Flexible Job-Shop Scheduling Problem with Sequencing Flexibility for Just-In-Time Production Systems

Alejandro Vital-Soto and Jessica Olivares-Aguila
Shannon School of Business
Cape Breton University
Sydney, NS, B1P 6L2, Canada
alejandro_vital@cbu.ca, jessica_olivares@cbu.ca

Abstract

Scheduling in a flexible job-shop environment is a crucial task that allows the smooth flow of materials. Traditionally, this problem considers a predetermined sequence of operations and due dates to deliver the jobs. In this paper, a new formulation of the Flexible Job-Shop Scheduling problem is presented. In the proposed model, flexible sequences for the jobs are allowed to enable more alternatives for scheduling. Additionally, just-in-time approach is considered in order to complete each job. Hence, the problem allocates operations to machines and sequence them according to precedence relationships. Moreover, jobs' deliveries need to be on time to satisfy customer's requirements and reduce storage costs. Therefore, a mixed-integer linear programming model is formulated to minimize the sum of weighted earliness and weighted tardiness simultaneously. The model is implemented in a numerical experiment to show its applicability. The proposed model is intended to be used in production systems that are just-in-time oriented.

Keywords
Flexible job-shop scheduling, Sequencing flexibility, Just-in-Time, Earliness and Tardiness.

1. Introduction

Manufacturing organizations looking to remain competitive in the environment look for strategies to provide product variety at the required time. Hence, different production systems have emerged to gain a competitive advantage. For instance, in Just-in-Time (JIT) systems, work-in-process movement during production and deliveries is carefully timed. Consequently, products are not sitting in the inventory, as they are delivered when they are needed. These deliveries cannot occur in advance as they would generate storage costs, and not after, they would cause customer dissatisfaction and probably a financial penalty.

Moreover, manufacturing settings have changed to allow production flexibility. In a Flexible Job Shop (FJS), several machines have the capability of processing each operation. Additionally, some product designs will enable the production processes to produce a job that does not follow a linear sequence of operations. Hence, this kind of product where job operations with no precedence constraints between them could offer the possibility of flexible sequencing (Birgin et al. 2015).

In the literature, many works have been dedicated to studying the Flexible Job Shop Scheduling problem (FJSP), just a few to the FJSP with sequencing flexibility and to the best of our knowledge, no paper has simultaneously studied the FJSP with sequencing flexibility and JIT considerations (FJSPS-JIT). Therefore, this paper considers the FJSP with sequencing flexibility and JIT deliveries. A mixed-integer linear programming (MILP) model is introduced to address the problem, and it is implemented in a numerical model to show its applicability.

The rest of the paper is organized as follows. In section 2, a literature review of the most representative studies is presented. In section 3, the problem definition and mathematical formulation are described. In section 4, the implementation and results of the model in a numerical example are presented. Finally, in section 5, conclusions and future research work are outlined.

2. Literature Review

The literature related to the FJSP has been growing since the 1990s. The FJSP was first presented by Brucker and Schlie (1990) as an extension of the classical job-shop scheduling problem (JSP). Unlike the JSP, in the FJSP, several machines are capable of producing each operation. Two simultaneous decisions are considered in the FJSP; the routing problem considers the allocation of operations to a machine out of a set of capable machines, and the scheduling problem or sequencing problem in which the sequence of all operations is given according to a defined precedence (Brandimarte 1993).

Due to the importance of the FJSP in real-case settings, a large growing body of literature has been investigated different perspectives of the problem. Therefore, various solution techniques have been implemented, for instance, mathematical models (Kim and Egbelu 1999; Thomalla 2001; Lee et al. 2002), metaheuristics (Pezzella et al. 2008; Xing et al. 2010) and hybrid techniques (Kacem et al. 2002; Li and Gao 2016). Furthermore, several extensions to the FJSP have been examined to represent more realistic situations.

The FJSP has been studied to optimize different objectives such as makespan, tardiness, total workload, etc. According to Chaudhry and Khan (2016), the minimization of makespan is the most common objective. However, makespan does not reflect the general objective in a manufacturing environment where due dates have to be meet (Vital Soto 2019).

In an effort to address the drawbacks of the minimization of makespan, consideration of the cost minimization of earliness and tardiness has been explored in job shop production systems. For instance, Huang and Yang (2008) studied the JSP with time windows. They proposed the objective function to minimize the total cost due to earliness and tardiness and a solution method based on ant colony optimization. Similarly, Drobouchevitch and Sidney (2012) examined and developed an algorithm to find solutions for the scheduling problem in parallel machines. They looked to determine the due date's optimal value to minimize a total cost function that considers earliness, tardiness and due date penalties. In the same vein, Yazdani et al. (2017) proposed a MILP formulation for the JSP. They used as objective function the minimization of the sum of maximum earliness and tardiness of all jobs. Also, they designed an approximate optimization method based on the imperialist competitive algorithm hybridized with a neighbourhood search to find solutions.

In order to assign priorities to the earliness and tardiness of the deliveries, some works focused on the JSP employed as objective function the minimization of the weighted earliness and tardiness. Thiagarajan and Rajendran (2005) integrated cost-based measures of performance to evaluate the JSP. They employed the sum of weighted earliness and weighted tardiness of jobs and proposed modifications for different dispatching rules assessed in a simulation model. Likewise, Yang et al. (2012) reviewed the JSP with customers' due dates and manufacturers' deadlines. They formulated the problem to minimize the sum of the weighted earliness and weighted tardiness and developed a genetic algorithm to solve the problem.

In the FJSP literature, just a few studies have employed earliness and tardiness as the objective function. Imanipour and Zegordi (2006) addressed the minimization of total weighted earliness and tardiness in an FJSP. They formulated a MILP and metaheuristic based on Tabu search to solve the problem. Likewise, Huang et al. (2013) modelled and proposed a solution method for the FJSP with due windows. The model minimizes the sum of weighted earliness and tardiness. Zuobao and Weng (2005) presented a multiagent scheduling method that intends to minimize the total weighted earliness and tardiness in a JIT environment. In the same way, Zambrano Rey et al. (2015) analyzed the FJSP in just-in-time production. They designed a genetic algorithm and particle swarm metaheuristics to address the problem. Both approaches aimed to minimize the mean-square due date deviation, quadratically penalizing earliness and tardiness costs.

Another relevant issue in the literature is the incorporation of JIT principles in scheduling. Products that are delivered before the due date generate an inventory cost. Conversely, products delivered after the due date may cause customers' dissatisfaction and penalties (Zambrano Rey et al. 2015). Hence, earliness and tardiness costs can be considered optimal criteria aligned with JIT principles (Jozefowska 2007).

Several studies have incorporated JIT consideration in scheduling. For instance, Weng and Fujimura (2011) proposed minimizing the average job earliness and tardiness in a flexible job shop environment for JIT scheduling. They implemented a method composed of offline schedule making and online job processing control. Benmansour et al.

(2014) investigated the scheduling problem on a single machine, trying to minimize the weighted sum of maximum earliness and maximum tardiness costs for a JIT environment. They proposed a MILP for this setting and one in which they considered periodic preventive maintenance. Tirkolaee et al. (2020) proposed a MILP for a flow shop scheduling with an outsourcing option and just-in-time delivery to minimize the production system's total cost and total energy consumption. The objective function related to the production cost uses the sum of total weighted completion time plus total processing cost as an economic measure. The other objective function focuses on the minimization of total energy consumption.

In real-world applications, it has been observed that the precedence relationships between operations do not always are defined linearly or sequentially. For instance, Gan and Lee (2002) noted that flexible process plans in scheduling allow more production flexibility and give cost savings in the mould industry. They proposed a branch and bound algorithm to minimize lateness while maximizing earliness. Similarly, Alvarez-Valdes et al. (2005) studied the scheduling problem in a glass factory where different operations could be performed in a different sequence. They developed a heuristic to minimize the total cost.

As noted from real settings, the precedence relationships between operations do not always follow a sequential order. Conversely, the precedence between operations can be defined by a directed acyclic graph (DAG). Therefore, Birgin et al. (2014) introduced the FJSP with sequence flexibility. They formulated a MILP to minimize makespan and created instances based on the printing industry to implement the model. As the model provides solutions for small instances, Birgin et al. (2015) proposed a list scheduling and beam search method to minimize makespan.

In a recent study, Vital-Soto et al. (2020) formulated a MILP for the FJSP with sequencing flexibility to minimize weighted tardiness. They also developed a hybrid bacterial foraging optimization algorithm that outperformed the best integer solutions of MILP when minimizing the weighted tardiness and the classical dispatching rules.

The studies presented thus far provide evidence that research on FJSP with sequencing flexibility has received little attention. Additionally, the considerations of just-in-time deliveries have been studied but not in the FSJP with flexibility. Moreover, it has been supported the usage of the minimization of earliness and tardiness in JIT scheduling. Hence, in this paper, a MILP for the FJSP with sequencing flexibility and just-in-time deliveries (FJSPS-JIT) is introduced with the objective to minimize the sum of weighted earliness and tardiness as presented in the next section.

3. Mathematical formulation for the FJSPS-JIT

The mathematical model presented by Vital-Soto et al. (2020) was modified and extended to include the just-in-time approach.

The FJSPS-JIT studies processing n jobs on m machines. The jobs are formed with β_j total number of operations o_{jk}. An arbitrary DAG defines the precedence among the operations. Operations of each job should be assigned and sequenced on a machine. Each job j has a due date d_j. The objective is to complete the jobs on time by minimizing the sum of the weighted earliness and tardiness.

Assumptions

- Precedence relationships among the operations of different jobs are neglected.
- Machines and jobs are accessible at time zero.
- Pre-emption is forbidden.
- Setup time is neglected.

Indices

j: Index of jobs, $j = 1,2, \dots, n$;
i: Index of machines, $i = 1,2, \dots, m$;
k: Index of operations $k = 1,2, \dots, \beta_j$;

Parameters

n: number of jobs;
m: number of machines;

β_j: total number of operations of job j;
o_{jk}: operation k of job j;
p_{ijk}: processing time of operation k of job j on machine i;
$b_{jkk'}$: $\begin{cases} 1 \text{ if the operation } k \text{ precedes operation } k' \text{ for job } j \\ 0 \text{ otherwise} \end{cases}$;
d_j: due date of job j;
w_j: tardiness penalty (weight) of job j;
r_j: earliness penalty of job j;
a_{ijk}: $\begin{cases} 1 \text{ if machine } i \text{ can process the operation } k \text{ of job } j \\ 0 \text{ otherwise} \end{cases}$;
λ: big number;

Variables
x_{ijk}: $\begin{cases} 1 \text{ if operation } k \text{ of job } j \text{ is processed on machine } i \\ 0 \text{ otherwise} \end{cases}$;
c_{ijk}: Completion time of operation k of job j on machine i;
c_j: Completion time of job j;
t_j: tardiness of job j;
e_j: earliness of job j;
$y_{ijkk'}$: $\begin{cases} 1 \text{ if operation } k \text{ goes before operation } k' \text{ of job } j \text{ on machine } i \\ 0 \text{ otherwise} \end{cases}$;
$q_{ii'jkk'}$: $\begin{cases} 1 \text{ if operation } k \text{ on machine } i \text{ goes before operation } k' \text{ on machine } i' \text{ of job } j \\ 0 \text{ otherwise} \end{cases}$;
$z_{ijj'kk'}$: $\begin{cases} 1 \text{ if operation } k \text{ of job } j \text{ goes before operation } k' \text{ of job } j' \text{ on machine } i \\ 0 \text{ otherwise} \end{cases}$;

The mathematical model is given as follows:

$$\min \sum_J r_j e_j + \sum_J w_j t_j \tag{1}$$

subject to:

$$\sum_{i=1}^{m} x_{ijk} = 1 \qquad \forall\, j,k \tag{2}$$
$$c_{i'jk'} \geq c_{ijk} + x_{i'jk'} \cdot p_{i'jk'} - \lambda\left(1 - x_{i'jk'}\right) \forall\, i,i',j,k,k' : b_{jkk'} = 1, a_{ijk} = 1,\ a_{i'jk'} = 1 \tag{3}$$
$$c_{ijk'} \geq c_{ijk} + p_{ijk'} - \lambda\left(3 - y_{ijkk'} - x_{ijk} - x_{ijk'}\right) \forall\, i,j,k,k' : k \neq k' \tag{4}$$
$$c_{ijk} \geq c_{ijk'} + p_{ijk} - \lambda\left(2 + y_{ijkk'} - x_{ijk} - x_{ijk'}\right) \forall\, i,j,k,k' : k \neq k' \tag{5}$$
$$c_{i'jk'} \geq c_{ijk} + p_{i'jk'} - \lambda\left(3 - q_{ii'jkk'} - x_{ijk} - x_{i'jk'}\right) \forall\, j,k,k' : k \neq k', i,i' : i \neq i' \tag{6}$$
$$c_{ijk} \geq c_{i'jk'} + p_{ijk} - \lambda\left(2 + q_{ii'jkk'} - x_{ijk} - x_{i'jk'}\right) \forall\, j,k,k' : k \neq k', i,i' : \mathrm{i} \neq \mathrm{i'} \tag{7}$$
$$c_{ij'k'} \geq c_{ijk} + p_{ij'k'} - \lambda\left(3 - z_{ijj'kk'} - x_{ijk} - x_{ij'k'}\right) \forall\, \mathrm{i}, \mathrm{j}, \mathrm{j'} : \mathrm{j} \neq \mathrm{j'}, \mathrm{k}, \mathrm{k'} \tag{8}$$
$$c_{ijk} \geq c_{ij'k'} + p_{ijk} - \lambda\left(2 + z_{ijj'kk'} - x_{ijk} - x_{ij'k'}\right) \forall\, i,j,j' : j \neq j', k, k' \tag{9}$$
$$c_{ijk} - p_{ijk} \geq -\lambda\left(1 - x_{ijk}\right) \forall\, i,j,k \tag{10}$$
$$c_{ijk} \leq \lambda\left(x_{ijk}\right) \forall\, i,j,k \tag{11}$$
$$c_j \geq c_{ijk}\ \forall\, i,j,k \tag{12}$$
$$t_j \geq c_j - d_j\ \forall\, j \tag{13}$$
$$t_j \geq 0\ \forall\, j \tag{14}$$
$$e_j \geq d_j - c_j\ \forall\, j \tag{15}$$
$$e_j \geq 0\ \forall\, j \tag{16}$$
$$c_j = d_j - e_j + t_j\ \forall\, j \tag{17}$$

$$x_{ijk} \leq a_{ijk} \; \forall \, i, j, k \tag{18}$$
$$q_{ii'jkk'} \geq d_{jkk'} \;\; \forall \, j, k, k': k \neq k', i, i': i \neq i' \tag{19}$$
$$c_{ijk} \geq 0 \; \forall \, i, j, k \tag{20}$$
$$c_j \geq 0 \; \forall \, j \tag{21}$$
$$x_{ijk} \in \{0,1\} \; \forall \, i, j, k \tag{22}$$
$$y_{ijkk'}, q_{ii'jkk'}, z_{ijj'kk'} \in \{0,1\} \; \forall \, i, i', j, k, k' \tag{23}$$

The objective function in Eq. (1) minimizes the sum of the weighted earliness and tardiness. Inequality (2) guarantees that an operation is chosen to be processed by only one machine. Inequality (3) defines the precedence between the operations. The assurance that a machine can only process an operation at a time is given by inequalities (4) and (5). Overlapping prevention of the same job with different machines in a specific time is dictated by inequalities (6) and (7). Inequalities (8) and (9) restrict the overlapping of operations for different jobs with the same machine. Completion time is defined by inequalities (10) and (11) when an operation has been assigned to a machine. The completion time of a job is defined by inequality (12). Inequalities (13) and (14) define the tardiness of a job. Earliness of a job is defined by inequalities (15) and (16). Inequality (17) prevents earliness and tardiness to both being non-zero at the same time. Inequalities (18) and (19) are logical constraints. The different types of variables are defined by inequalities (20)-(23).

4. Experimentation

The mathematical formulation has been tested in a small instance referred to as JIT-1. JIT-1 is comprised of 4 jobs, 3 machines and several operations per job. Precedence relationships are presented in Figure 1. For instance, as can be observed from Figure 1, operations for Job 1 can be processed in two different sequences, i.e. (o_{11}, o_{12} and o_{13}) or (o_{11}, o_{13} and o_{12}).

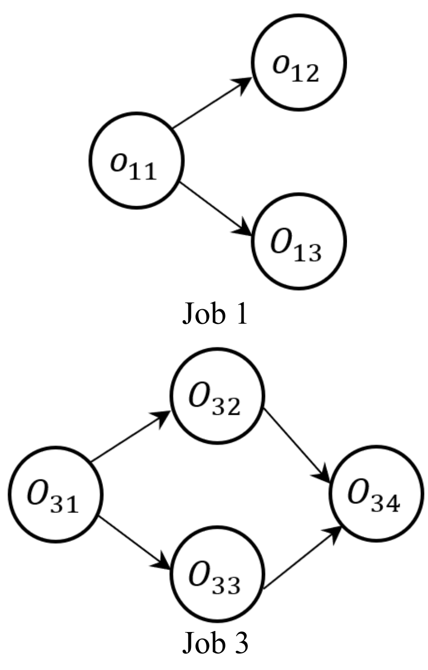

Figure 1. Precedence graphs for each job of JIT-1.

Table 1 shows the processing times (p_{ijk}) that were randomly generated from a uniform distribution with parameters (3,18). In addition to that, due dates (d_j), earliness penalties (r_j) and tardiness penalties (w_j) were randomly created using a uniform distribution with parameters (12,50), (10,15) and (10,15), respectively. For instance, in Table 1, the element "0" represents that the operations are not compatible or cannot be assigned to that machine. As an example, operation o_{11} can be processed on machine 1 ($i = 1$) and machine 3 ($i = 3$) with processing times $p_{111} = 10$ and $p_{311} = 3$. However, o_{11} cannot be processed on machine 2 ($i = 2$).

Table 1. Data for JIT-1 with four jobs and three machines.

		Machines (i)					
Jobs (j)	o_{jk}	$i = 1$	$i = 2$	$i = 3$	d_j	r_j	w_j
Job 1	o_{11}	10	0	3	27	4	3
	o_{12}	4	0	11			
	o_{13}	0	11	5			
Job 2	o_{21}	7	10	13	36	3	1
	o_{22}	0	11	0			
	o_{23}	13	6	13			
	o_{24}	9	7	0			
Job 3	o_{31}	14	3	0	29	5	4
	o_{32}	0	12	8			
	o_{33}	0	0	12			
	o_{34}	6	11	9			
Job 4	o_{41}	11	0	15	31	6	7
	o_{42}	13	0	13			
	o_{43}	0	7	7			
	o_{44}	9	15	0			

Xpress Optimizer Version 35 has been employed to implement the MILP. The experiment was performed on a PC with an Intel(R) Core (TM) i7-10510U CPU 1.80 GHz processor and 16GB of RAM. The computational time to solve JIT-1 was 1.6 seconds. In Figure 2, the objective search is presented by showing the path to the optimal solution.

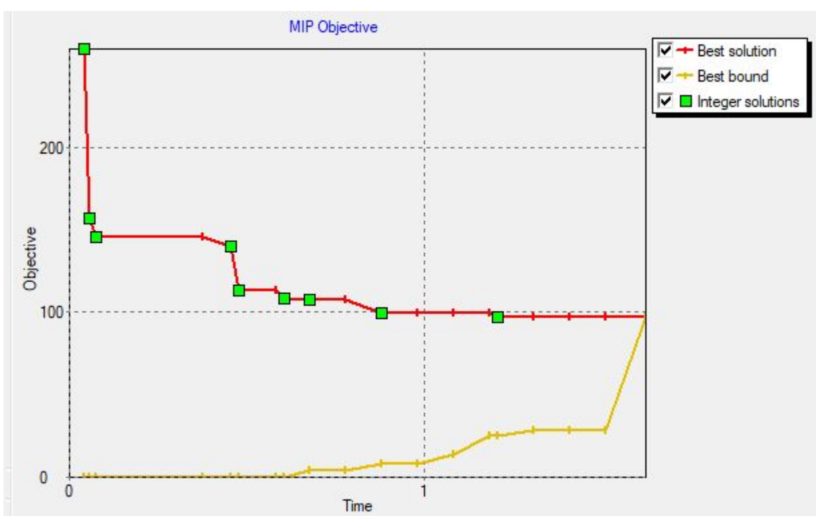

Figure 2. JIT-1 objective search for the optimal solution.

The results of the variables x_{ijk} are shown in Table 2. Additionally, in Table 3, the results regarding the completion time (c_j), earliness (e_j), tardiness (t_j) and the objective function calculation are displayed. The optimum solution provided by Xpress Optimizer is 97 units.

Table 2. $\boldsymbol{x_{ijk}}$ variables result.

		Machines ($\boldsymbol{i}$)		
Jobs ($\boldsymbol{j}$)	$\boldsymbol{x_{ijk}}$	$\boldsymbol{i=1}$	$\boldsymbol{i=2}$	$\boldsymbol{i=3}$
Job 1	x_{i11}	0	0	1
	x_{i12}	1	0	0
	x_{i13}	0	1	0
Job 2	x_{i21}	0	1	0
	x_{i22}	0	1	0
	x_{i23}	0	1	0
	x_{i24}	0	1	0
Job 3	x_{i31}	0	1	0
	x_{i32}	0	0	1
	x_{i33}	0	0	1
	x_{i34}	0	0	1
Job 4	x_{i41}	1	0	0
	x_{i42}	1	0	0
	x_{i43}	0	1	0
	x_{i44}	1	0	0

Table 3. Scheduling results.

Jobs ($\boldsymbol{j}$)	$\boldsymbol{d_j}$	$\boldsymbol{c_j}$	$\boldsymbol{r_j}$	$\boldsymbol{e_j}$	$\boldsymbol{t_j}$	$\boldsymbol{w_j}$	$\boldsymbol{w_j t_j}$	
1	27	28	3	0	1	3	3	
2	36	55	1	0	19	1	19	
3	29	32	4	0	3	4	12	
4	31	40	7	0	9	7	63	
			$\sum_J r_j e_j$	0		$\sum_J w_j t_j$	97	$\sum_J r_j e_j + \sum_J w_j t_j = 97$

A Gantt chart has been developed to present the results, as shown in Figure 2. The Gantt chart plots time against machines and displays the assignment of each operation, of each job, to the available machines.

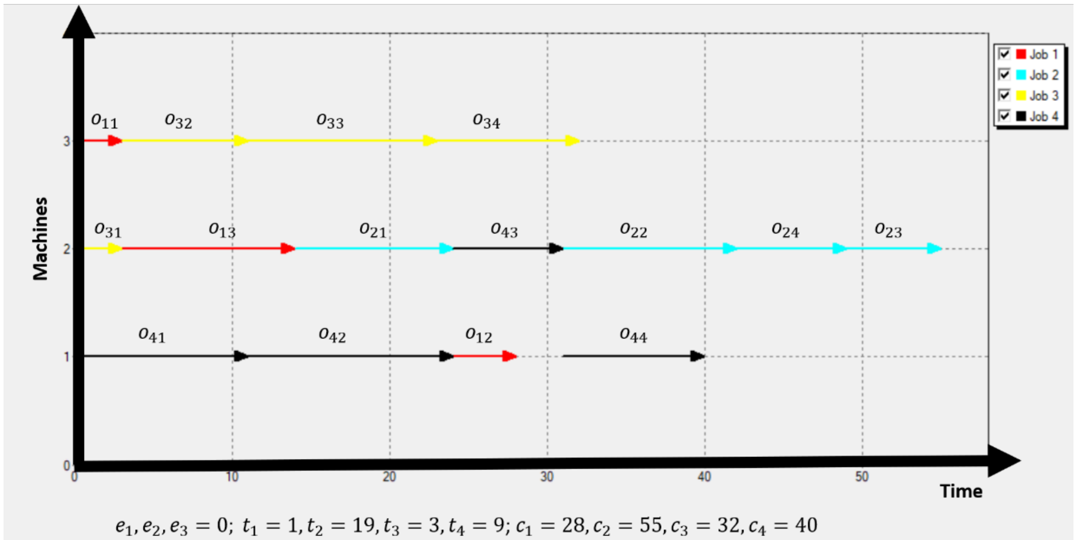

Figure 3. Gantt chart for each job of JIT-1.

From Figure 3, it is worth noting that for Job 1, the chosen sequence is (o_{11}, o_{13} and o_{12}). This validates the application of the model introduced, as the consideration of sequencing flexibility can provide better results in a JIT environment.

5. Conclusion

Fierce competition in the market has encouraged organizations to look for ways to minimize waste. In order to align with this trend, JIT scheduling helps to minimize the costs related to early and tardy deliveries. Additionally, flexible job shops allow the production of a job that may have different processing sequences. Hence, in this paper, a MILP formulation has been introduced to address the FJSP with sequence flexibility and just-in-time deliveries. The developed model minimizes the sum of weighted earliness and tardiness of the deliveries.

The model was tested in a small example, finding the optimal solution and demonstrating that the consideration of sequencing flexibility and JIT environment represent a real-world problem. The model can be used to solve small to medium instances, and it can serve for representation purposes. The model's significance relies on the inclusion of more realistic settings that many industries have and have been studied independently.

Future research avenues consider creating larger instances, implementing real scenarios, and developing a solution method for larger cases such as metaheuristics.

Acknowledgements

This work was partially funded by Cape Breton University through project number 4081046.

References

Alvarez-Valdes, R., A. Fuertes, J. M. Tamarit, G. Giménez, and R. Ramos. 2005. "A heuristic to schedule flexible job-shop in a glass factory." *European Journal of Operational Research* 165 (2):525-34. doi: https://doi.org/10.1016/j.ejor.2004.04.020.

Benmansour, Rachid, Hamid Allaoui, Abdelhakim Artiba, and Saïd Hanafi. 2014. "Minimizing the weighted sum of maximum earliness and maximum tardiness costs on a single machine with periodic preventive maintenance." *Computers & Operations Research* 47:106-13. doi: https://doi.org/10.1016/j.cor.2014.02.004.

Birgin, Ernesto G, Paulo Feofiloff, Cristina G Fernandes, Everton L De Melo, Marcio TI Oshiro, and Débora P Ronconi. 2014. "A MILP model for an extended version of the Flexible Job Shop Problem." *Optimization Letters* 8 (4):1417-31.

Birgin, Ernesto G, JE Ferreira, and Débora P Ronconi. 2015. "List scheduling and beam search methods for the flexible job shop scheduling problem with sequencing flexibility." *European Journal of Operational Research* 247 (2):421-40.

Brandimarte, Paolo. 1993. "Routing and scheduling in a flexible job shop by tabu search." *Annals of Operations Research* 41 (3):157-83. doi: 10.1007/BF02023073.

Brucker, P., and R. Schlie. 1990. "Job-shop scheduling with multi-purpose machines." *Computing* 45 (4):369-75. doi: 10.1007/BF02238804.

Chaudhry, Imran Ali, and Abid Ali Khan. 2016. "A research survey: review of flexible job shop scheduling techniques." *International Transactions in Operational Research* 23 (3):551-91. doi: https://doi.org/10.1111/itor.12199.

Drobouchevitch, Inna G., and Jeffrey B. Sidney. 2012. "Minimization of earliness, tardiness and due date penalties on uniform parallel machines with identical jobs." *Computers & Operations Research* 39 (9):1919-26. doi: https://doi.org/10.1016/j.cor.2011.05.012.

Gan, P. Y., and K. S. Lee. 2002. "Scheduling of Flexible-Sequenced Process Plans in a Mould Manufacturing Shop." *The International Journal of Advanced Manufacturing Technology* 20 (3):214-22. doi: 10.1007/s001700200144.

Huang, Rong-Hwa, and Chang-Lin Yang. 2008. "Ant colony system for job shop scheduling with time windows." *The International Journal of Advanced Manufacturing Technology* 39 (1):151-7. doi: 10.1007/s00170-007-1203-9.

Huang, Rong-Hwa, Chang-Lin Yang, and Wei-Che Cheng. 2013. "Flexible job shop scheduling with due window—a two-pheromone ant colony approach." *International Journal of Production Economics* 141 (2):685-97. doi: https://doi.org/10.1016/j.ijpe.2012.10.011.

Imanipour, N., and S. H. A. D. Zegordi. 2006. "A HEURISTIC APPROACH BASED ON TABU SEARCH FOR EARLY/TARDY FLEXIBLE JOB SHOP PROBLEMS." *Scientia Iranica* 13 (1):1-13.

Jozefowska, Joanna. 2007. *Just-in-time scheduling: models and algorithms for computer and manufacturing systems*. Vol. 106: Springer Science & Business Media.

Kacem, Imed, Slim Hammadi, and Pierre Borne. 2002. "Pareto-optimality approach for flexible job-shop scheduling problems: hybridization of evolutionary algorithms and fuzzy logic." *Mathematics and Computers in Simulation* 60 (3):245-76. doi: https://doi.org/10.1016/S0378-4754(02)00019-8.

Kim, K. H., and P. J. Egbelu. 1999. "Scheduling in a production environment with multiple process plans per job." *International Journal of Production Research* 37 (12):2725-53. doi: 10.1080/002075499190491.

Lee, Young Hae, Chan Seok Jeong, and Chiung Moon. 2002. "Advanced planning and scheduling with outsourcing in manufacturing supply chain." *Computers & Industrial Engineering* 43 (1):351-74. doi: https://doi.org/10.1016/S0360-8352(02)00079-7.

Li, Xinyu, and Liang Gao. 2016. "An effective hybrid genetic algorithm and tabu search for flexible job shop scheduling problem." *International Journal of Production Economics* 174:93-110. doi: https://doi.org/10.1016/j.ijpe.2016.01.016.

Pezzella, F., G. Morganti, and G. Ciaschetti. 2008. "A genetic algorithm for the Flexible Job-shop Scheduling Problem." *Computers & Operations Research* 35 (10):3202-12. doi: https://doi.org/10.1016/j.cor.2007.02.014.

Thiagarajan, S., and Chandrasekharan Rajendran. 2005. "Scheduling in dynamic assembly job-shops to minimize the sum of weighted earliness, weighted tardiness and weighted flowtime of jobs." *Computers & Industrial Engineering* 49 (4):463-503. doi: https://doi.org/10.1016/j.cie.2005.06.005.

Thomalla, Christoph S. 2001. "Job shop scheduling with alternative process plans." *International Journal of Production Economics* 74 (1):125-34. doi: https://doi.org/10.1016/S0925-5273(01)00119-0.

Tirkolaee, E. Babaee, A. Goli, and G. W. Weber. 2020. "Fuzzy Mathematical Programming and Self-Adaptive Artificial Fish Swarm Algorithm for Just-in-Time Energy-Aware Flow Shop Scheduling Problem With Outsourcing Option." *IEEE Transactions on Fuzzy Systems* 28 (11):2772-83. doi: 10.1109/TFUZZ.2020.2998174.

Vital-Soto, Alejandro, Ahmed Azab, and Mohammed Fazle Baki. 2020. "Mathematical modeling and a hybridized bacterial foraging optimization algorithm for the flexible job-shop scheduling problem with sequencing flexibility." *Journal of Manufacturing Systems* 54:74-93. doi: https://doi.org/10.1016/j.jmsy.2019.11.010.

Vital Soto, Alejandro Vital. 2019. "Flexible Job-shop Scheduling Problem with Sequencing Flexibility: Mathematical Models and Solution Algorithms."

Weng, W., and S. Fujimura. 2011. Study and application of scheduling method for just-in-time production in flexible job shops. Paper presented at the 2011 IEEE International Conference on Industrial Engineering and Engineering Management, 6-9 Dec. 2011.

Xing, Li-Ning, Ying-Wu Chen, Peng Wang, Qing-Song Zhao, and Jian Xiong. 2010. "A Knowledge-Based Ant Colony Optimization for Flexible Job Shop Scheduling Problems." *Applied Soft Computing* 10 (3):888-96. doi: https://doi.org/10.1016/j.asoc.2009.10.006.

Yang, Hong-an, Qi-feng Sun, Can Saygin, and Shu-dong Sun. 2012. "Job shop scheduling based on earliness and tardiness penalties with due dates and deadlines: an enhanced genetic algorithm." *The International Journal of Advanced Manufacturing Technology* 61 (5):657-66. doi: 10.1007/s00170-011-3746-z.

Yazdani, Maziar, Aldeida Aleti, Seyed Mohammad Khalili, and Fariborz Jolai. 2017. "Optimizing the sum of maximum earliness and tardiness of the job shop scheduling problem." *Computers & Industrial Engineering* 107:12-24. doi: https://doi.org/10.1016/j.cie.2017.02.019.

Zambrano Rey, Gabriel, Abdelghani Bekrar, Damien Trentesaux, and Bing-Hai Zhou. 2015. "Solving the flexible job-shop just-in-time scheduling problem with quadratic earliness and tardiness costs." *The International Journal of Advanced Manufacturing Technology* 81 (9):1871-91. doi: 10.1007/s00170-015-7347-0.

Zuobao, Wu, and M. X. Weng. 2005. "Multiagent scheduling method with earliness and tardiness objectives in flexible job shops." *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)* 35 (2):293-301. doi: 10.1109/TSMCB.2004.842412.

Biographies

Alejandro Vital-Soto is an Assistant Professor of Operations Research and Management Science in the Shannon School of Business at Cape Breton University, Canada. He earned a B.S. in Industrial Engineering from the University of Puebla (BUAP), Mexico and a Master of Science in Industrial Engineering from the University of the Americas Puebla (UDLAP), Mexico. He received his Ph.D. in Industrial and Manufacturing Systems Engineering at the University of Windsor, Canada. His research interests include production scheduling, lot-sizing, process planning and reconfigurable manufacturing systems.

Jessica Olivares-Aguila is an Assistant Professor of Supply Chain Management in the Shannon School of Business at Cape Breton University, Canada. She earned a B.S. and a Master of Science in Industrial Engineering from the University of the Americas Puebla (UDLAP), Mexico. She received her Ph.D. in Industrial and Manufacturing Systems Engineering at the University of Windsor, Canada. Her research interests include supply chain management and design, product design and manufacturing systems.