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IFAC PapersOnLine 55-10 (2022) 1613–1618

A Matheuristic based on Ant Colony System for the Combined Flexible Jobshop Scheduling and Vehicle Routing Problem ⋆

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Abstract: Nowadays, market behavior and globalization mean that end consumers are waiting very quickly for their orders to be delivered. This context forces companies to have high availability of finished products. For this reason, the industries that make up the supply chains are obliged to implement strategies to meet this customer need. One efficient practice is the integration of production and transportation activities. In the literature, few research works integrate the scheduling of production tasks with the vehicle routing. This paper aims at proposing a solution approach for the combined problem. The production system configuration is defined as a flexible jobshop, while the distribution problem is modeled as a vehicle routing problem. The proposed approach consists of two parts. First, production makespan is minimized through a hybrid algorithm based on ant colony system and local search. Then, the routing problem is solved optimally using mathematical programming in order to minimize the total travel time. Benchmark instances from the literature are adapted to deal with the combined problem. Experimental results show the effeciency and effectiveness of the proposed algorithm.

Keywords: Flexible jobshop, Vehicle Routing Problem, Ant Colony, Metaheuristic, Local Search, Mixed Integer Linear Programming.

1. INTRODUCTION

In globalized complex production systems, decisions regarding production and transportation are tradionally made separately, generating inefficiencies from both economic and client loyalty perspectives (Díaz-Madroñero et al., 2017). The rise of e-commerce thanks to current technological and production management paradigms (e.g., the Internet, Just-in-Time, etc.) does make customers to expect great speed for the processing and delivery of their orders. This context forces companies to have high availability of finished products (Ballou, 2004). This increase in inventory levels does not allow taking into account their impact on logistics costs of the product (Mentzer et al., 2001), which can be about 30% of the product's final cost (Min and Zhou, 2002; Thomas and Griffin, 1996), in addition to transportation and inventory holding, that may represent about 50-66% of the total logistics costs, according to empirical studies (Ballou, 2004).

In the search of alternatives that allow obtaining a balance between customer satisfaction and logistics costs, the integration of production and transport activities in the design of supply chains has become an important factor for success, in regard to both operational and competitive dimensions (Abreu et al., 2021). By doing so, it is possible to achieve a reduction in total operating costs of between 3% and 20% (Solina and Mirabelli, 2021). Traditionally, scientific literature has approached production scheduling and transportation planning activities independently of each other, ignoring their mutual impacts, requirements, and restrictions. However, in recent years interest has been generated in performing these activities in an integrated manner (Kumar et al., 2020). The literature has witnessed this integration in real world systems, such as furniture manufacturing (Mohammadi et al., 2020), consumer electronics (Li et al., 2008), perishable products (Armstrong et al., 2008; Geismar et al., 2008; Liu and Liu, 2020; Viergutz and Knust, 2014), newspapers (Chiang et al., 2009; Russell et al., 2008; Russell, 2013), and chemotherapies (Kergosien et al., 2017).

Building in those previous works, this paper aims to propose a solution approach for the integrated production scheduling and transportation problem. The configuration of the production system is defined as a flexible jobshop, while the distribution problem requires the design of transportation routes modeled as a vehicle routing problem. The integrated scheduling-routing problem is solved using a metaheuristic procedure. To the best of our knowledge, the current work is the first in the academic literature that approaches such a scheduling configuration together with vehicle routing.

This paper is organized as follows. Section 2 reviews the academic literature related to the problem under study. The problem itself is formally described in Section 3. The proposed solution approach is detailed in Section 4, while the results of computational experiments are presented in Section 5. The paper concludes in Section 6 and outlines some opportunities for future research.

⋆ Supported by School of Engineering Universidad de La Sabana.

10.1016/j.ifacol.2022.09.621

Table 1. Summary of related works.

Publication	Scheduling	Vehicle routing problem						Objective function			
		TSP	Infinity fleet	Heterogeneous fleet	Homogenous fleet	Capacitated vehicle	Time windows	Multi-Objective	Cost	Regular criteria	Ecological
Mohammadi et al. (2018)	**FSP**			✓		✓				✓	
Yagmur and Kesen (2020)	**FSP**	✓				✓				✓	
Chevroton et al. (2021b)	**FSP**			✓					✓		
Chevroton et al. (2021a)	**FSP**				✓	✓			✓		
Ehm et al. (2016)	**HFS**			✓		✓			✓	✓	
Martins et al. (2021)	**HFS**	✓				✓				✓	
Wang et al. (2016)	**HFS**		✓	✓		✓			✓		
Ehm and Freitag (2016)	**HFS**	✓				✓				✓	
Lacomme et al. (2016)	**HFS**	✓				✓				✓	
Wang et al. (2020)	**FSP**		✓		✓				✓		
Rahman et al. (2021)	**HFS**			✓		✓			✓		
Zeddam et al. (2020)	**HFS**			✓		✓	✓	✓	✓		
Basir et al. (2018)	**FS**		✓		✓	✓			✓		
Lee and Chen (2001)	**FS**				✓	✓				✓	
Abreu et al. (2021)	**OP**	✓				✓				✓	
Meinecke and Scholz-Reiter (2014)	**JS**				✓	✓			✓		
Liao and Wang (2019)	**JS**						✓		✓		✓
Qin et al. (2021)	**HFS**		✓							✓	
Mohammadi et al. (2020)	**FJS**			✓		✓	✓	✓	✓	✓	
This paper	**FJS**	✓	✓							✓	

2. RELATED LITERATURE

The integration of production scheduling and vehicle routing decisions has increased over the last few years, with most of works studying single stage production systems with one machine or parallel machines in the production stage. Literature review papers are proposed by Díaz-Madroñero et al. (2017); Kumar et al. (2020); Moons et al. (2017). Some works have studied production systems with multiple stages (see Table 1). Majority of such works focused flowshops (FSP) or hybrid flowshops (HFS), while few works have studied openshops (OP), jobshops (JS) and flexible jobshops (FJS). Table 1 also highlights the different characteristics of such problems in regards to the vehicle routing stage, and the objective function under study.

3. PROBLEM DESCRIPTION

In the classical jobshop scheduling problem (JS) a set of n production orders $B = \{B_1, \ldots, B_n\}$. The set of operations required to process each B_i are represented as $S_i = \{O_{i,1}, \ldots, O_{i,s}\}$. Each operation $O_{i,j}$ has to be processed on a set M of m machines that are always available for processing. Each machine can only process one operation at a given time. Each production order has a fixed processing route, which may be different from the others.

The disjunctive graph is used to describe the main features and model the JS. Dauzère-Pérès and Paulli (1997) defines the disjunctive graph for JS as $G = (V, A, E)$, where V is the set of nodes, A the set of conjunctive arcs and E the set of disjunctive arcs. Within the set V of nodes, there are all the operations $O_{i,j}$ of the problem, a node 0 indicating the batch release date and n nodes θ_i indicating the completion date of each batch. Figure 1 deepens the concept of the disjunctive graph for the JS. In this figure, we can see all its components of the disjunctive graph; for example, the set E is represented as the dotted lines connecting a pair of nodes in both directions. Also in the figure 1, the set A is represented as the continuous lines connecting two pairs of operations belonging to the same order.

In the flexible jobshop configuration (FJS), the machine required to execute operation $O_{i,j}$ is not provided in advance, instead, it must be selected from a subset $R_{O_{i,j}} \subseteq M$ of eligible machines. Therefore, the processing time $P_{O_{i,j}}$ of operation $O_{i,j}$ depends on the selected machine from $R_{O_{i,j}}$. The processing of a production order cannot be interrupted once started.

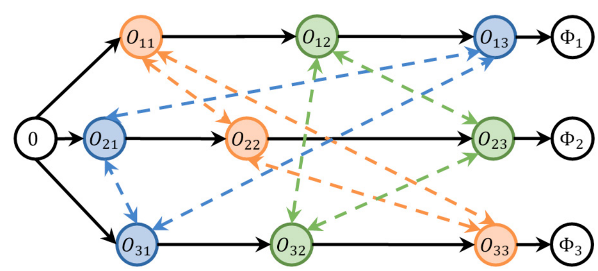

Fig. 1. Disjunctive graph

Once each production order is finished, it is shipped in trucks with unlimited capacity. The fleet of trucks is infinite. Trucks leave the factory every two hours and load the finished orders before starting their respective delivery route. The first vehicle is shipped two hours after the production phase of the first batch is completed. For the last trip, the truck leaves once the production of the last order has been completed.

Each production order B_i is composed of a set of products $B_i = \{J_{i,1} \ldots J_{i,n}\}$. All products J_i must be delivered to a customer with a known location. Without lost of generality, we consider that the vehicle must return to the factory once the delivery route has been finished. Therefore, the order delivery problem can be solved multiple times as a traveling salesman problem (TSP). In addition, each route includes a trip start time H_i, a total trip time D_i and the delivery time of the last order CR_i. The longest delivery time CR_{Max} is defined as $\max\{CRi\} \forall i \in R$.

In the TSP model, there is a set of n clients that we call nodes and a set of routes between each coordinate called arcs. Let $G' = (V', A')$ be a complete undirected graph, where $V'(1 \ldots n)$ is the set of nodes, and A' is the set of arcs connecting each pair of nodes. Each arc has a nonnegative integer value $C_{l,h}$ that represents the time that a vehicle travels from node l to node h. To determine the travel time from one customer to another, the travel speed is needed.

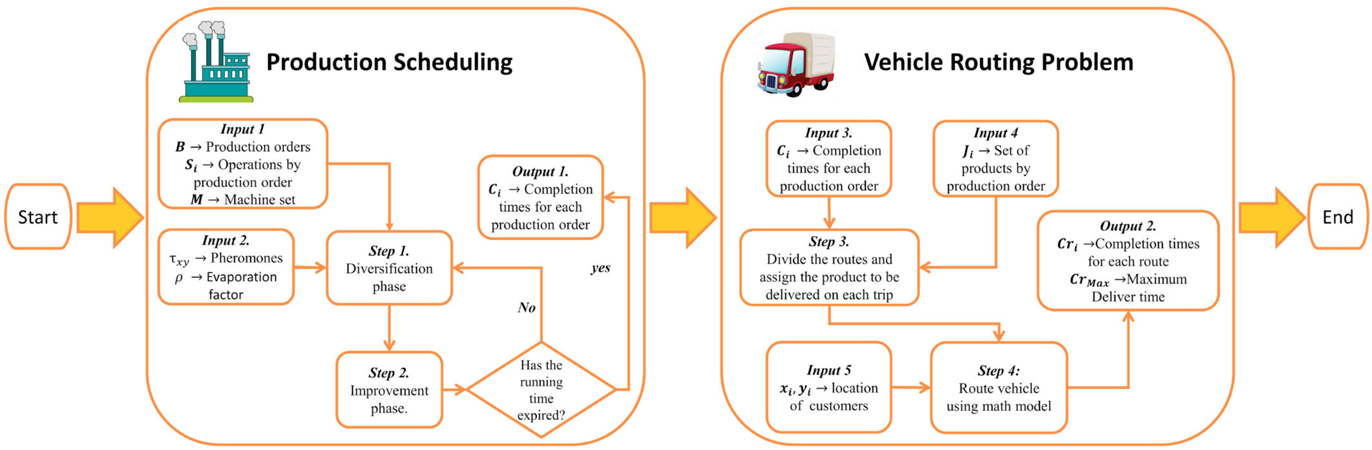

Fig. 2. Proposed solution approach

4. PROPOSED SOLUTION APPROACH

This paper proposes the solution approach shown in figure 2 to solve the FJS-TSP. This solution approach starts from an input data set containing the set of production orders B, the set of machines M and the set of products S_i. To minimize the makespan in the FJS, an algorithm coupling ant colony system and local search has been designed. This algorithm is explained in detail in the section 4.1. Once the runtime of the hybrid algorithm is finished, the solution for the production stage, including the completion times for each production order C_i are obtained. Based on these C_i, the routes are divided and solved using the mathematical model explained in section 4.2. Finally, the completion times of each route are obtained and the maximum delivery time is calculated. The proposed solution procedure belongs to the family of matheuristic algorithms since it couples a hybrid metaheuristic with mathematical programming.

4.1 Production Scheduling

To solve the production scheduling problem, we propose a hybrid algorithm that consists of two phases. The first one is the diversification phase and the second one is the improvement phase. The diversification phase is based on the ant colony system algorithm and inspired by García-León and Torres Tapia (2020). In this algorithm, each ant $k \in K$ constructs a feasible solution in parallel. Each ant k finds each machine production route by tracking the artificial pheromones; to this end, k must solve the disjunctive arcs of each machine by using equation (1), which represents the probability of selecting an arc $x \rightarrow y_i$ that belongs to the set of possible feasible solutions Y, where τ_{xy_i} represents the pheromones of the arc, v the visibility of the path, i is the set index of possible connections to the operation x, V is defined as $\frac{1}{w}$, where w is the starting time of operation y_i, and finaly, α and β represent the coefficient preference. When $\alpha > \beta$ means that the algorithm is based on its history (pheromones), otherwise it is based on the start time of the operation.

$$P^k_{xy_i} = \frac{(\tau_{xy_i})^{\alpha}(v_{xy_i})^{\beta}}{\sum_{\forall i \in Y}(\tau_{xy_i})^{\alpha}(v_{xy_i})^{\beta}} \ \forall i \in I \tag{1}$$

$$\tau_{xy} = (1-\rho)\tau_{xy} + \Delta\tau^{Best}_{xy} \tag{2}$$

$$\Delta\tau^{Best}_{xy} = \begin{cases} \frac{1}{M_{best}}, & \text{if the arc } (x,y) \in \text{Best ant} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

Once all k ants finish building their respective solution, the ant with the lowest makespan K_{best} is selected. Next, the pheromones of all the xy arcs are updated using equation (2), where ρ represents the evaporation percentage, and $\Delta\tau^{Best}_{xy}$ is defined as the operation that appends pheromones to the arcs that belong to the K_{best} solution (see equation (3)). The number of pheromones added to the K_{best} arcs is calculated as $\frac{1}{M_{best}}$, where M_{best} is the Makespan of k_{best}. Finally, K_{best} is the initial solution of the improvement phase.

The improvement phase is composed of the hill descent algorithm. To implement this algorithm, we use the neighbourhood N_2 proposed by García-León et al. (2019), which focuses on moving the operations belonging to the critical route of the batches that affect the value of the criterion to be optimized (i.e., makespan). Based on the efficiency demonstrated by Taillard (1994) in which inverting arcs is a feasible move, we have used this and the estimation functions proposed by Mati et al. (2011). When the improvement phase is over, the algorithm is returned to the diversification phase until the end of the allotted running time.

4.2 Vehicle Routing Problem

In this phase, the starting time of each route is first established. Next, the production orders are assigned to the corresponding vehicle. After that, to calculate the shortest delivery route for each trip, we use a mixed-integer programming model to minimize the total travel time. This mathematical model is presented next. Binary decision variables are defined as $X_{l,h} = 1$ if the route connects node (i.e., client) l with node (i.e., client) h, and 0 otherwise, representing weather the arc between client l and h is used in the tour. Auxiliary variables u_l is defined as the number of nodes visited until node l; it is used to guarantee subtour elimination.
Objetive function

$$min\ f = \sum_{\forall l \in N} \sum_{\forall h \in N} C_{l,h} X_{l,h} \tag{4}$$

Subject to,

$$\sum_{\forall l \neq h} X_{l,h} = 1 \quad \forall l \in N \tag{5}$$

$$\sum_{\forall h \neq l} X_{l,h} = 1 \quad \forall l \in N \tag{6}$$

$$u_l + 1 - u_h + (n-1)(1 - X_{l,h}) \leq n - 2 \quad \forall\, l,h \in N \tag{7}$$

The objective function is shown in equation (4) and minimizes the tour time. Constraints (5) and (6) are equilibrium equations and represent that the vehicle must enter and exit all nodes only once. Finally, Constraints (7) is employed to calculate U_i.

5. COMPUTATIONAL EXPERIMENTS

The proposed solution approach was run on a PC with 4.1 GHz, 4 cores and 20 GB RAM. Since there are not benchmark instances available in the literature for the problem under study, experiments were carried out by adapting the datasets from Hurink et al. (1994) for the flexible jobshop problem and datasets from Solomon (1987) for the vehicle routing stage.

The mathematical model proposed in section 4.2 was coded in Python using the Gurobi 9.1.2 optimiser and the CPLEX 20.10 solver. On the other hand, the hybrid algorithm proposed in section 4.1 was coded in Java and run for 100 seconds per instance. The parameters related to the elitist ant colony were definded to be four ants performing the search in parallel, an evaporation factor of 6% and an initial pheromone level of 0.35. Additionally, in order to divide the routes, it was established that each vehicle starts its delivery every 2 hours from the factory.

For each instance evaluated in this computational experiment, table 2 shows the number of machines available, the number of production orders and the number of products that make up each order. For the flexible jobshop, we present the makespan obtained and the seconds needed to solve with the proposed hybrid algorithm. For the vehicle routing problem, the number of customers and the number of routes are presented. Finally, the calculated CR_{Max} and the computation time needed to solve the problem are shown.

The results obtained in table 2 show that for the instances containing 5 and 3 machines the algorithm is highly efficient and the biggest gap with respect to the best known solution (BKS) is 2.1%. For the instances with 10 machines and 10 production orders the algorithm has an efficiency varying from 0.8% and 3.2%. In case of larger instances, the algorithm obtains an efficiency of minimum 8% and maximum 12%.

Similarly, for the vehicle routing problem it is deduced that the number of orders influences the total number of routes needed to cover the delivery. Finally, it is concluded that the makespan represents between 50% and 75.5% of CR_{Max}.

6. CONCLUSIONS

This paper proposed an approach to solve the combined problem of flexible jobshop scheduling and vehicle routing. Based on the analysis of current academic literature, this integrated problem has not yet been extensively analyzed, thus this paper is one of the first contributions. To solve the scheduling problem, a hybrid ant colony-iterated local search algorithm is proposed. The vehicle routing problem in the second stage is solved using mathematical programming as a multiple traveling saleman problem (TSP) with each vehicle starting deliveries every given number of hours.

Computational experiments were carried out using created benchmark instances inspired from the literature for each independent problem. The objective function is coposed of the makespan for production and the total travel time for the distribution. Results showed the efficiency of the proposed solution approach.

After the findings of this paper, several opportunities for further research are identified. For instance, several sets of parameters of the metaheuristic can be tested, followed by the design of a solution procedure dealing with integrated problem (not sequentially). It would also be interesting to formulate a multi-objective algorithm, to minimize for example the maximum delivery time and routing costs. In addition, other constraints could be added to the problem, such as time windows, machine blocking, setup times, capacity of vehicles, etc.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by a postgraduate scholarship from the School of Engineering Universidad de La Sabana, Colombia, awarded to the first author. Part of this work was carried out while the second author was Visiting Professor at COSYS-GRETTIA Université Gustave Eiffel, France.

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Table 2. Results of computational experiments

Production								Transport			Total	
Instance	Number of prod. ord.	Number of machines	Number of prod. per order	Makespan	BKS	GAP (%)	CPU-Time (Seconds)	Total customers	Total routes	CPU- Time (Seconds)	CR_{max}	CPU time total (Hours)
TMR0	4	3	5	990	990	0,0%	0,48	20	2	1,37,E-01	1369	0,00
TMR1	10	5	5	609	609	0,0%	1,03	50	4	4,41,E+03	1014	1,23
TMR2	10	5	5	655	655	0,0%	39,69	50	3	3,42,E+01	867	0,02
TMR3	10	5	5	559	550	1,6%	307,29	50	2	1,00,E+04	934	2,86
TMR4	10	5	5	568	568	0,0%	44,56	50	2	2,00,E+04	932	5,57
TMR5	10	5	5	503	503	0,0%	0,89	50	3	1,00,E+04	918	2,78
TMR6	15	5	5	833	833	0,0%	1,84	75	3	1,51,E+04	1412	4,19
TMR7	15	5	5	778	762	2,1%	8,68	75	3	1,05,E+04	1504	2,92
TMR8	15	5	5	845	845	0,0%	37,68	75	3	2,01,E+04	1341	5,60
TMR9	15	5	5	878	878	0,0%	171,87	75	4	1,00,E+04	1626	2,83
TMR10	15	5	5	866	866	0,0%	3,49	75	4	1,00,E+04	1571	2,79
TMR11	20	5	5	1106	1103	0,3%	50,11	100	3	2,00,E+04	1598	5,58
TMR12	20	5	5	960	960	0,0%	46,00	100	4	3,00,E+04	1656	8,35
TMR13	20	5	5	1053	1053	0,0%	82,17	100	6	1,00,E+04	1995	2,80
TMR14	20	5	5	1123	1123	0,0%	2,88	100	6	2,22,E+04	1829	6,18
TMR15	20	5	5	1132	1111	1,9%	300,37	100	3	1,09,E+04	1931	3,12
TMR16	10	10	5	915	892	2,5%	245,70	50	1	1,19,E+02	1258	0,10
TMR17	10	10	5	719	707	1,7%	111,76	50	2	1,00,E+04	1380	2,81
TMR18	10	10	5	854	842	1,4%	375,24	50	2	7,02,E+02	1709	0,30
TMR19	10	10	5	822	796	3,2%	566,74	50	2	2,67,E+02	1576	0,23
TMR20	10	10	5	864	857	0,8%	172,11	50	3	2,42,E+01	1551	0,05
TMR21	15	10	5	1097	1009	8,0%	407,39	75	3	5,05,E+02	1798	0,25
TMR22	15	10	5	970	880	9,3%	222,57	75	3	1,38,E+02	1794	0,10
TMR23	15	10	5	1037	950	8,4%	378,73	75	3	3,74,E+02	1743	0,21
TMR24	15	10	5	1000	908	9,2%	351,76	75	2	1,00,E+04	1920	2,88
TMR25	15	10	5	1028	936	8,9%	322,11	75	3	1,82,E+03	1825	0,60
TMR26	20	10	5	1243	1107	10,9%	578,49	100	4	1,00,E+04	2213	2,94
TMR27	20	10	5	1335	1181	11,5%	502,03	100	4	8,41,E+01	2099	0,16
TMR28	20	10	5	1287	1142	11,3%	553,95	100	4	1,14,E+04	2077	3,32
TMR29	20	10	5	1243	1111	10,6%	488,21	100	4	1,06,E+04	2104	3,09
TMR30	20	10	5	1360	1195	12,1%	24,25	100	4	1,83,E+02	2010	0,06

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