An optimization model for the storage assignment of the references under ergonomics constraints

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Abstract: Part feeding activities are vital for assembly operations performed in many manufacturing environments of many different industries. These activities ensure that components, which are stored at the supermarket, are delivered to the assembly stations. This process begins with picking operations, during which components are retrieved from the shelves of the supermarket and loaded on the tow trains. Such operations are known for being time demanding and stressful for the operators due to their repetitiveness and the high level of fatigue required to perform them. To ameliorate workers' well-being, to improve efficiency, and to reduce costs, many companies are striving to improve all the phases connected to the part feeding process. In this paper, we aim to present an optimization model that solves the Storage Assignment (SA) of the components and takes into consideration the fatigue level of operators through the energy expenditure level of the picking process. This model assigns each reference to a certain shelf of the supermarket in order to minimize the costs of the picking procedures integrating as a constraint the maximum acceptable energy expenditure that workers can spend in a typical working day of 8 hours. Unlike previous studies, this model considers the possibility for the operators to walk to reach an area of the supermarket rather than drive. Furthermore, the energy expenditure of each activity is considered, including the one related to mounting and dismounting actions from the tow train. Therefore, this model offers a representation of the picking process that is more realistic than the ones of any other model previously developed. A numerical example is discussed to show the implementation process and the capabilities of this approach.

Keywords: Storage assignment; Picking; Human factors; Rest Allowance.

1. Introduction

The picking process is a vital part of the line feeding procedure. In this process, operators move around the supermarket on tow trains. Following a predetermined picking list, operators retrieve components or references from the shelves of the supermarket and loaded them on the tow trains. According to Tompkins et al. (2010), the picking process accounts for about 55% of the total annual operating costs of the supermarket. Furthermore, traveling and searching operations are responsible for more than 70% of the total picking time (Tompkins et al. 2010). Therefore, to improve the procedures of a supermarket, it is necessary to enhance such searching and traveling operations. There are four main approaches that can be used to improve the picking process (Ene and Örztürk, 2012):

- Batch-picking operations: which consists in assigning the references that are closer to each other to the same operators (batching), thus, decreasing the traveling time.
- Zone picking improvements: in this approach, the supermarket is divided into zones. Ideally, each operator performs the picking operations in one and only one zone of the supermarket.
- Routing order picking: this approach relies on Shortest Path Problems (SPP), Traveling Salesman Problem (TSP), and Vehicle Routing Problem (VRP) to minimize the traveling distance.
- Reference placement: the references are placed in the supermarket so that the traveling operations are optimized. This approach is divided into Storage Allocation and Storage Assignment. The former allocates a certain amount of space of the shelves to each reference, and the latter locates the references in the supermarket.

Although these approaches are broadly studied in the literature, a model that considers the energy expenditure together with improvements for the picking operations is absent. The approach presented in this paper is an improvement of a model previously described in Zangaro et al. (2018). The model combines the Storage Assignment and the TSP to minimize the traveling time and considers the energy expenditure of the operators' activities. This is a more accurate and holistic representation of the problem, and, therefore, it can lead to results that better represent the real problems.

The paper is structured as follows. Section 2 provides a literature review about the integration of human aspects in the picking operations in the supermarket. In Section 3, the problem is described in detail while, in Section 4, the mathematical model is presented. The numerical case study and the results are analyzed in Section 5. Finally, Section 6 provides conclusions and future perspectives.

2. Literature Review

Improving the picking operations in a supermarket is a problem that has been widely discussed in the literature (Kovács, 2011; Muppani and Adil, 2008; Pan et al., 2012; Petersen et al., 2005).

Hsieh and Huang (2011) present two heuristic approaches to batch the components to be picked. The models are compared for computational times with similar models and are tested by simulation experiments. Eventually a sensitivity analysis is performed to show the importance of the batching procedures. Although batch-picking is a valid approach to be used, there are also other approaches that can be used to improve the picking operations.

Ene and Örtürk (2012) describe a two-stage sequential model for the storage assignment and picking process. This model assigns each carton of the references to one slot of the shelves of the supermarket. This leads to a higher level of accuracy in the Storage Assignment. However, it is not possible to consider the volume or the area of the references as sometimes it might happen in real cases. Furthermore, this technique affects the possibility to place the references in a way that the operators can easily find them, or the searching process is appropriate for the operators. Any ergonomic consideration on the picking activities and how this affects the picking process have been neglected. It is important to consider the ergonomic workload in order to ensure that the performance of the picking operations is maintained. Finally, Ene and Örtürk (2012) present a sequential approach which solves firstly the Storage Assignment problem and then the batching and routing problem of the picking operations. Although this is a model which might lead to lower computational times, it might also lead to solutions that are not globally optimal. On the other hand, a simultaneous approach reaches a global optimal solution. Therefore, there is the need to consider simultaneously the Storage Assignment and the routing problem in order to reach better solutions.

However, the proposed models largely ignore workers' characteristics or human factors, which leads to results that are only partially realistic. To the best of our knowledge, only few papers consider the workers' features during the milk run planning and scheduling models.

In particular, Grosse et al. (2015) propose a conceptual framework for integrating human factors into the planning of models in supermarkets and warehouses activities and hypothesize that doing so improves the performance of an order picking system and workers' well-being.

Calzavara et al. (2018) present an optimization model for the Storage Assignment problem. This model considers the workload and energy expenditure of the picking operations. The Ovako Working Posture Analysis System index is used to evaluate the posture of the operators that has been studied with a motion capturing system. This allows considering holistically the problem under the financial point of view. An industrial case is presented and discussed. Although this model considers the energy expenditure of the picking operations, its assumptions are different from the model discusses in the current paper. Indeed, Calzavara et al. (2018) do not consider the possibility for the operator to walk to the picking locations.

Polak-Soinska (2018) presents an empirical study on which, in three assembly plants, the energy expenditure of workers dedicated to the picking in the supermarket area has been measured in order to evaluate the critical tasks. According to the author for each scenario, it is necessary to adopt new strategies to reduce workers' fatigue. Even if author suggests some modifications to reduce the energy expenditure of workers no mathematical models is here proposed and so this can represent a limitation of this study.

As can be seen, the current state of the literature shows that the picking problem is still currently studied, and subject of constant debate for improvements. However, there is a lack in the literature on models can be used to define the set of activities each worker has to do. In particular, until now no papers have discussed the possibility for the operator to reach the locations of the supermarket on foot. Furthermore, also mounting and dismounting operations have not been considered in the current state of the literature. For this reason, the approach presented in this paper is innovative since it considers different assumptions from any other approach previously published.

3. Problem Description

According to Battini et al. (2010), many manufacturing environments employ the supermarket concept. This approach involves introducing an intermediate storage between the racks of the assembly stations and other larger centralized warehouses.

A supermarket is composed of multiple shelves where references are stored, and other pieces of equipment where empty containers and boxes are placed. The supermarket concept has two main features. Supermarkets satisfy the needs of an intermediate storage for medium containers, which cannot be stocked on the racks of the assembly line and must be delivered to the assembly stations in a timely manner. Furthermore, the shelves of the supermarkets are shaped and sized so that the operators can manually retrieve the references. These activities are known as picking operations (Battini et al., 2015).

In a supermarket, there are a certain number of references that are stored on the shelves. These references are usually stored in two kinds of containers: cardboard boxes and reusable containers. The number of items in each container and the number of containers retrieved by the operators vary from one reference to another. A supermarket can be divided into areas where the operators stop to retrieve the components. In each area there are a certain number of shelves. The shelves are organized in multiple levels, and each reference is store in only one of them. The level at which a reference is stored and the weight of the reference can affect the worker's energy expenditure and, consequently, the picking time. For this reason, it is possible to store the references in such a way that the energy expenditure of the operators is minimized. Considering Figure 1 (Section 5), references stored in the lower level require a higher energy expenditure to be picked despite the ones stored in the middle or in the upper level. For instance, the references that are heavier can be placed on the level at arm's reach.

Since the VRP or the Inventory Routing Problem (IRP) has already been solved for the replenishment operations of the assembly stations, it is already known which tow train will visit which station and which references are delivered. As a result, the references that must be picked up by one tow train are already set. The picking lists, which enumerates the components that must be picked by each train, are assumed non-modifiable. Therefore, it is not the aim of this paper to select the references that must be picked up by each tow train. The shelves of the supermarket are usually supplied with forklifts that unload the pallets from big trucks that arrive in a nearby receiving area. Although these refilling operations are performed weekly, it is not the aim of this paper to consider or optimize such activities.

To perform the picking operations, operators use tow trains or can walk in the supermarket area if it is possible. Tow trains are composed of an electrically powered engine and a few wagons (Battini et al., 2015). Operators drive around the supermarket, stop at the picking locations and retrieve the items, load the items on the tow train, and drive to the next location. They continue this process until all the items on a picking list have been collected. Whenever an operator reaches a location, he or she must dismount the vehicle. This activity has an energy expenditure which depends on the kind of vehicles used. As defined previously, operators have the possibility to walk to reach a nearby area of the supermarket to retrieve some references and avoid mounting and dismounting operation, or to drive around the supermarket on the tow train.

For each worker, it is also important to ensure that the whole energy expenditure spent during the picking process must be lower than the maximum acceptable working level, o, as described in Battini et al. (2016) and adapted from Price (1990). We can assume this value equals to 4.3 kCal/min for a healthy worker (30 years old) that works 8 hours per day.

4. Mathematical Model

In the supermarket, there are N areas where the operator can perform the picking operations. These N areas of the supermarket, as well as its entrance (0), are encoded in M. Each of these areas n host a shelf for storing the references. The shelves are divided into L levels. Each of these shelves has a certain dimension s_{nl} for its levels l. There are I references that must be stored in the supermarket. Each of these references i has a certain dimension d_i, and an energy expenditure z_{il} and a picking time t_{il} which depends on its weight and the level l where reference i is stored. It is possible to use the formulas described in Calzavara et al. (2017) to calculate the energy expenditure z_{il} of the picking operations of reference i from level l shelves.

Furthermore, there are K tow trains that are tasked to pick up the references from the supermarket. Matrix a_{ki} describes which train k needs to pick up which reference i. For instance, a_{hi} has a value equal to 1 if train h picks up the reference i, 0 otherwise.

Indexes:

- $k = 1, \ldots, K$: operators that perform the picking;
- $n = 1, \ldots, N$: areas of the supermarket;
- $m = 0, \ldots, N$: nodes of the supermarket;
- $i = 1, \ldots, I$: references that are stored in the supermarket;
- $l = 1, \ldots, L$: levels of the shelves.

Input Parameters:

- d_i: the dimension of the i reference;
- a_{ki}: the element of the matrix that describes whether reference i must be picked up by train k (binary);
- s_{nl}: the size of the shelves at level l placed along the area n;
- z_{il}: the energy expenditure of picking procedures for reference i from level l;
- o: maximum ergonomic hourly energy expenditure per operator;
- c_{nm}: traveling time with tow train between picking location n and m;
- v_{nm}: walking time between picking location n and m;
- h: energy expenditure for walking operations;
- t_{il}: the picking time for reference i from level l
- h: energy expenditure for walking operations without loads;
- h': energy expenditure for walking operations with loads;
- h'': energy expenditure for driving operation;
  e_{ud}: energy expenditure for mounting and dismounting actions from the vehicle;
- t_{ud}: time for both mounting and dismounting actions from the tow train;
- w_i: weight of component i;
- w_{max}: maximum recommended transportable weight during walking;
- w_s: maximum weight of the references that can be loaded on the same shelf.

Decision variables:

- p_{inl}: describes if the reference i is assigned to the level l of the shelf in the area n (binary);
- X_{nmk}: is the traveling trip between n and m of vehicle k (binary);
- Y_{nmk}: is the walking trip between n and m of vehicle k (binary);
- T_k: is the picking time of the operator k;
- U_{nk}: dummy variable of train k at station n.

Objective function: minimize the picking time.

The objective function (1) aims at minimizing the total picking time. The total picking time consists of the sum of all the picking time of all the operators K.

$$\min \sum_{k=1}^{K} T_k \quad (1)$$

$$T_k = \sum_{n=0}^{N}\sum_{m=0}^{N} X_{nmk}\, c_{nm} + 2\sum_{n=0}^{N}\sum_{m=0}^{N} Y_{nmk}\, v_{nm} + t_{ud}\left(\sum_{n=0}^{N}\sum_{m=0}^{N} X_{nmk} - 1\right) + \sum_{i=1}^{I} p_{inl} a_{ik} t_{il}\ , \quad \mathrm{k} = 1,\ldots,\mathrm{K} \quad (2)$$

$$\sum_{n=1}^{N}\sum_{l=1}^{L} p_{inl} = 1, i = 1, \ldots, I \quad (3)$$

$$\sum_{i=1}^{I} p_{inl}\, d_i \le s_{nl}, n = 1, \ldots, N, l = 1, \ldots, L \quad (4)$$

$$\sum_{i=1}^{I}\sum_{l=1}^{L} p_{inl}\, a_{ki} / I \le \sum_{m=0}^{M} X_{mnk} + \sum_{m=1}^{M} Y_{mnk}\ , \quad k = 1, \ldots, K, n = 1, \ldots, N \quad (5)$$

$$h'' \sum_{n=0}^{N}\sum_{m=0}^{N} X_{nmk} c_{nm} + e_{ud}\sum_{n=0}^{N}\sum_{m=0}^{N} X_{nmk} + (h + h')\sum_{m=0}^{N}\sum_{n=0}^{N} Y_{mnk} v_{nm} + \sum_{i=1}^{I} p_{inl} a_{ik} z_{il} \le \left(\frac{O}{60}\right) T(k), k = 1, \ldots, K \quad (6)$$

$$\sum_{n=1}^{M}(X_{nmk}) = \sum_{n=1}^{M}(X_{mnk})\ , m = 0, \ldots, N, \quad k = 1, \ldots, K \quad (7)$$

$$U_{0k} = 1, k = 1, \ldots, K \quad (8)$$

$$U_{nk} \ge 2, U_{nk} \le N, k = 1, \ldots K, n = 1, \ldots N \quad (9)$$

$$U_{nk} - U_{mk} + N(X_{nmk}) \le N - 1, \quad k = 1, \ldots K, n, m = 1, \ldots N \quad (10)$$

$$X_{mmk} = 0, Y_{mmk} = 0, k = 1, \ldots, K, m = 1, \ldots, M \quad (11)$$

$$Y_{n0k} = 0, Y_{0nk} = 0, k = 1, \ldots, K, n = 1, \ldots, N \quad (12)$$

$$\sum_{m=1}^{N} Y_{nmk} \le N \sum_{m=0}^{N} X_{nmk}\ , k = 1, \ldots, K, \quad n = 1, \ldots, N \quad (13)$$

$$\sum_{m=0}^{N} Y_{mnk} \le \left(\frac{w_s}{w_{max}} - \frac{\sum_{l=1}^{L} p_{inl} w_i}{w_{max}}\right) / \left(\frac{w_s}{w_{max}} - 1\right), a_{ik} = 1, k = 1, \ldots, K, n = 1, \ldots, N, i = 1, \ldots, I \quad (14)$$

$$T_k \ge 0, p_{inl}, X_{nmk}, Y_{nmk} \in \{0,1\}, U_{nk} \in \mathbb{N} \quad i = 1, \ldots, I, n = 1, \ldots, N, k = 1, \ldots, K, l = 1, .. L \quad (15)$$

The picking time consists of the traveling time on the tow train, the walking time of the operators from and to the areas, the mounting and dismounting time from the tow train, and the time to retrieve the references from the shelf, as described in (2). In this case, there is the need to subtract 1 from the total number of visited nodes as the operator is already in the tow train when arrives or departs from the supermarket. (3) ensures that each reference i can only be assigned to one and only one shelf l of one area of the supermarket n. Notice that it is not relevant on which side of the aisles a reference is located. This formulation aims simply at locating the references within an area of the supermarket, so that other ergonomic and optimization approaches can be implemented and adjusted even with high frequency. The size of the shelves that are stored in a certain area n must not exceed the available space, as outlined in (4). The size of the shelves, as well as the size of the items, can be measured in area, volume, or the number of slots or cartons. Unlike previous models that consider the number of slots of a shelf, this model allows considering different shapes for each component. The operator k must travel through an area n if there is a reference i, which must be picked up by a train k, and is placed in the aisle n, as described in (5). In this case, there is the possibility for the operator to walk or to drive to the location. These activities are encoded respectively in y_{mnk} and x_{mnk}. (6) calculates the energy expenditure of the picking operations. This consists of the driving operations, the mounting and dismounting operations, the walking operations, and the picking operations. Such energy must be lower than or equal to the maximum recommended ergonomic level during the picking time. Every time a vehicle reaches a node, the operator must also exit from it, as described in (7). (8), (9), and (10) ensure subtour elimination for the TSP. This is to avoid the possibility for the tow train to perform loops among the areas of the warehouse without departing from the entrance 0. A vehicle or an operator cannot depart and arrive from and to the same station m, as outlined in (11). (12) ensures that an operator cannot walk to the entrance 0 or from it to reach an area n. This is to ensure that the operator cannot enter the supermarket on foot and perform picking operations without a tow train. An operator can depart on foot from an area n to reach any other area m only if he or she has already reached the same area n on the tow train, as outlined in (13). N is to ensure that the operator can depart from an area n multiple times on foot. (14) ensures that if an operator must pick up a certain number of components from area n and the sum of their weights is higher than the maximum recommended transportable weight w_{max}, then it is not possible for the operator to reach the area n on foot. Eventually, (15) defines the decision variables.

5. Numerical Example

This section discusses and describes a numerical example inspired by a real-industrial case. This case refers to a supermarket of an original equipment manufacturer (OEM) where tow trains are retrieving components for the assembly line. As previously described, the picking list, i.e. the number and the references that must be picked up by the operator, cannot be changed or altered.

In this case, there are three levels L of the shelves where references are stored, as depicted in Figure 1.

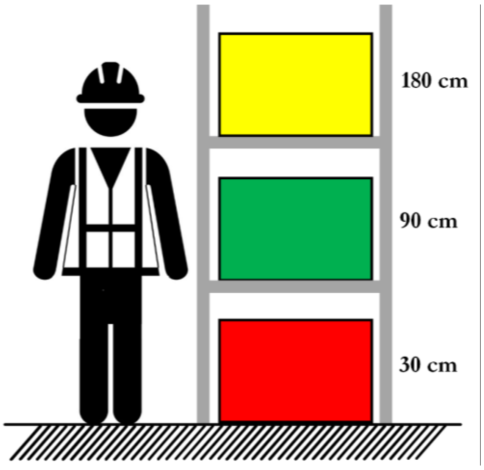

Figure 1: Levels of the shelves

As we can see, for each level there is a different ergonomic risk. In particular, according to the equations presented in Calzavara et al. (2017), a worker's energy expenditure in the medium level can be equal to 0.08 kCal/s for small and light references and it can be increased to 0.12 kCal/s for heavy components. The medium level can be considered as the more ergonomic one as a worker has to move the arms under the shoulders level and the legs are straights. The upper level requires from 0.18 kCal/s to 0.375 kCal/s as worker, in this case, has to pick the reference from a level higher than the shoulders one. Finally, the lower level represents the less ergonomic one on which references can be stored. In fact, worker must bend to pick up the reference. In this case the energy expenditure can change from 0.225 kCal/s to 0.625 kCal/s according to the weight and the size of the reference.

The layout of the area of the supermarket is depicted in Figure 2. There are four areas of the supermarket N where the operator stops to retrieve the references. The shelves are placed in both the sides of each road. Each of this area is an aisle where the tow train can drive through. As can be seen, there are some paths that can be used by the operators to reach the areas of the supermarket. Some of these paths can only be used by the operators to walk in both directions among the areas of the supermarket since they are not large enough for a tow train. On the other hand, tow trains can drive through a limited number of roads in the supermarket. A tow train cannot perform U-turns while driving through an aisle of the supermarket. An area in the rear of two shelves is used for the replenishment operations of the shelves.

In our case study, there are 40 references I that must be stored in the supermarket, and 4 tow trains K are used for the picking operations. In order to test the model, we variate the weight of the components, the energy expenditure for the picking activities, and the picking time.

The minimum and maximum energy expenditure rate (EE), expressed in kCal/s, for all activities related to the whole picking process are listed in Table 1.

Table 2, Table 3, Table 4, and Table 5 contain all the results of the computation when two maximum weights of the reference are used. According to the maximum weight considered we have obtained several instances considering as the maximum weight a percentage of the maximum value initially analyzed. Moreover, references have several weights and it is for this reason that in some cases, even if the maximum weight is very high, workers can decide to go to pick a reference by foot. In order to show the savings that can be achieved, we provide, in Table 2 and 4, the results when the operator can travel on foot and, in Table 3 and Table 5, when such activity is not allowed.

These tables include the total time for the picking operations, the number of trips performed by the operator while driving, the number of trips performed by the operator while waking, the total driving time, and the total walking time.

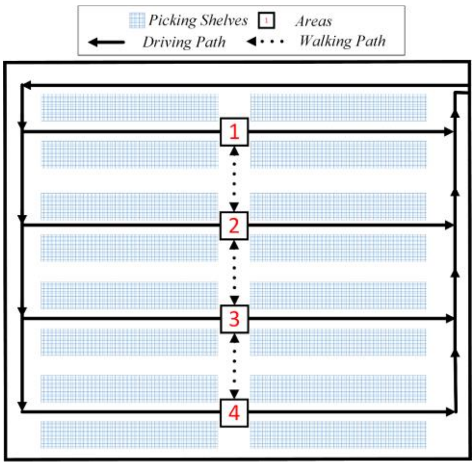

Figure 2: Supermarket area

Table 1: Energy expenditure rate for typical picking activities in the supermarket area.

Activity	Min EE [kCal/s]	Max EE [kCal/s]
Picking a reference from the low level	0.225	0.625
Picking a reference from the medium level	0.08	0.12
Picking a reference from the high level	0.18	0.375
Activity	**EE [kCal/s]**	
Walking from an area to another one without references	0.125	
Walking from an area to another one with references	0.17	
Driving activities	0.05	
Mounting and dismounting actions from the tow train	0.09	

Table 2: Results considering 20 kg as maximum weight (Time reported in seconds)

Weight of the Reference	Total Picking Time	Driving Trips	Walking Trip	Driving Time	Traveling Time on Foot
175%	1446	7	2	302	10
160%	1355	7	2	302	10
145%	1263	7	2	302	10
130%	1172	7	2	302	10
115%	1080	7	2	302	10
100%	989	7	2	302	10
85%	897	7	2	302	10
70%	799	5	3	302	15
55%	700	5	4	284	20
40%	609	5	4	284	20
25%	517	5	4	284	20

Table 3: Results considering 20 kg as maximum weight (Time reported in seconds)

Weight of the Reference	Total Picking Time	Driving Trips	Driving Time
175%	1515	9	320
160%	1424	9	320
145%	1332	9	320
130%	1241	9	320
115%	1149	9	320
100%	1057	9	320
85%	966	9	320
70%	898	9	320
55%	838	9	320
40%	746	9	320
25%	655	9	320

It is easy to see that, in both cases, when the weights of the components decrease, the number of times that worker reaches the picking area by foot increases. Moreover, in every case, the maximum acceptable working energy expenditure is respected as in our model we have included also this constraint so each time the EE is lower than 4.3 kCal/min. In both cases, we can note that for a lower maximum weight the total picking time tends to decrease as the walking trip tends to increase and, consequently, the time to reach an area by foot is lower than that one requires to reach the same area with the tow train. This is also due to the way on which tow trains can move among the supermarket aisles.

Table 4: Results considering 15 kg of maximum weight (Time reported in seconds)

Weight of the Reference	Total Picking Time	Driving Trips	Walking Trips	Driving Time	Traveling Time on Foot
175%	1179	7	2	302	10
160%	1111	7	2	302	10
145%	1042	7	2	302	10
130%	973	7	2	302	10
115%	905	7	2	302	10
100%	830	5	3	302	15
85%	760	6	3	293	15
70%	685	5	4	284	20
55%	616	5	4	284	20
40%	548	5	4	284	20
25%	479	5	4	284	20

Table 5: Results considering 15 kg of maximum weight (Time reported in seconds)

Weight of the Reference	Total Picking Time	Driving Trips	Driving Time
175%	1248	9	320
160%	1180	9	320
145%	1111	9	320
130%	1042	9	320
115%	974	9	320
100%	929	9	320
85%	864	9	320
70%	823	9	320
55%	754	9	320
40%	685	9	320
25%	617	9	320

6. Conclusion

In this paper, a new optimization approach has been presented. This approach allows to route the tow trains and the operators among the areas of the supermarket and to locate the references in the shelves. This is an innovative approach that represents the problems in a more realistic way, as it allows the operator to travel on foot. The implementation of this approach leads to a lower picking time and a better ergonomic workload for the operators. The method has been implemented and tested on a numerical case inspired by a real-industrial problem.

Further research should focus on analyzing more deeply the possibility to combine walking and driving operations during the picking operations. More operators' features can be integrated into the model such as the age, the weight and the working time. This would allow optimizing even further the picking activities, to combine ergonomic and economic considerations, and to improve the storage assignment procedure.

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