sequence-dependent preparation time in the literature on scheduling issues. The present study aims to model a flexible flow shop scheduling problem without unemployment by considering sequence-dependent preparation times in order to minimize the maximum completion time of works. To date, no research has been conducted to consider such an issue in flow shop problems (Alsunki *et al.*, 2020; Singh *et al.*, 2020; Kormishkina *et al.*, 2021; Ishenin *et al.*, 2021). The remainder of the study is structured, as follows: Section 2 reviews the literature related to the topic under study while Section 3 defines the problem and the model's premises. Section 4 provides the mathematical modeling of the problem, whereas Section 5 focuses on the validation of the proposed mathematical model by LINGO software, solves the proposed problem using genetics algorithm (GA) and compares its quality and solution time with the mentioned software. Finally, Section 6 concludes and makes suggestions for future studies.

2. LITERATURE REVIEW

Bernik (2021) were the first scholars who evaluated NPFSPs for the first time. In a study, they proposed a polynomial algorithm for a flow shop problem in a certain mode with two machines with the objective function of minimizing the total completion time of works. Ferina *et al.* (2021) studied an NPFSP with the objective function of minimizing the maximum completion time for the first time and proposed a branch-and-bound procedure for solving the problem. In a study, Narain and Bagga (2005) focused on n-job, 2-machine flow shop scheduling problems working under a "no-idle" constraint. They developed a branch-and-bound structure to solve the model and considered the objective function to be the minimization of mean flow shop. In the end, it was proven that the problem with the objective function of the total makespan of works was of NP-hard type.

Saadani *et al.* (2003) treated the scheduling problem of three-stage permutation flow-shop configuration with no-idle machines. The idle characteristic is a very strong constraint, which can seriously affect the value of the makespan criterion. They proposed a heuristic to solve this problem with O(nlogn) complexity. Based on the previous study, Kamburowski (2004) identified a simple network representation of the makespan that provided a better insight into the problem and improved the solution obtained for the no-idle flow shop problem. Saadani *et al.* (2005) investigated a no-idle flow shop problem, for which they proposed a mixed integer programming model and then developed a heuristic based on the idea that the problem could be modeled as a traveling salesman problem. In a study, Kalczynski and Kamburowski (2005) focused on the problem of finding a job sequence that minimizes the makespan in m-machine flow shops under the no-idle condition. Since the problem was NP-hard, they proposed a constructive heuristic for solving the problem that significantly outperformed heuristics known so far. Niu and Gu (2006) developed an improved genetic-based particle swarm optimization for no-idle permutation flow shops with fuzzy processing time. Goncharov and Sevastyanov (2009) considered a flow shop problem with no-idle constraints and the objective function of minimizing the makespan of jobs. These researchers developed several polynomial-time heuristics for special cases of 3 and 4 machines based on the geometric method. Nagano and Januário (2013) evaluated a no-idle flow shop scheduling problem with the objective of minimizing the makespan.

Tasgetiren *et al.* (2013) presented a variable iterated greedy algorithm (IG) with differential evolution designed to solve the no-idle permutation flow shop scheduling problem. The parameters of the algorithm included the destruction size and the probability of applying the IG algorithm to an individual. Pan and Ruiz (2014) studied the mixed no-idle extension where only some machines had the no-idle constraint. They used an NEH-based heuristic to construct a high-quality initial solution. Sun and Gu (2017) proposed a novel hybrid estimation of the distribution algorithm and cuckoo search (CS) algorithm to solve the NIPFSP with the total tardiness criterion minimization. The computational results indicated the proper performance of the hybrid algorithm presented in the foregoing study. Yazdani and Naderi (2016) considered the problem of scheduling no-idle hybrid flow shops. They developed a mixed-integer linear programming model to mathematically formulate the problem with the objective function of minimizing the maximum completion time of tasks. In the end, two metaheuristics based on variable neighborhood search and GAs were developed to solve larger instances. The computational results were indicative of the superior performance of GA.

Nagano *et al.* (2019) addressed the issue of production scheduling in a no-idle flow shop environment and proposed a quality constructive heuristic instance following an extensive review of the literature. According to their results, integration of the heuristic method with the IG algorithm led to the higher efficiency of heuristic methods. Goli *et al.* (2019) developed a mathematical model for scheduling manufacturing systems, where AGV was used for the transportation of parts. Improved GA was applied to solve the scheduling problem in the mentioned condition. The literature review revealed a lack of study on the hypothesis of sequence dependence of preparation times in NIPFSPs with the objective function of minimizing the maximum completion time of jobs, which is addressed in the present research.

3. STATEMENT OF THE PROBLEM AND PREMISES

The NPFSP is developed from a flexible flow shop problem, where the machines are not allowed to be idle from the commence of the first job until finishing the last job. Therefore, delays in the start of jobs must occur in a way that the constraints related to the unemployment of each machine are guaranteed to be zero. The preparation times in the problem assessed are sequence-dependent. The evaluated problem is exhibited in the form of $FSS|no-idle,SDST|C_{max}$ based on the symbolizing by Graham *et al.* (1979) which express the NPFSP with sequence-dependent preparation times. The objective function is to minimize the maximum makespan of jobs. The following premises are considered for the problem:

The preparation time of machines is sequence-dependent. The idle time of the machine is equal to zero (there is no idle interval between the commence of the first job until finishing all tasks). There are parallel and similar machines in each stage (workstation). Notably, simultaneous performance of two operations of a job is not feasible. In other words, each task at each stage (station) should only be processed on one of the parallel and identical machines. There is no interruption- i.e., a task remains on the machine until its processing is completed. There is no cancelation during the tasks, meaning that if an operation of a job is being processed, the next operations must also be processed. The transportation time between the machines is trivial, and there is unlimited storage between stations. Each machine is unable to process more than one job at a time. In addition, technical constraints are recognized and inflexible, and there is no stochastic mode, meaning that the processing times, preparation times and the number of jobs have crisp values. There is no downtime and machines are constantly available during the programming period.

4. MATHEMATICAL MODELING OF THE PROBLEM

The indices used for modeling the problem are defined below:

4.1 Indices and Sets

n : number of jobs
j, i : index of jobs $j, i = \{1, 2, \dots, n\}$
m : number of stages (stations)
k : index of stages (stations) $k = \{1, 2, \dots, m\}$
m_k : number of machines at the k stage
l : index of the machine at the k stage $l = \{1, 2, \dots, m_k\}$
h : index of the sequence of jobs on each machine $h = \{1, 2, \dots, h_k\}$

4.2 Model Parameters

p_{ik} : processing duration of the i-th job at the k stage

SUP_{ijk} : preparation time of the j-th job if the j-th job is immediately processed after the i-th job in the k stage. Given the similarity of machines at each stage, this parameter is independent of the machine index.

M : a big positive number

4.3 Decision Variables

C_{max} : maximum completion time of jobs

X_{ijklh} : a binary variable; 1, if the j-th job is placed in the h position in the l machine immediately after the i-th job in the k stage and the j-th and i-th jobs are placed in the h and h-1 positions, respectively; otherwise, 0.

R_{iklh} : a binary variable; 1, if the i-th job is placed in the h position of the l machine at the k stage; otherwise, 0.

S_{ik} : the start time of processing the i-th job at the k stage

SB_{klh} : the start time of processing a job that is placed in the h position of the l machine at the k stage.

4.4 Mathematical Model

4.4.1 Objective Function

$$\text{minimize } C_{max} \tag{1}$$

4.4.2 Constraints

$$\sum_{h=1}^{h_k}\sum_{l=1}^{m_k} R_{iklh} = 1 \qquad \forall_{i,k} \tag{2}$$

$$\sum_{i=1}^{n} R_{iklh} \le 1 \qquad \forall_{k,l,h} \tag{3}$$

$$X_{ijklh} = R_{iklh-1} \times R_{iklh}; \qquad \forall_{i\neq j,k,l,h>1} \tag{4}$$

$$S_{ik} \ge S_{i,k-1} + P_{i,k-1}; \qquad \forall_{k>1,i} \tag{5}$$

$$SB_{ik} \le (1 - R_{iklh}) \times M + SB_{klh}; \ \forall_{i,k,l,h} \tag{6}$$

$$SB_{klh} \le (1 - R_{iklh}) \times M + S_{ik}; \quad \forall_{i,k.l.h} \tag{7}$$

$$SB_{klh} = SB_{klh-1} + \sum_{i=1}^{n} R_{iklh-1} \times P_{i,k} + \sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n} X_{ijklh} \times SUP_{ijk} \quad \forall_{k,l,h>1} \tag{8}$$

$$C_{max} \ge S_{ik} + \sum_{h=1}^{h_k}\sum_{l=1}^{m_k} R_{iklh} \times P_{ik}; \qquad \forall_{i,k} \tag{9}$$

$$S_{ik} \ge 0; \qquad \forall_{i,k} \tag{10}$$

$$SB_{klh} \ge 0; \qquad \forall_{k,l,h} \tag{11}$$

$$C_{max} \ge 0; \qquad \forall_{i,k} \tag{12}$$

$$R_{ijklh} = \{0,1\} \quad ; \qquad \forall_{i,k,l,h} \tag{13}$$

$$X_{ijklh} = \{0,1\} \quad ; \qquad \forall_{i\neq j,k,l,h>1} \tag{14}$$

4.5 Model Description

In this model, Equation 1 is the objective function of the problem, which minimizes the maximum completion time of jobs. Constraints 2 and 3 guarantee that the operations of each job at each station are placed in a position of the sequence of jobs on the machine. Constraints 4 means that the X_{ijklh} the variable is equal to one if the j-th job is placed in the sequence of jobs on the l machine at the k stage following the i-th job and if the j-th and i-th jobs are placed in h and h-1 positions, respectively. Otherwise, it will be zero (in other words, the variable of X_{ijklh} will be equal to one when the variables of R_{jklh} and $R_{jkl,h-1}$ are both equal to one). In addition, the mentioned constraints make the model nonlinear, and linearization of the model is addressed in the next stage. Constraints 5 tune the start time of processing each job on each workstation. In other words, a job will not be processed in a station until its processing is completed in the previous station. Constraints 6 and 7 are defined for tuning the start time of processing each job in each station and the start time of jobs on the machines. Constraints 8 is defined for tuning the start time of jobs on each machine of stations. These constraints are added to the model to determine the start time of jobs on the machine and indicate that the processing of the j-th job cannot be initiated until the processing of the previous job is not finished and the preparation time of the j-th task, which depends on the previous i-th job, is not passed. In addition, the equal sign guarantees the no-idle hypothesis (machine unemployment occurs when the start time of the current job is larger than the finish time of the previous job plus the preparation time. However, using equality in the constraints will prevent idle time. Meanwhile, the sequence-dependent preparation times between the jobs existing in the sequence will be calculated and applied). Constraints 9 calculate the objective function, which is minimizing the completion time of jobs. Finally, constraints 10-14 determine the nature of the decision variables of the model.

5. Solution method

5.1 Model linearization

Constraints make the model nonlinear due to the existence of a multiplication sign between the decision variables. Therefore, Constraints 4 are replaced by constraints 15 and 16 to develop a linear model (Meng and Pan, 2021).

$$X_{ijklh} + 1 \geq R_{ikl,h-1} + R_{jklh}; \qquad \forall_{i \neq j,k,l,h>1} \qquad (15)$$

$$2 \times X_{ijklh} \leq R_{ikl,h-1} + R_{jklh}; \qquad \forall_{i \neq j,k,l,h>1} \qquad (16)$$

In the next section, the mathematical model is solved by LINGO software at small scales, followed by presenting GA to solve the problems and compare the solution time and quality of LINGO software to the GA which is described as follows.

5.2 Proposed Genetic Algorithm

From the 1960s onward, there has been an extensive development of modeling living creatures' behaviors to increase the robustness of the existing algorithms or create new algorithms for optimal problem-solving. In short, algorithms developed based on this type of thinking are recognized as evolutionary algorithms, one of the most popular of which is the GA. This nature-inspired algorithm is widely applied in various problems. The GA is an evolved search method based on natural selection and genetics, which uses a structured but random approach to exploit genetic data in pursuit of new search routes. GA is applied in a wide range of scientific fields. The algorithm is developed and used in the present study to optimize the proposed mathematical model.

Since the problem presented in the research encompasses two sections of: A) allocating jobs to machines at each stage, and B) determining the sequence of jobs allocated to each machine at each stage, the solution of the problem is displayed in the form of a matrix with K rows and N columns (K is the number of stages and N is the number of jobs). Each tow shows the sequence of jobs at each stage. The matrix has a value in the range of zero-one. First, the numbers in each row are divided by the number of parallel machines available. For instance, if there are two parallel machines in the first stage, numbers in the range of 0-0.5 will be allocated to the first machine and numbers in the range of 0.5-1 will be assigned to the second machine. Similarly, if there are three parallel machines, numbers in the ranges of 0-0.333, 0.333-0.666, 0 and 1, and 0.666-1 will be allocated to the first-third machines, respectively. The same process is carried out for a higher number of machines. Afterwards, the jobs assigned to each machine are arranged from small to large. This, in fact, shows the sequence of jobs on each machine. For instance, assume that N=5, K=2, and M=[23], meaning that there are two machines in the first stage and three machines in the second stage. The example solution strand of the problem is shown in Table 1.

Table 1. Example solution with five jobs and two stages

0.04	0.941	0.271	0.331	0.675
0.295	0.491	0.694	0.225	0.844

The order of jobs in the first stage is, as follows:
1-3-4
5-2
In the second stage, the order of jobs is, as follows:
4-1
2
3-5

The fit function considered for each chromosome of each generation is equal to the value of the objective function or Cmax, and the initial population is generated by producing a uniform random number between 0 and 1. Some of the most common parent selection methods are the Roulette wheel, the random method, the ranking method, and the competitive selection method. In this article, the parent selection process is completely random for the crossover due to the nature of GA, which is based on a random search. There are several methods for the crossover operator in chromosomes that use the numbers zero and one and integers. In this regard, some of the conventional methods are listed below:

One-point crossover, two-point crossover, multipoint crossover, uniform crossover, three-parent crossover, PPX crossover, and sorted crossover. Other crossover techniques are used in chromosomes in which real numbers are used for coding. In this regard, one of these methods is the intermediate propagation method, in which the value of the child variable is a linear combination of parent variables (Equation 17).

$$\begin{aligned} x_1^0 &= \lambda_1 x_1 + \lambda_2 x_2 \\ x_2^0 &= \lambda_1 x_2 + \lambda_2 x_1 \end{aligned} \qquad (17)$$

where X2 and X1 are parent variables, X’2 and X1 are child variables and $\lambda 2, \lambda 1$ are linear coefficients.

$$\lambda_1, \lambda_2 \geq 0$$

Crossover operations are often implemented on a percentage of the population. A coefficient of 0.8 or 80% is considered for the problem under study. In this article, the crossover is carried out in intermediate propagation or linear combination form. First, a parameter named Landa is randomly generated in the range of [-0.2 1.2]. Afterwards, the linear combination of two parents is calculated and introduced as children. It is notable that if the cell’s value is higher than one, it will be changed to one, and if it is less than zero, it will be changed to zero. In the problem of the present study, 20% of chromosomes are changed by the mutation operator. This value is obtained due to choosing an 80% coefficient for the crossover operator. To carry out the mutation process, we select 20% of the cells on each chromosome (response strand) and change their value randomly. If 20% of the number of cells is not an integer, it will be rounded to the nearest multiple of five. The mechanism of survival selection is such that children produced better than the parents are