ECONOMIC AND PERFORMANCE ANALYSIS OF DUAL-BAY VERTICAL LIFT MODULES (VLMS)

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Abstract

Warehouse picking is one of the most time and cost consuming activities in a warehouse, often requiring the presence of human operators, who travel within the aisles to retrieve the items needed by the customers. Several studies demonstrate that the travelling activity can represent even the 50% of the total picking time, with a subsequent creation of a separate storage and picking area for small objects. In the last years, new solutions for order picking systems have been developed, especially for small items. One of these solutions requires Vertical Lift Modules (VLMs), storage columns with extractable trays. In this paper, the employ of dual-bay VLMs, compared to a traditional bin-shelving warehouse, has been analysed from an economic point of view. Some mathematical formulations have been developed, to estimate the total annual cost and the respective convenience limits of both systems, according to their productivity. Moreover, some useful guidelines for practitioners are derived.

Keywords: Vertical Lift Module, Warehouse, Order Picking, Cost, Performance

1 INTRODUCTION

Warehouse picking is the activity of retrieving items from their storage locations to fulfill different customers’ orders [1]. Due to the high flexibility and to the lower operative costs, this activity is usually performed by human operators, walking or travelling with a picking cart through the aisles of the warehouse in which the various products are stored [1, 2]. Such picking strategy is also called picker-to-parts picking, and, as widely demonstrated in literature, it is characterized by a high incidence of the travel time, which usually amounts to the 50% of the total order processing time [3]. Moreover, this aspect is even more crucial when the pick and the storage of small items are considered. In fact, small dimension products are often stored in pallets, too, with a consequent waste of space and, hence, time [4]. Therefore, one of the most effective ways for reducing the total picking time and, hence, for reaching a higher system throughput, should consider the decrease of the travel time [5, 6]. This objective can be obtained, for example, by dedicating a different forward area to small objects picking [2], or by introducing new storage systems that ease the picking activity [7]. In this latter case, the new systems could be automated solutions, leading to a parts-to-picker strategy. Some examples are miniloads, other AS/RS systems like the Autostore® [8], or the ones employing particular automated guided vehicles able to move the shelving towards the picker according to the picking orders, like the KIVA robots developed by Amazon robotics [9]. Of course, the implementation of automated solutions should consider an important trade-off, between the benefits that these systems can carry, and the related emerging costs.

In this paper, an innovative parts-to-picker picking system for small objects is introduced and analyzed. The system consists of a dual-bay Vertical Lift Module (VLM), used for the storage of the items and for the dynamic picking of the picker. Due to the recently introduced technical modernizations, VLMs are attracting always more attention in several contexts, leading also to new interesting applications [10]. Therefore, it becomes necessary to study this kind of systems, both from a technical and an economical point of view. In fact, even if the implementation of a VLM is not so expensive, especially compared to other automated storage solutions (as for example KIVA robots), it is important to properly consider all the aspects and the characteristics that affect the final cost of such a configuration. Here, an economical evaluation of a VLM picking system is carried out. Moreover, the proposed mathematical model is used to compare this picking system to a traditional picker-to-parts picking area with traditional shelving and aisles. The modelling of both systems and their critical comparison can lead to the proposal of some useful guidelines, that can help practitioners to understand the real convenience of a VLM system, together with the borders of its adoption.

The remainder of the paper is structured as follows. In the next section, a brief literature review concerning small objects picking, vertical lift modules and economic modelling is presented. Then, in Section 3, the economic models, both of the VLM picking system and of the traditional system, are presented and explained. In Section 4, the comparison of the two systems is reported, together with the discussion of the obtained results. Finally, Sections 5 and 6 are for the limitations and future researches and for the conclusions, respectively.

2 LITERATURE REVIEW

In picker-to-parts warehouses, the pickers travel in the aisles, searching for the items and collecting them in order to complete their order list. In case of a traditional order picking warehouse, where the items are stored on pallets that are positioned on the lower stocking locations of the shelves, the pickers use electric pallet trucks to move inside the aisles and to transport one or more mixed pallets, made of the items collected during his order picking activity. The expected average time per order line of this system is typically at least about 40-50 s/line, where the main part is related to the travelling and searching activities [3]. Moreover, the picking of the items could have a relevant impact also on the ergonomics level, especially when the operators are picking the last items from the pallet [11].

Therefore, it is often suggested to store small-dimensions items in a separate forward area, in which they are not stored in pallets but in other specific storage systems [2, 7]. In fact, it has already been demonstrated in literature that this approach can significantly speed up the picking
process, thanks to a reduction of the storage space dedicated to every single item and, then, to a reduction of the travelled distances [2, 4]. Moreover, the use of alternative storage solutions for small objects can improve the picking activity, both in terms of time and ergonomic effort [12].

The most common systems used for the storage and the picking of small-dimensions items can be divided into two main categories: static picker-to-parts solutions and dynamic parts-to-picker ones [7, 13]. Static systems usually require the storage of goods in racks or in other structures that are fixed in one place and, therefore, usually simple and not expensive. Some examples of static systems are: bin-shelving, often equipped with specific devices (containers, dividers etc.), modular drawer cabinets, movable aisle systems, flow rack systems. On the other side, in a dynamic system the items are brought to the picker by an equipment, that is usually supported by automated systems, as well as computer software tools. Dynamic solutions can typically assure higher space utilization, also taking advantage of the vertical space, that is normally not used very well in the static solutions. Examples of dynamic systems are: vertical carousels, horizontal carousels, single-bay and dual-bay vertical lift modules, miniload AS/RS systems, A-frames and picking machines, like the robots developed by Amazon robotics [9, 13].

All these solutions present different advantages and disadvantages, that could lead to different possible applications, according to the aspects that you want to give priority to. Generally, the factors that have to be considered are the dimensions of the stored bins, the allocation of each product code and its picking frequency [4]. According to the picking frequency of the item and to its storage allocation, one storing solution can turn out to be more suitable than another. It is then important to estimate the throughput of each alternative, together with their costs, to understand their most proper applicability field.

A Vertical Lift Module (VLM) is a dynamic storage solution composed of several trays, in which the items are stored, and of an automated storage and retrieval system, needed to retrieve, transport and deliver a tray at a time in front of the operator. Thanks to the recent development of such storing systems, the employ of VLMs has interestingly expanded, also in warehouse picking contexts [10, 14]. In particular, the introduction of dual-bay VLMs allows the picker to work in parallel to the system: while the picker has in front of him a certain tray, the AS/RS can independently store the previous tray and retrieve the following one. Of course, this can lead to an improved throughput of the picking activity, since the picker does not have to walk to reach the items to pick, and also the search and the pick of the item are eased [15]. Although Vertical Lift Modules possible applications are promising, they have received until now very few consideration in literature. The first relevant contribution, dealing with single-bay VLMs is [16]. It is focused on the proposal of formulations that can be useful to estimate the storage and retrieval cycle times of the system. Another more recent research is [10], in which exactly dual-bay VLMs are studied. Finally, [14] proposes to employ dual-bay VLMs for a fast processing of small-objects picking orders, by introducing the so-called VLM fast picking system, and by studying some possible solutions that can speed up the overall configuration, like class-based storage assignment of the items, batch retrievals of the trays and order batching. All these contributions are mainly investigating the performance of VLM, in terms of times estimation and throughput improvement. On the other side, for now there are no studies that are dealing with the economic impact that a VLM can have in a warehouse, especially compared to a traditional warehousing system.

The study of the economic contribution of a warehousing system generally should consider its most relevant costs items. For example, [7] suggest to take into account the building, the equipment within it, the value of the material to be stored and the cost of the operation. On the other hand, [17] propose to focus on the initial investment, on the shortage costs and on the costs associated to the storage policy. In their review, Gu et al. [18] state that the warehouse layout and configuration can effectively affect its construction and maintenance costs, the material handling costs, as well as the storage capacity, the space utilization and the equipment utilization. As far as warehouse picking is concerned, the comparison of different picking approaches from an economic perspective has not received, for now, a proper attention. Some researches state that the most important costs are related to the time needed for the processing of a picking order [1, 18]. Therefore, researches on this topic mainly propose to reduce costs by reducing the picking time [19]. This can be achieved, for example, by reducing the travel time, through the reduction of the distances travelled by the operators, or by using paperless picking devices, that can decrease the search and pick time [3, 6, 20].

Figure 1. Analysed systems. (a) Traditional bin-shelving warehouse, (b) Dual bay Vertical Lift Module.

### 3 COST MODELS FOR SMALL ITEMS WAREHOUSING SOLUTIONS

In this Section the two cost models for the evaluation of the considered storing systems are presented. They refer to a
traditional warehouse shelving and to a Vertical Lift Module, respectively (Figure 1).

3.1 Traditional warehouse cost model
The first storing solution here analysed is a traditional warehouse suitable for small items picking, made of bin-shelving and aisles [2]. Here, it is considered to have a set of static racks on the ground floor and a further set of racks on a mezzanine system (Figure 1, a). In such a picker-to-parts system, the picking operators walk within the various aisles to retrieve the items reported on their picking list and put them in the picking carts. In this case, the travel time is usually lower than in a typical case-pick-from-pallet warehouse [2, 14]. However, it becomes important to properly define the storage allocation of each item in the picking area, which is impacting both on the refilling process and on the dimension of the area. The more space is dedicated to each item in the picking area, the lower is the number of refilling processes, but the higher is the travelling time.

The formulation of the Total Cost for this traditional warehouse \( TC_{WH} \) is composed of two terms. The first term refers to the space cost, while the second one is for the workforce cost:

\[
TC_{WH} = C_{sp} \cdot k_{WH} \cdot \frac{V}{Sl_{WH} \cdot H} + C_{sp} \cdot \frac{Q \cdot E(CT)_{WH}}{3600} \cdot h_y \tag{1}
\]

where, in the space cost term, \( C_{sp} \) is the annual floor space cost per square meter, \( k_{WH} \) is the floor space cost coefficient, which includes both the rack and the mezzanine system, \( V \) is the total volume of the stocked items, \( Sl_{WH} \) is the saturation level of the shelving and \( H \) is the plant height. In the workforce cost term, instead, \( C_{op} \) is the hourly operator cost, \( Q \) is the productivity required for the system, usually expressed in picking lines per hour, \( E(CT)_{WH} \) is the average cycle time per line, that is the time averagely needed to pick an item reported on the picking list, and \( h_y \) is the number of working hours in a year. The cycle time can also take into account of the time needed for the refilling activity, which mainly depends on the storage system and on the frequency of the refills [4].

3.2 Dual-bay VLM cost model
The second picking system for small items considers the employ of a dual-bay Vertical Lift Module. A Vertical Lift Module (VLM) is a closed storage column with various trays containing the stored items (Figure 1, b). These trays are stored and retrieved by an automated system: according to the picking list, the system brings the required tray to the picking bay, so that the picker can process his order. In this case, the picking strategy is parts-to-picker, with the operator standing in front of the VLM picking bay, waiting for the retrieval of the trays containing the required items to pick. Moreover, the dual-bay allows the picker to work in parallel with the storage and retrieval system: while the operator is picking from a certain tray, the AS/RS can store the previous tray and then retrieve the following one, resulting in a higher system throughput [14].

Similarly to the formulation of the Total Cost for a traditional bin-shelving warehouse, also the formulation for a dual-bay VLM is composed of two terms, the space cost and the workforce cost:

\[
TC_{VLM} = N_{VLM} \left( C_{sp} \cdot A_{VLM} + C_{VLM} \right) + C_{op} \cdot \frac{Q \cdot E(CT)_{VLM}}{3600} \cdot h_y \tag{2}
\]

Here, the space cost includes both the space occupied by the VLM, obtained multiplying \( C_{sp} \) by the area required for one VLM and for the working space of the operator, \( A_{VLM} \), and the annual cost of the VLM \( C_{VLM} \). The sum of these two costs are then multiplied by the number of required VLMS \( N_{VLM} \). On the other hand, in the workforce cost the only difference with respect to \( TC_{WH} \) is \( E(CT)_{VLM} \), average cycle time per line in case of picking from VLM system, usually expressed in seconds. This cycle time can be easily related to the VLM system productivity \( Q_{VLM} \) with:

\[
Q_{VLM} = \frac{3600}{E(CT)_{VLM}} \tag{3}
\]

By introducing

\[
k_{VLM} = \frac{C_{sp} + C_{VLM}}{C_{op}} \tag{4}
\]

as the floor space cost coefficient for the VLM, and considering

\[
A_{VLM} = \frac{V}{Sl_{VLM} \cdot H} \tag{5}
\]

with \( Sl_{VLM} \) saturation level of the VLM. Formula (2) can be rewritten as

\[
TC_{VLM} = N_{VLM} \left( C_{sp} \cdot k_{VLM} \cdot \frac{V}{Sl_{VLM} \cdot H} + C_{op} \cdot \frac{Q \cdot E(CT)_{VLM}}{3600} \cdot h_y \right) \tag{6}
\]

Finally, it is also possible to define a formulation for the calculation of the number of required VLMS \( N_{VLM} \):

\[
N_{VLM} = \max \left( \left\lfloor \frac{Q \cdot E(CT)_{VLM}}{3600} \cdot \frac{V}{V_{VLM}} \right\rfloor \right) \tag{7}
\]

where \( V_{VLM} \) is the storage capacity of the vertical lift module, expressed in cubic metres.

4 SYSTEMS EVALUATION AND COMPARISON
Once that the two cost models are defined, it is possible to use them to evaluate and compare the two storage systems, and, therefore, the two different picking approaches.

4.1 Economic comparison formulation
As far as the scope of the present paper is concerned, the following comparison focuses on an economic comparison of the two systems, traditional bin-shelving warehouse and dual-bay VLM. This evaluation aims at defining a VLM convenience region, that corresponds to a set of conditions in which the employ of a VLM picking system would be preferable than a traditional bin-shelving warehouse.

This VLM convenience region starts from the following condition:

\[
TC_{VLM} \leq TC_{WH} \tag{8}
\]

In order to reach a proper formulation for the comparison, the following hypotheses are assumed: \( N_{VLM} = 1, V < V_{VLM} \).
Moreover, the term \( R_Q \), productivity ratio, is introduced:

\[
R_Q = \frac{E(CT)_{WH}}{E(CT)_{VLM}}
\]  \( (9) \)

Then, by substituting Formulas (1) and (2) in Formula (8) and by considering also (3) and (9), the final formulation for the systems comparison turns out to be:

\[
C_{op} \cdot \frac{V}{H} \left( \frac{k_{VLM}}{SL_{VLM}} - \frac{k_{WH}}{SL_{WH}} \right) \left( R_Q - 1 \right) \leq Q^* \leq 1 \]  \( (10) \)

### 4.2 Parametrical analysis

The formulations previously introduced are used here to perform a first parametrical analysis that can help the derivation of some preliminary results. Table 1 reports the input values assumed for the considered parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
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<tbody>
<tr>
<td>( H )</td>
<td>( m )</td>
</tr>
<tr>
<td>( V_{VLM} )</td>
<td>( m^2 )</td>
</tr>
<tr>
<td>( k_{WH} )</td>
<td>( \text{s} )</td>
</tr>
<tr>
<td>( SL_{WH} )</td>
<td>( % )</td>
</tr>
<tr>
<td>( C_{op} )</td>
<td>( \text{€/(m}^2 \cdot \text{year}) )</td>
</tr>
<tr>
<td>( C_{VLM} )</td>
<td>( \text{€/year} )</td>
</tr>
<tr>
<td>( h_y )</td>
<td>( \text{h/year} )</td>
</tr>
<tr>
<td>( R_Q )</td>
<td>( \text{h/year} )</td>
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In the following, the results of the performed analysis are reported through different graphs. All graphs illustrate the trend of \( Q^*/Q_{VLM} \) between 0 and 100%, representing the maximum value, as imposed in Formula (10). This trend is represented according to the varying of the other parameters: \( V \), variable between 40 m\(^3\) and 60 m\(^3\) with a step of 2 m\(^3\); \( C_{VLM} \), equal to 18,000 €/year or 24,000 €/year, and \( C_{op} \), equal to 80 €/m\(^2\) or 120 €/m\(^2\). Moreover, it has been considered that operators work in two work shifts, resulting in \( h_y = 3,520 \) h/year, or in only one, with \( h_y = 1,760 \) h/year. The productivity ratio \( R_Q \) is equal to 1.5 and 2, corresponding to \( E(CT)_{WH} = 60 \) s and \( E(CT)_{VLM} = 40 \) s or \( E(CT)_{WH} = 60 \) s and \( E(CT)_{VLM} = 30 \) s, respectively. Considering Formula (10), in fact, it can be easily demonstrated that the choice threshold depends only on \( R_Q \), regardless of the specific values of \( E(CT)_{WH} \) and \( E(CT)_{VLM} \).

Figure 2 shows the trend of Formula (10), representing the threshold choice between the traditional bin-shelving warehouse and the VLM, with \( C_{op} = 80 \) €/m\(^2\) and \( R_Q = 1.5 \). First of all, it can be seen that the threshold changes according to the hourly cost of the operator; in particular, it is higher for a lower hourly cost. Moreover, the increase of \( V \), the total volume of the stocked items, leads to a decreasing trend of \( Q^*/Q_{VLM} \); the decrease is then steeper for the lower values of \( C_{op} \). Figure 3, instead, reports the same kind of analysis but with a higher annual floor space cost per square meter, \( C_{op} = 120 \) €/m\(^2\). Figure 3 shows an evident overall difference compared to Figure 2: if the space has a higher cost, the threshold choice between the traditional bin-shelving warehouse and the VLM is lower. Hence, the VLM turns out to be the best choice also for lower values of \( Q^*/Q_{VLM} \); because it allows to store the items more efficiently, with a higher saturation of the available space.
Figure 4 represents a further changing with respect to Figure 2: a higher difference in the respective cycle times \( E(CT)_{WH} \) and \( E(CT)_{VLM} \), that are one the double of the other, with \( R_Q = 2 \). Also in this case, the threshold generally moves down, and the varying of the stocked volume is less impacting. Moreover, the difference among the various thresholds, corresponding to different values of \( C_{sp} \), is lower, meaning that here the hourly cost of the operator has a lower effect on the final formulation.

Figure 5 shows how the thresholds change when the cost of the VLM is higher \( (C_{VLM} = 24,000 \text{ €/year}) \). In this case, of course, the threshold moves up, with a wider convenience area for the traditional bin-shelving warehouse with respect to the previous results shown in Figure 2. The same effect emerges from the comparison of Figures 4 and 6: a higher VLM cost leads to a shift of the choice thresholds, even if in this case the movement is restrained. This means that the higher VLM cost impacts less when the VLM is faster, compared to the traditional warehouse \( (R_Q = 2 \) instead of \( R_Q = 1.5 \))

Finally, Figure 7 shows the same scenario of the analysis of Figure 4, but considering that the systems are used for only one daily work shift \( (h_y = 1,760 \text{ h/year}) \). The convenience regions of the two systems change in favour of the traditional bin-shelving warehouse: if the systems are less used, then it is more probable that the traditional bin-shelving warehouse is the best option. This is even more true for \( C_{sp} = 15 \text{ €/h} \): when the operators are cheaper, the threshold reaches 60%. Moreover, it is interesting to see how the results of this last scenario are completely comparable to the ones of the scenario reported in Figure 2. The corresponding values of \( Q^*/Q_{VLM} \) are the same.
As already stated, this paper represents a first study that needs to be deepened. Of course, the analysis has to continue with an extension of the parametrical analysis, by considering more variables and by enlarging the input dataset. Moreover, it would be interesting to add the terms useful to better consider the refilling activity, which is different for the two systems and which has a relevant impact on the storage allocation, on the travelled distances and, then, on the overall time [2, 4].

6 CONCLUSIONS AND FUTURE RESEARCHES

The present paper has reported a mathematical formulation useful to compare two storage systems for order picking: a traditional bin-shelving warehouse and a dual-bay Vertical Lift Module. The model starts with the proposal of two cost models, which consider, for both systems, the most common emerging costs, like the occupied space cost, also depending on its saturation, together with the workforce cost. Moreover, these two cost models have been put into relation, to derive a single synthetic formulation. This depends on the annual floor space cost per square meter, on the annual operator cost, on the volume saturation levels of the two systems, on the ratio of the cycle times of the two systems and on their productivity. The application of the formulation in the parametrical analysis showed that the productivity ratio $Q^{*}/Q_{VLM}$ is not very sensible to the total volume of the stocked items, while it is to the annual floor space cost per square meter and to the annual cost of the VLM.

Future researches on this topic will consider the suggestions reported on Section 5 to overcome the current limitations of the model. It would then also be interesting to extend the analysis to other small-items storage systems, to derive a complete tool for their evaluation and comparison. This could help the choice of their most proper application in real warehouse picking contexts.

7 REFERENCES


