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AN ALGORITHM FOR THE CAPACITATED VEHICLE ROUTING PROBLEM FOR PICKING APPLICATION IN MANUAL WAREHOUSES

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ABSTRACT

Given that warehouses play a central role in modern supply chains, this study proposes the application of an algorithm for the capacitated vehicle routing problem (CVRP) based on the two-index vehicle flow formulation developed by Baldacci, Hadjiconstantinou, and Mingozzi (2004) for picking purposes in manual warehouses. The study of Theys et al. (2010) is first used to represent the warehouse using a Steiner traveling salesman problem (TSP). Then, a calculation of the picking tour's length is obtained applying the Manhattan distance. Finally, the algorithm for the CVRP is solved through a cutting plane with the addition of termination criteria related to the capacity of picker. The study analyzes four different warehouse configurations, processing five picking list each. The analysis is carried out exploiting the commercial software MATLAB®, to determine the solution that minimize distance of the order picking tour. The results obtained in MATLAB® show the effectiveness of the chosen algorithm applied to the context of manual order picking.

Keywords: order picking, picking distance, capacitated vehicle routing problem, manual warehouse.

1 INTRODUCTION

Warehouse management is a primary issue for logistics companies (Cheng et al. 2015). The logistics cost relating to warehouse processes, including receiving, storage, order picking and shipping, is often high (De Santis et al. 2018). Among these internal operations, order picking, i.e. the process of retrieving products from their storage locations in a warehouse in order to satisfy the requests of the customers, is an important and yet tedious task (Hsieh and Tsai 2006; Muter and Öncan 2015). To be more precise, order picking process is considered the most laborious task in warehouses accounting for up 65% of the total operating costs (Gademann and van de Velde 2005; De Koster, Le-Duc, ans Zaerpour 2012; Žulj et al. 2018). For this reason, both researchers and logistics managers consider order picking as a promising area for productivity improvement (De Santis et al. 2018).

The travel time of pickers is an increasing function of the travel distance, which was investigated in many papers and considered one of the primary optimization conditions (Karasek 2013). The travel time is influenced by order picker routing policies, which determine the sequence of item retrieval in the warehouse and the sequence in which aisles are traversed (Grosse, Glock, and Ballester-Ripoll 2014). However, the performance depends greatly on the layout and size of the warehouse, the size and characteristics of orders and the order-picker capacity (Dukic and Oluic 2007; Bottani, Montanari, and Rinaldi 2019). Sure enough, the problem becomes more complex if the carrying capacity of the order picker is limited (Grosse, Glock, and Ballester-Ripoll 2014).

The problem of picking an order is the one of determining the sequence in which locations should be visited to minimize total cost (or time), which leads to the traveling salesman problem (TSP) (Daniels, Rummel, and Schantz 1998). In particular, the generic order picking problem is configurable as a Vehicle Routing Problem (VRP), which consists of constructing a set of at most *m* vehicle routes of least total distance, according to a portfolio of capacity and time constraints, and in order to simultaneously satisfy a group of retrieval requests (Ferrari, et al. 2003).

However, according to our knowledge, the picker's capacity is rarely considered when dealing with order picking problems. A VRP algorithm (and in particular an algorthm for the CVRP problem) is expected to well capture the order picking problem in the case of capacity constraints.

These gaps will be addressed in the present study, by applying an algorithm for the capacitated vehicle routing problem (CVRP) to the manual picking process. The chosen algorithm has been proposed by Baldacci, Hadjiconstantinou, and Mingozzi (2004) and is based on the two-index vehicle flow formulation. The result of the algorithm, i.e. the estimate of the picking distance, shows the effectiveness of this algorithm to solve a manual order picking problem with capacity constraints.

The paper proceeds as follows. The next section describes the simulation strategy adopted to estimate the picking distance and provides some preliminary information about the warehouse under examination.

Section 3 details the configurations considered and the main results obtained in this study. Section 4 discusses the main findings and concludes by highlighting the main limitations of this work and suggesting future research directions.

2 METHODOLOGY

2.1 Algorithms

From a methodological point of view, the study of Theys et al. (2010) is first used to represent the warehouse using a Steiner TSP; then, a calculation of the picking tour's length is obtained applying the Manhattan distance. Finally, the algorithm for the CVRP developed by Baldacci, Hadjiconstantinou, and Mingozzi (2004) is solved through a cutting plane with the addition of termination criteria related to the capacity of picker. The analysis is carried out exploiting the commercial software MATLAB®, to determine the best solution that minimize distances of the order picking tour.
To be more precise, in the following we will present the formulation of the CVRP.
A graph G= (V', E) is given where V'={0,1,…,n} is the set of n+1 vertices and E is the set of edges. A nonnegative cost d_{ij} is associated with each edge {i, j}∈E. Let OP=={1,…,op} be the number of order picker with same capacity Q located in depot. Also, let OP(S) be the number of order picker with Q capacity required to pick up the required items in S.
The integrality constraint is defined as follows:

$$x_{ij} = \begin{cases} 1, \forall (i,j) \in E \backslash \{\{0,j\}: j \in V\} \\ 0, \qquad otherwise \end{cases} \quad (1)$$

Now, the two-index problem can be mathematically formulated as the follows:

$$minimize\ (F)\ z(F) = \sum_{\{i,j\}\in E} x_{ij}\, d_{ij} \quad (2)$$

$$\sum_{\{i,j\}\in\delta(\{h\})} x_{ij} = 2\,, \forall h \in V \quad (3)$$

$$\sum_{\{i,j\}\in\delta(\{S\})} x_{ij} \geq 2OP(S)\,, \forall S \in T \quad (4)$$

$$\sum_{j\in V} x_{0j} = 2OP \quad (5)$$

where T={S:S⊆V, |S|≥2}. Constraint (3) is the degree constraints for each customer, i.e. each vertex must have an incoming and an outgoing arc. Constraint (4) is the cutting constraint which, for any subset S of customers that does not include the depot, imposes that at least OP(S) vehicles enter and leaves S. Constraint (5) states that OP vehicles must leave and return to the depot.

The solution of the problem is not unique, because of the presence of more pickers. Hence, when running the algorithm, MATLAB® returns the first solution found that satisfies constraints 2-5. A check has been set in MATLAB® to verify that the solution returned meets the capacity constraint. In the case the solution found also meets this constraint, it is considered as the optimal solution to the problem. Otherwise, the algorithm is run again to identify a new solution.

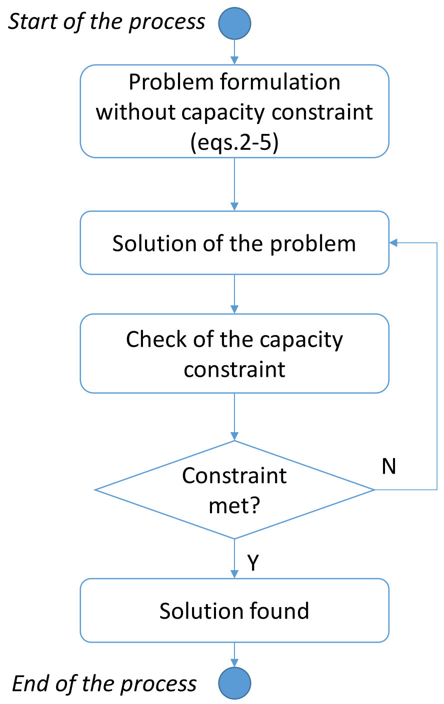

Figure 1: Flowchart of the algorithm in MATLAB®

2.2 Warehouse settings

The picking environment in this paper is as follows:

- rectangular warehouse;
- manual picker-to-parts order picking system;
- random storage of items in the warehouse;
- depot located at the top left corner of the warehouse;
- the picking area uses double-side shelves with a total storage capacity of 640 SKUs;
- each SKUs is 1.30x1.00 meter in width and depth, respectively;
- aisle width is 2.50 meters.

3 CONFIGURATIONS ANALYSIS

For the purpose of testing the algorithm in various settings, 4 different warehouse configurations are evaluated in this study:

- One block warehouses – 10 items –picker capacity = 300
- One block warehouses – 20 items –picker capacity = 600
- Three block warehouses – 10 items –picker capacity = 300

- Three block warehouses – 20 items –picker capacity = 600.

For each configuration, 5 picking lists of the same length are processed.

To model a capacity constrained problem, a weight is assigned to each item in the warehouse. The weight, expressed in kg, is generated by MATLAB® as a random number with values ranging between 0 and 100 (step 1). The picker's capacity instead, depends on the length of the order picking list: for a picking list of 10 items, the picker's capacity is set at 300, while for a picking list of 20 items, the picker's capacity is set at 600. In the picking lists with an equal number of items (i.e. 10 or 20), the same products (weights) are considered, regardless of the warehouse layout. The same consideration can be made for picking lists of 20 items. Moreover, the instances of the problem are calculated for a number of pickers equal to two and three.

In the following sections, the analysis of various configurations for the estimation of the picking distance is shown. For all configurations, an evaluation of the distance and computational time required to order picking activities is provided.

3.1 One block warehouses – 10 items – picker capacity=300

In this scenario, the configuration with one block warehouses, picking list of 10 items and picker's capacity of 300 is analyzed. The results obtained from application of the algorithm are shown in Table 1 for the five order lines for the reference configuration.

Table 1: Order picking distance for one block warehouses with 10 Items (picker's capacity = 300)

ORDER LINE	TOTAL WEIGHT [kg]	NUMBER OF PICKERS	WEIGHT FOR PICKER [kg]	DISTANCE [m]	COMPUTATIONAL TIME [s]
1	408	2	185	**326.4**	2.456
			223		
		3	21	**348.8**	2.615
			204		
			183		
2	379	2	273	**278.4**	1.278
			106		
		3	21	**319.2**	1.012
			106		
			252		
3	632	2	-	-	-
			-		
		3	260	**432.2**	0.978
			75		
			297		
4	485	2	279	**280.2**	1.322
			206		
		3	34	**306.6**	1.159
			184		
			267		
5	424	2	138	**258.6**	1.322
			286		
		3	21	**268.8**	1.021
			111		
			292		

As can be seen from Table 1, for all order lines, when increasing the number of pickers, a longer order picking distance is found. Nonetheless, it is interesting to note, that in the third order line with two pickers, the constraint of the picker's capacity is not met; for this order line, therefore, the shortest distance is obtained where the number of pickers equals 3. Whereas, the trend of the computational time generally is inverse: decreasing the number of pickers involves an increase in the computational time. For first order line only, decreasing the number of pickers generates a lower computational time.

3.2 One block warehouses – 20 items – picker capacity=600

In this scenario, the configuration with one block warehouses, picking list of 20 items and picker's capacity of 600 is analyzed. The picking distances and computational times are shown in Table 2 for the five order lines evaluated.

Table 2: Order picking distance for one block warehouses with 20 items (picker's capacity = 600)

ORDER LINE	TOTAL WEIGHT [kg]	NUMBER OF PICKERS	WEIGHT FOR PICKER [kg]	DISTANCE [m]	COMPUTATION TIME [s]
1	787	2	193	**430.4**	3.875
			594		
		3	21	**450.8**	2.273
			172		
			594		
2	1117	2	580	**496.8**	2.491
			537		
		3	580	**517.2**	2.354
			34		
			503		
3	884	2	599	**418.6**	2.532
			285		
		3	270	**428.8**	1.934
			593		
			21		
4	948	2	383	**522.2**	3.215
			565		
		3	35	**532.4**	2.773
			331		
			582		
5	1198	2	600	**525**	141.276
			598		
		3	75	**539**	211.992
			546		
			577		

As can be seen from the table above, for all order lines, decreasing the number of pickers involves a shorter order picking distance. It is interesting to note that the trend of the computational time is opposite: when increasing the number of pickers, the computational time decreases. For the last order line only, decreasing the number of pickers causes a decrease in the shorter computational time as well.

3.3 Three block warehouses – 10 items – picker capacity=300

In this scenario, the configuration with three block warehouses, picking list of 10 items and picker's capacity of 300 is analyzed. The picking distances and computational times obtained with this configuration are shown in Table 3.

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Table 3: Order picking distance for three block warehouses with 10 items (Picker's Capacity = 300)

ORDER LINE	TOTAL WEIGHT [kg]	NUMBER OF PICKERS	WEIGHT FOR PICKER [kg]	DISTANCE [m]	COMPUTATION TIME [s]
1	408	2	247	**273.4**	3.2681
			161		
		3	21	**313.8**	1.6411
			173		
			214		
2	379	2	84	**263.7**	1.1561
			295		
		3	63	**304.5**	0.9844
			21		
			295		
3	632	2	-	-	-
			-		
		3	75	**336.5**	1.6062
			297		
			260		
4	485	2	189	**251.6**	1.255
			296		
		3	70	**284.3**	1.6078
			119		
			296		
5	424	2	135	**234.6**	1.3793
			289		
		3	111	**255**	1.4678
			24		
			289		

As can be seen from Table 3, for all order lines, again the increase in the number of pickers involves a (slight) worsening of picking distance. Nonetheless, it is interesting to note that for the third order line with two pickers the constraint of picker's capacity is not respected. This result was also found in the configuration with one block warehouse and two pickers. For this order line, therefore, the shortest distance is obtained when the number of pickers equals 3. However, in this configuration, the computational time does not follow a linear trend: sometimes, it increases with the increase in the number of pickers, while sometimes it decreases.

3.4 Three block warehouses – 20 items – picker capacity=600

In this scenario, the configuration with three block warehouses, picking list of 20 items and picker's capacity of 600 is analyzed. The results obtained from application of the algorithm are shown in Table 4 for the five order lines for the reference configuration.

Table 4: Order picking distance for three block warehouses with 20 items (Picker's Capacity = 600)

ORDER LINE	TOTAL WEIGHT [kg]	NUMBER OF PICKERS	WEIGHT FOR PICKER [kg]	DISTANCE [m]	COMPUTATION TIME [s]
1	787	2	193	**336.1**	2.964
			594		
		3	21	**376.5**	4.147
			172		
			594		
2	1117	2	580	**326**	2.696
			537		
		3	34	**357.9**	2.883
			580		
			503		
3	884	2	285	**317.3**	19.749
			599		
		3	46	**337**	10.023
			239		
			599		
4	948	2	412	**342.6**	1.770
			536		
		3	35	**360.8**	1.646
			377		
			536		
5	1198	2	598	**361.2**	6.856
			600		
		3	75	**392.9**	1.827
			575		
			548		

The results shown in the table above confirm the trend previously observed, i.e. for all order lines, decreasing the number of pickers involve a decrease in the picking distance. However, it is interesting to note that in this configuration, the computational time does not follow a linear trend: sometimes, it decreases with the number of pickers, while sometimes it increases.

4 DISCUSSIONS AND CONCLUSIONS

This paper has proposed an application of an algorithm for the CVRP based on the two-index vehicle flow formulation developed by Baldacci, Hadjiconstantinou, and Mingozzi (2004) for the problem of minimizing the travel distance of pickers in manual warehouses. In particular, the study of Theys et al. (2010) was first used to represent the warehouse using a TSP. The estimate of the picking tour's lenght was then obtained through the Manhattan distance. Finally, the algorithm for the CVRP developed by Baldacci, Hadjiconstantinou, and Mingozzi (2004) is solved through a cutting plane with the addition of termination criteria related to the capacity of picker. The rationale for the choice of this algorithm is that the picking problem is frequently modelled as a TSP, of which the VRP is a special case; therefore, a VRP algorithm is expected to well capture the order picking problem. Moreover, CVRP model by Baldacci, Hadjiconstantinou, and Mingozzi (2004) takes into account the vehiche capacity in the problem formulation. This is an important (and innovative) point, as the picker's capacity, on the contrary, is rarely considered when dealing with order picking problems. Rather, when modelling a manual order pickng process, researchers typically assume that the picker has enought capacity to pick all the items included in the picking list.

In general terms, the best results from the proposed approach were observed with three block warehouses, in terms of the total distance covered. To be more precise, considering the first picking list of the first and third configuration (picking list of 10 items), it is interesting to note that the best solution in terms of distance travelled is returned by the three block warehouses configuration, both in the scenario with two and three pickers. The outcomes can be used by warehouse and logistics managers to identify the configuration of warehouses on which to focus with the aim to reduce the travel distance (and thus the order picking cost), considering the capacity of picker.

From a technical perspective, it should be mentioned that the results obtained with the proposed approach cannot be compared with either the traditional heuristic routing policies (e.g. S-shape, largest gap or return) or with metaheuristic approaches available in literature, because none of these approaches takes into account the capacity of the picker when modelling the problem. Therefore, a benchmark to evaluate the performance of the proposed approach is not available (to the best of the authors' knowledge) at the time of writing. This could be seen as a limitation of the present work, as it prevents judging the performance of the proposed model. At the same time, however, as this paper takes into account the picker's capacity among the problem constraints, the results returned could represent a viable benchmark for similar studies to be carried out in the future.

A further limitation of the analysis made in this paper is that the present work does not take into account the combination of several orders into a single order to fulfill small orders (e.g., online orders directly by the final customer) in a batch picking process. Similarly, the situation with large orders, that need to be split up into smaller batches that are to be picked successively, is not taken into account in the model, as well. This could be a future adjustment to be made to the problem modelled. Finally, multiple order pickers in the same area can cause wait times due to picker blocking and increases the risk of accidents in the warehouse; these aspects are not included in the present evaluation, so they could be considered in future research activities.

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