

Formulations for joint order picking problems in low-level picker-to-part systems

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ABSTRACT

This article introduces several mathematical formulations for the joint order picking problem (JOPP) in low-level picker-to-part warehousing systems. In order to represent real warehousing environments, the proposed models minimize performance measures such as travel distance, travel time and tardiness, considering multi-block warehouses, due dates, and multiple pickers. The number of constraints and decision variables required for each proposed model is calculated, demonstrating the complexity of solving medium and long-sized problems in reasonable computing time using exact methods, so it is still recommendable to solve these JOPP using metaheuristics. The proposed models can be followed as a reference for new solution methods that yield efficient and fast solutions.

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1. INTRODUCTION

Within warehouse operations, the order picking is responsible for retrieving products from shelves to fulfill customer orders, while pickers use a picking device through the warehouse. Thus, poor picking performance results in non-fulfillment of deliveries to customers, incorrect shipments, high labor costs, and additional shipping costs [1]. This is even more evident in picker-to-part systems, where the order picking becomes a repetitive and labor-intensive process [2] generating between 50-70% of the operating costs of a warehouse [3]. Therefore, in the field of warehouse management, it is valuable to optimize all the activities related to order picking in warehouses and distribution centers.

In order to optimize order picking operations, several problems like the order batching problem (OBP), batch sequencing problem (BSP), batch assignment problem (BAP), and picker routing problem (PRP) must be solved. The OBP groups or combines several customer orders into batches [4], thus reducing the traveled distance and the picking time [3]. The BSP schedules the sequence for batches, while the BAP assigns batches to the available pickers to minimize tardiness [5]. The PRP plans tours to be followed by the pickers to retrieve all the items from the assigned batches in the shortest time and distance [6].

Typically, order picking problems are solved individually in the literature but recently have been addressed jointly, because grouping orders in batches and sequencing batches affect both the planning of picking tours and the due dates compliance. However, solving joint order picking problems implies a challenge to propose rapid and practical solutions, especially when considering realistic warehouse features. Given that the number of orders in picking operations tends to be high, and the products and items

required by order are complex and diverse, the OBP, BSP, BAP, and PRP are considered NP-Hard problems [7].

Consequently, it is necessary to propose mathematical formulations that allow identifying the fundamental constraints and variables in the JOPP, considering realistic warehousing environments like orders with due dates, multiple-block layouts, and multiple pickers with picking devices to fulfill objective functions considering the travel distance, travel time and tardiness. In this way, the recent study of [8] formulates the joint order batching, routing and picker scheduling problem to minimize the total order pick time assuming certain conditions to guarantee the applicability in practice in a spare parts warehouse.

However, it is necessary to formulate equations for minimum distances and travel times between all the picking locations to facilitate the formulation of the PRP as a classic TSP in single-block and multi-block warehouses and propose variations of joint order picking problems specifying different objective functions and operation assumptions. Likewise, it is required to compute how many variables and restrictions are generated by each mathematical formulation to establish the size of a JOPP and decide if it is reasonable to solve it by using exact or approximate methods.

Based on the abovementioned, this article focuses on formulating several JOPP for low-level picker-to-part systems taking into account several features of warehouses and distribution centers and shows the complexity of these problems by calculating the number of constraints and variables involved. Likewise, this study provides minimum distances and travel times between picking locations to solve the routing problem as a TSP. Therefore, through objective functions, constraints, and variables, this study provides mathematical formulations for joint order picking models to guide researchers focused on finding exact solutions to small-sized problems or approximate solutions using approximate methods such as metaheuristics

2. PROPOSED METHOD

In low-level picker-to-part systems, pickers travel through the picking aisles and retrieve items placed in the first height level, so vertical movements are neglected. In this manner, the PRP is solved as a Steiner TSP (STSP) and is considered as a classical TSP, which is NP-Hard [9], when the minimum distances for all nodes (picking locations) are computed [10]. These distances are measured by Manhattan distances. Therefore, the Manhattan distance d_{ij} between two picking locations i and j in a single-block warehouse is calculated using (1), where R and F respectively represent the y -coordinate of the rear and front of the warehouse layout.

$$d_{ij} = \begin{cases} |x_i - x_j| + |y_i - y_j|, & \text{if } i \text{ and } j \text{ belong to the same picking aisle} \\ |x_i - x_j| + \min\{|y_i - R| + |R - y_j|, |y_i - F| + |F - y_j|\}, & \text{otherwise} \end{cases} \quad \text{for } 1 \leq i \neq j \leq L \quad (1)$$

In multi-block warehouses, where $m, n \in H$ and H is the number of blocks, (2) calculates the distance $d_{i^m j^n}$ between picking location i belonging to block m and picking location j belonging to block n .

$$d_{i^m j^n} = \begin{cases} |x_{i^m} - x_{j^n}| + |y_{i^m} - y_{j^n}|, & \text{if } i \text{ and } j \text{ belong to the same picking aisle} \\ |x_{i^m} - x_{j^n}| + \min\{|y_{i^m} - R| + |R - y_{j^n}|, |y_{i^m} - F| + |F - y_{j^n}|\}, & \text{otherwise} \end{cases} \quad \text{for } 1 \leq i \neq j \leq L \quad (2)$$

Given v as the speed of the picking device, (3) computes the travel time t_{ij} between i and j for a single-block warehouse.

$$t_{ij} = \begin{cases} \frac{|x_i - x_j| + |y_i - y_j|}{v}, & \text{if } i \text{ and } j \text{ belong to the same picking aisle} \\ \frac{|x_i - x_j| + \min\{|y_i - T| + |T - y_j|, |y_i - B| + |B - y_j|\}}{v}, & \text{otherwise} \end{cases} \quad \text{for } 1 \leq i \neq j \leq L \quad (3)$$

Similarly, for multi-block warehouses, the travel time t_{ij} between picking location i belonging to block m and picking location j belonging to block n is calculated using (4).

$$t_{ij} = \begin{cases} \frac{|x_i^m - x_j^n| + |y_i^m - y_j^n|}{v}, & \text{if } i \text{ and } j \text{ belong to the same picking aisle} \\ \frac{|x_i^m - x_j^n| + \min\{|y_i^m - R| + |R - y_j^n|, |y_i^m - F| + |F - y_j^n|\}}{v}, & \text{otherwise} \end{cases} \quad \text{for } 1 \leq i \neq j \leq L \quad (4)$$

Consequently, (1-4) provide the minimum distance and travel time between picking locations for single-block and multiple-block warehouses, allowing formulating the PRP as a TSP within joint order picking problems. Additionally, the following assumptions are considered for the formulation of the proposed JOPP models: All tours start and end at the depot; Each picker has a picking device assigned; picking devices present homogenous speed and capacity; the width of picking aisles is sufficient to allow picking devices crossing aisles in both directions, so picker blocking is not considered; the capacity of a picking device is greater than the size of a batch; order splitting is not considered; the information about customer orders is available before the order picking planning.

Based on (1-4) for travel distance and travel time, and the aforementioned assumptions, mathematical models are proposed for the joint order batching and picker routing problem (JOBRP), joint order batching, batch assignment and picker routing problem with multiple pickers (JOBARP), and joint order batching, batch assignment, batch sequencing, and picker routing problem (JOBASRP). Indices, sets, parameters, and decision variables considered for these JOPP are mentioned below.

Sets and parameters

B is the set of batches

K is the set of orders

L is the set of storage locations

P is the set of picking devices

G is the set of scheduling positions

S is a subset of storage locations

d_{ij} is the distance between picking locations i and j

t_{ij}^p is the travel time between picking locations i and j

C is the capacity of a picking device

w_k is the capacity requirement of order k

v is the horizontal velocity of a picking device

dd_k is the due date of order k

$s_{ik} =$

$\begin{cases} 1, & \text{if an item in order } k \text{ is picked from } i; \\ 0, & \text{otherwise.} \end{cases}$

Decision variables

$X_k^b = \begin{cases} 1, & \text{if order } k \text{ is assigned to batch } b; \\ 0, & \text{otherwise.} \end{cases}$

$V_p^b = \begin{cases} 1, & \text{if batch } b \text{ is assigned to picking device } p; \\ 0, & \text{otherwise.} \end{cases}$

$Y_{ij}^b = \begin{cases} 1, & \text{if } i \text{ is visited directly after } j \text{ in batch } b; \\ 0, & \text{otherwise.} \end{cases}$

$Z_i^b = \begin{cases} 1, & \text{if } i \text{ is visited in batch } b; \\ 0, & \text{otherwise.} \end{cases}$

$R_{gp}^b = \begin{cases} 1, & \text{if } b \text{ is assigned to position } g \text{ in picking device } p; \\ 0, & \text{otherwise.} \end{cases}$

c_g^p Completion time for a batch in position g in device p

c_k Completion time of order k

τ_k Tardiness of order k

3. RESEARCH METHOD

The following JOPP formulations are based on mathematical programming models, proposing an objective function to optimize and constraints using decision variables to integrate the order picking problems addressed in the JOBRP, JOBARP, and JOBASRP. According to the constraints posed for each JOPP, the calculation of the binary variables, continuous variables, and constraints is presented

3.1. JOBRP to minimize total traveled distance

The proposed formulation for the JOBRP is based on [11, 12], and its formulation was verified with similar models proposed by [13, 14]. Within order picking activities, transportation involves more than 50% of the time and cost for completing orders [3], for this reason, the reduction of travel times represents a potential for improving the picking process, and reduce activities that do not add value. Therefore, the JOBRP aims to minimize the travel distance to improve the operational efficiency of warehouses. Then, the JOBRP can be formulated as follows

$$\text{Min } Z = \sum_{b \in B} \sum_{i \neq j \in L} \sum_{j \neq i \in L} d_{ij} * Y_{ij}^b \quad (5)$$

$$\sum_{b \in B} X_k^b = 1 \quad \forall k \in K \quad (6)$$

$$\sum_{k \in K} w_k * X_k^b \leq C \quad \forall b \in B \quad (7)$$

$$Z_i^b \geq s_{ik} * X_k^b \quad \forall b \in B, k \in K, i \in L \quad (8)$$

$$\sum_{j \in L, j \neq i} Y_{ij}^b = Z_i^b \quad \forall b \in B, i \in L \quad (9)$$

$$\sum_{i \in L, i \neq j} Y_{ij}^b = Z_j^b \quad \forall b \in B, j \in L \quad (10)$$

$$\sum_{i \in S, j \in L \setminus S} Y_{ij}^b \geq Z_i^b \quad \forall b \in B, S \subset L \quad (11)$$

$$X_k^b, Y_{ij}^b, Z_i^b \in \{0,1\} \quad \forall b \in B, k \in K, i, j \in L \quad (12)$$

The (5) optimizes the total traveled distance. Constraints (6) ensure that each customer order is processed in exactly one route, while constraints (7) guarantee to satisfy the capacity of the picking device. Constraints (8) ensure that a picking position is visited only once per batch, and join the OBP with the PRP. Constraints (9) and (10) enforce that each picking location is visited once in each batch, and guarantee only one predecessor and successor to each picking location, while constraints (11) aims to prevent any sub-tour of the TSP. Constraints (12) are the domain restrictions on the decision variables. This model consists of $|K||B| + |B||L| + |B||L|^2$ binary variables, zero continuous variables, and $|K| + |B| + |K||B| + 2|B||L| + |K||B||L| + 2|B||L|^2$ constraints. The final term of constraint calculation is due to constraints (11).

3.2. JOBARP to minimize total travel time

The proposed model for the JOBARP differs primarily from the JOBRP as it considers multiple pickers that simultaneously retrieve products to satisfy customer orders, as is the case in real environments for medium and large-sized warehouses. Therefore, it is necessary to consider the assignment of batches to multiple pickers to recover all customer orders in the shortest possible time, thus improving operational efficiency and customer service. The JOBARP model is based on the proposals of [15, 16], and was complemented with the proposals of [17] that also address models with multiple pickers. The JOBARP can then be formulated as follows.

$$\text{Min } Z = \sum_{p \in P} \sum_{b \in B} \sum_{i \neq j \in L} \sum_{j \neq i \in L} t_{ij}^p * V_p^b * Y_{ij}^b \quad (13)$$

$$\sum_{k \in K} X_k^b = 1 \quad \forall k \in K \quad (14)$$

$$\sum_{p \in P} V_p^b = 1 \quad \forall b \in B \quad (15)$$

$$\sum_{k \in K} w_k * X_k^b * V_p^b \leq C \quad \forall b \in B, p \in P \quad (16)$$

$$Z_i^b \geq s_{ik} * X_k^b \quad \forall b \in B, k \in K, i \in L \quad (17)$$

$$\sum_{j \in L, j \neq i} Y_{ij}^b = Z_i^b \quad \forall b \in B, i \in L \quad (18)$$

$$\sum_{i \in L, i \neq j} Y_{ij}^b = Z_j^b \quad \forall b \in B, j \in L \quad (19)$$

$$\sum_{i \in S, j \in L \setminus S} Y_{ij}^b \geq Z_i^b \quad \forall b \in B, S \subset L \quad (20)$$

$$X_k^b, Y_{ij}^b, Z_i^b, V_p^b \in \{0,1\} \quad \forall p \in P, b \in B, k \in K, i, j \in L \quad (21)$$

The objective function (13) of the JOBARP minimizes the total travel time. Constraints (14) ensure each customer order is grouped in only one batch, while constraints (15) ensure each batch is assigned to exactly one picking device. Constraints (16) ensure the capacity of a picking device is not exceeded. Constraints (17) show that a picking location can be passed only once by the customer order k in batch b, and directly relates the order batching problem with the routing picking problem. Constraints (18) and (19) ensure the uniqueness of the picking route by arranging a predecessor and one successor to each picking position. Constraints (20) ensure a complete picking route, avoiding sub-tours in the TSP. Constraints (21) are the domain restrictions on the decision variables. Furthermore, this model consists of $|K||B| + |B||L| +$

$|B||P| + |B||L|^2$ binary variables, zero continuous variables, and $|K| + |B| + |K||B| + 2|B||L| + 2|B||P| + |K||B||L| + 2|B||L|^2$ constraints. The final term of constraint calculation is due to constraints (20).

3.3. JOBASRP to minimize total tardiness

Although some studies have focused on minimizing the traveled distances [11], or the maximum completion time of customer orders [1], it has been detected that minimizing the tardiness tends to be the best-suited performance measure for warehouse optimization problems [8, 18], because tardiness takes into account customer satisfaction, and by minimizing tardiness customer orders can be delivered on agreed due dates [7]. Therefore, the proposed model for the JOBASRP considers due dates and is based on the proposals of [7, 19]. Some elements were also extracted from the models of [10], who minimize tardiness and consider multiple pickers. Due to batches must be sequenced in each picking device in the JOBASRP, it is necessary to use Equation (3) and Equation (4) to compute the travel time for each picking device for single-block and multi-block warehouses. The JOBASRP can be formulated as follows.

$$\text{Min } Z = \sum_{k \in K} \tau_k \quad (22)$$

$$\sum_{b \in B} R_{gp}^b \leq 1 \quad \forall g \in G, p \in P \quad (23)$$

$$\sum_{p \in P} \sum_{g \in G} \sum_{b \in B} X_k^b * R_{gp}^b = 1 \quad \forall k \in K \quad (24)$$

$$\sum_{k \in K} w_k * X_k^b * R_{gp}^b \leq C \quad \forall b \in B, p \in P, g \in G \quad (25)$$

$$Z_i^b \geq s_{ik} * X_k^b \quad \forall b \in B, k \in K, i \in L \quad (26)$$

$$\sum_{j \in L, j \neq i} Y_{ij}^b = Z_i^b \quad \forall b \in B, i \in L \quad (27)$$

$$\sum_{i \in L, i \neq j} Y_{ij}^b = Z_j^b \quad \forall b \in B, j \in L \quad (28)$$

$$\sum_{i \in S, j \in L \setminus S} Y_{ij}^b \geq Z_i^b \quad \forall b \in B, S \subset L \quad (29)$$

$$\sum_{b \in B} (R_{1p}^b * \sum_{i \neq j \in L} \sum_{j \neq i \in L} t_{ij}^p * Y_{ij}^b) \leq c_1^p \quad \forall p \in P \quad (30)$$

$$c_{g-1}^p + \sum_{b \in B} (R_{gp}^b * \sum_{i \neq j \in L} \sum_{j \neq i \in L} t_{ij}^p * Y_{ij}^b) \leq c_g^p \quad \forall p \in P, g \in G \setminus \{1\} \quad (31)$$

$$c_k = \sum_{p \in P} \sum_{g \in G} \sum_{b \in B} X_k^b * R_{kp}^b * c_g^p \quad \forall k \in K \quad (32)$$

$$\tau_k = \max\{0, c_k - dd_k\} \quad \forall o \in O \quad (33)$$

$$c_g^p, c_k, \tau_k \geq 0 \quad \forall g \in G, p \in P, k \in K \quad (34)$$

$$X_k^b, Y_{ij}^b, Z_i^b, R_{gp}^b \in \{0,1\} \quad \forall g \in G, p \in P, b \in B, k \in K, i, j \in L \quad (35)$$

The objective function (22) minimizes the total tardiness of all customer orders. Constraints (23) ensure that each batch is scheduled at exactly one position in exactly one picking device, while constraints (24) ensure that each customer order has to be served in one tour. Constraints (25) guarantee to satisfy the capacity of each picking device. Constraints (26) show that a picking location can be passed only once by the customer order k in batch b . Constraints (27-29) are typical constraints in TSP ensuring the solution represents a Hamilton cycle [13]. Constraints (29) ensure a complete picking route, avoiding sub-tours in the TSP. Equations (30) determine the completion time of the first batch of each order picker, while Equations (31) guarantee that two batches do not overlap and ensure time feasibility. Constraints (32) ensure the completion time of customer orders grouped in a batch equals the completion time of this batch. Constraints (33) define the tardiness of each order. Constraints (34), (35) are the domain and non-negativity restrictions on the decision variables.

Likewise, constraints (24), (25) join the OBP with the batch assignment and batch sequencing, constraints (26) join the OBP with the PRP, and constraints (30), (31) join the batch assignment and batch sequencing problem with the picker routing problem. Additionally, this model consists of $|K||B| + |B||L| +$

$|B||L|^2 + |B||G||P|$ binary variables, $2|K| + |G||P|$ continuous variables, and $5|K| + |K||B| + 3|G||P| + 2|B||G||P| + 2|B||L|^2 + |K||B||L|$ constraints.

4. RESULTS AND DISCUSSION

This section analyzes the size of the proposed models based on the warehouse-size (storage locations) and operational volume (customer orders). When considering 50 customer orders and 5 picking devices, Figure 1 shows how binary variables and constraints grow exponentially as the warehouse-size increases for the JOBRP, JOBARP and JOBASRP. This is mainly due to the quadratic elements $|B||L|^2$ in the calculation of binary variables and constraints in the JOPP models.

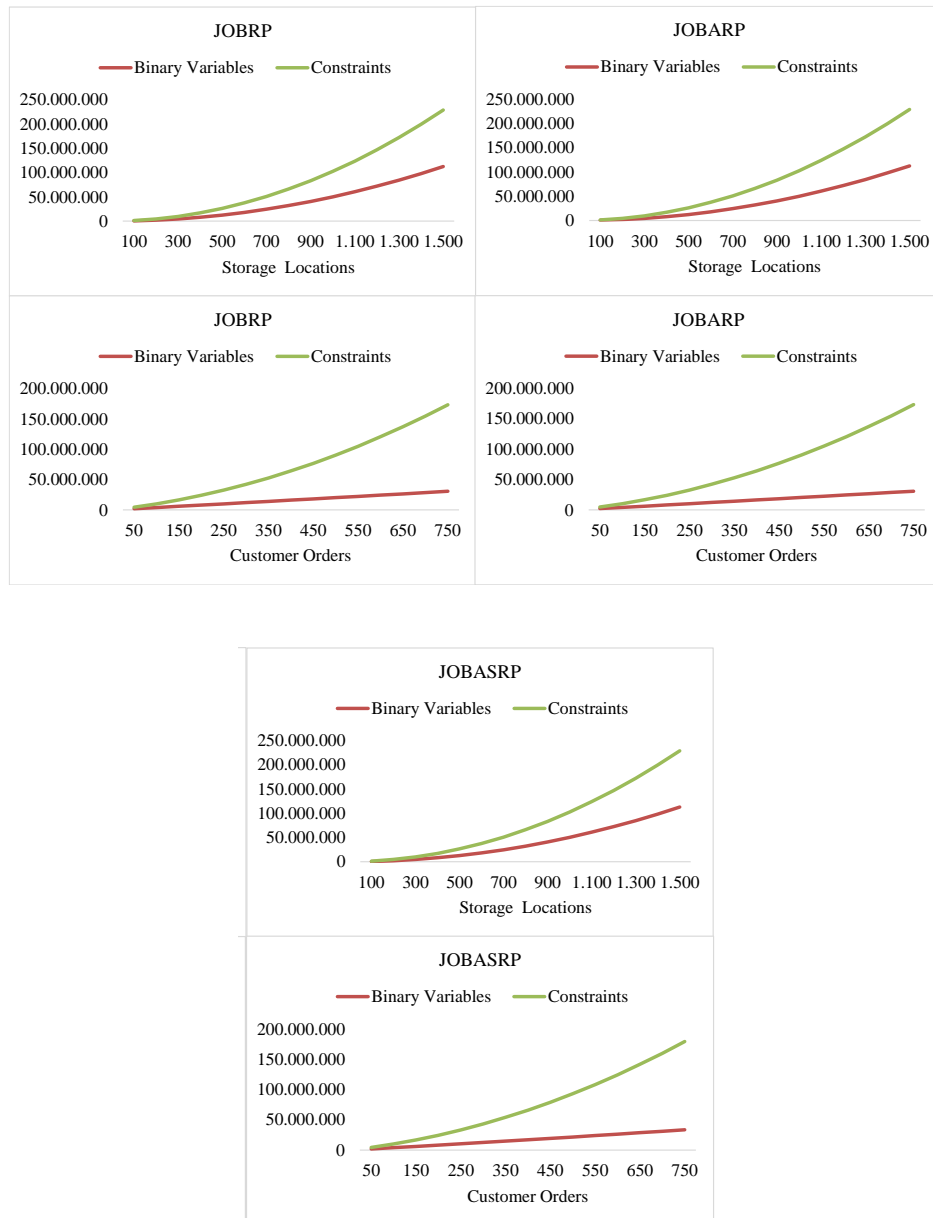


Figure 1. Number of constraints and binary variables vs storage locations and customer orders

Likewise, Figure 1 shows how binary variables and constraints grow exponentially as the number of customer orders increases for the proposed models when considering a warehouse with 200 storage locations and 5 picking devices. This is caused by elements such as $|K||B|$ and $|K||B||L|$ since the maximum number of batches B is equal to the total number of customer orders K , thus representing quadratic

components in the calculation of constraints. On the other hand, binary variables do not manage to show exponential growth in spite of presenting quadratic elements $|K||B|$, it is because the elements $|B||L|^2$ mainly determines the number of binary variables, especially in medium and large-size warehouses with 500-3,000 storage locations.

Analyzing the difference between the proposed models, the JOBARP presents $2|B||P|$ more constraints and $|B||P|$ more binary variables than the JOBRP model, so both problems can be considered similar in size, since, in large-size problems considering 200 orders (200 batches) and 5 picking devices, the models will differ in 2,000 constraints and 1,000 binary variables. Since the maximum number of batches and scheduling positions to assign a batch in a picking vehicle is equal to the number of customer orders, the JOBASRP model presents $3|K| + |K||P| + 2|P||K|^2$ more constraints and $|K|^2|P| - |K||P|$ more binary variables than the JOBARP model. Thus, when considering 200 customer orders and 5 picking devices, the models will differ in 400,200 constraints and 199,000 binary variables; however, this will only represent an increase of 1.66% in the number constraints and 2.48% in the number of binary variables in a problem considering a warehouse with 200 storage locations. Consequently, adding features such as due dates for the calculation of completion times and tardiness, and multiple pickers does not significantly affect the size of a joint order picking problem because the number of binary variables and restrictions increases significantly when the warehouse-size (storage locations) and the number of customer orders increase.

In this sense, finding exact solutions for joint order picking problems in a reasonable time is increasingly challenging, thus, the main solution approaches in the literature in recent years focus on metaheuristics and heuristics methods, as shown in Table 1. Similarly, branch-and-cut methods and other exact solution approaches have tried solving the picker routing problem for small and medium-sized problems. However, exact methods to solve medium and large-size joint order picking problems have not yet been found, especially when considering features of realistic warehouse environments, which is why metaheuristic methods prevail as the most suitable option to obtain high-quality solutions in short computing times for NP-Hard problems since the decisions made at a joint order picking problem must be taken repetitively on a daily basis. The most used metaheuristics for JOPPs are GA to improve total travel paths in logistics tasks [20], PSO [21], ACO and SA to solve the TSP [22], VND, VNS, ALNS, and ILS algorithms. Likewise, other nature-based metaheuristics could be adapted to solve the JOPP formulated in this study to provide efficient solutions in short computing times [23].

Table 1. Solution approaches for joint order picking problems

Problem	Solution approach	Realistic warehouse environments	Author
JOBRP	Savings heuristic and branch-and-cut algorithm	Multiple pickers, multi-block warehouse	[24]
	Iterated local search (ILS) and heuristic derived from an exact solution approach	Multi-block warehouse	[25]
	Batching heuristic and ant colony optimization (ACO)	Multi-block warehouse, 3D warehouse	[13]
	Order-center and batch-center heuristic, and particle swarm optimization (PSO)	Multi-block warehouse	[12]
	PSO and ACO	None	[11]
	Simulated annealing (SA) and an optimal A*-algorithm	Multi-block warehouse, 3D warehouse	[26]
	Heuristics improved with a SA, and routing policies	None	[14]
	Genetic algorithms (GA)	Due dates, 3D warehouse, multi-objective approach	[27]
JOBARP	Variable neighborhood descent (VND) and variable neighborhood search (VNS)	Multi-pickers, due dates	[19]
	Hybrid rule-based algorithm (batching and assigning rules)	On-line, multiple pickers	[16]
	Assignment rules and adaptive large neighborhood search (ALNS)	Multiple pickers, pickers with differences in skills	[15]
	FBLPT -based algorithm and Batching heuristic	On-line, multiple objective approach, multiple delivery vehicles	[28]
JOBASRP	Hybrid-coded GA and ACO algorithm	Due dates	[7]
	Variable neighborhood descent and Lin-Kemighan-Helsgaun heuristic	Multi-pickers, multi-block warehouse, due dates	[10]
	ILS algorithm	Multi-pickers, multi-block warehouse, due dates, 3D warehouse	[8]

Therefore, it is expected that studies and investigations in joint order picking problems will increase, including one or several features of realistic warehouse environments mentioned in Table 1, such as online customer order arrivals (time windows approaches), multiple pickers, pickers with different skills, multi-block warehouses, non-conventional layouts, 3D warehouses, due dates, and approaches considering conflicting objectives and a tradeoff between them [29], thus, providing solutions that allow to improve both

the operative efficiency (operative costs) and the customer service (on-time deliveries). Likewise, it is expected that the proposed models for the JOPP are extended to be more realistic when considering multiple pickers and congestion in narrow-aisle warehouses, and considering multiple pickers and splitting to assign a single batch among several pickers, minimizing makespan [30], tardiness, earliness, and total traveled distance. In this way, the models and solutions of the JOPP will be suited to the reality of warehouse operations, hence improving the overall efficiency of the supply chains, especially for B2C e-commerce companies.

5. CONCLUSION

We have investigated several joint order picking problems for low-level picker-to-part systems (JOBRP, JOBARP, and JOBASRP), which are known to be NP-hard. The size of the problems related to the proposed formulations for the JOBRP, JOBARP and JOBASRP has been calculated through the number of constraints and binary variables according to storage locations and customer orders. From these results, we observed the size of JOPPs grows in greater proportion as warehouse-size increases, so it is still recommendable to solve these problems using metaheuristics, which have proved to be the best solution approach to provide efficient and fast solutions, as required on daily based operations in warehouses and distribution centers. Consequently, this work becomes the framework for researchers interested in solving JOPPs, providing mathematical models, interactions between variables and the size of the problems according to the number of orders and warehouse contableations considered. Therefore, the novel technical results of this study are threefold: the proposal of mathematical formulations for several JOPP considering minimum travel distances and travel times to model the PRP as a TSP, the calculation of binary variables and restrictions to set the NP-Hard nature of these problems according to the number of orders and warehouse size and the exploration of different metaheuristic algorithms to adapt to each JOPP. Further research should devise formulations for the JOPP considering other realistic warehouse environments such as non-conventional warehouse layouts, 3D warehouses, pickers with heterogeneous skills, online approaches, multi-objective approaches, congestion, and splitting, and even integrate joint order picking operations with shipping and delivery operations.

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