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Performance Analysis of Traditional and Trilateral Forklifts in Warehouse Material Handling: A Technical-Economic Evaluation and Simulation Study

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Abstract

This study analyzes the technical and economic aspects of selecting different types of material handling equipment within a warehouse and evaluates their impacts on the system's performance. Specifically, the attention is focused on two main types of equipment used for material handling, namely the traditional forklift and the trilateral forklift. This study starts with a preliminary market analysis, then it simulates the implementation of the equipment types within a warehouse model with a pallet rack layout. The comparative analysis of the two material handling solutions is presented and illustrated so as to investigate the existence of a more efficient solution and on the optimization margins in terms of warehouse performance. Finally, the study suggests possible further investigations to be carried out in future research activities.

Keywords: warehouse, simulation approach, forklift, optimization.

1. Introduction

For increasing the performance of a warehouse, rather than an industrial plant as a whole, one of the most critical activities is the correct choice of the material handling equipment (MHE). As indicated in the work performed by Kulak (2005) first, and by Stephens and Mayers (2013) later, the total operating cost of MHE ranges from 40% to 80% of the warehouse cost. Making these operations more efficient can thus generate consequent savings in operating costs, up to 30% (Kulak, 2005).

There are several types of forklifts available on the market, each intended for specific operating conditions; a general classification will be explained in the next chapter.

Preliminarily, it should be noted that nowadays within most warehouses, products are picked manually, and, in this context, the most expensive machines turn out to be forklifts. This is why several studies have focused on the optimization of their performance. For instance, Burinskiene (2011) used a simulation model targeting the optimal usage of forklift trucks by determining the potential savings on travel distance by equipping them with RFID systems as opposed to using paper format to perform picking activities. In another study, Burinskiene (2015) developed a simulative model and tested different scenarios in order to examine new optimized routing methods for forklifts.

From an energetic point of view, several studies have investigated the impact of these machinery in terms of their energetic consumptions or environmental impact. Atashi Khoei et al. (2023), through the implementation of mixed linear programming and dynamic programming models, addressed the issue of the energy consumption of the forklifts used by pickers during the fulfilment of their picking missions. In this context, an attempt is made to find the most energy-efficient route that minimizes energy consumption, consequently the CO_2 emissions, whilst ensuring the fulfilment of the requested picking list.

Meanwhile, Lee et al. (2022) developed an algorithm for solving the electrical forklift routing problem. In this context the algorithm provides the route that balanced the picking list size and the battery charge level constraints. Other studies (Facchini et al., 2016; Boenzi et al., 2017) evaluate the use of electrically operated solutions by equally comparing them with and to ordinary fuel solutions (diesel), to determine the most efficient.

Moreover, precisely because of the large number of resources required, special attention is paid to the methodologies of selecting the correct machinery needed and the choice of decision-making criteria. The study conducted by Mahmutagić et al. (2021) is an example of a forklift selection model whose usage is intended to provide robust business decision support.

At the same time, in a recent study targeting a Cargo company, Ulutaş et al (2023) implemented models suitable for multicriteria decision-making techniques to determine the weights to be assigned to different selection criteria, and then to identify the optimal MHE for industries. This study also found that among the selection criteria of forklifts, as highlighted by managers, the most impactful were purchasing price, lifting height and loading capacity, respectively. A less relevant but not insignificant role is also played by the possibility of being able to purchase spare parts and, therefore, to some extent also the maintainability of the machinery.

In line with this last aspect, Senker (2016) noted that in industrial contexts that makes use of forklifts intensively, it is of paramount to ensure that, when the trucks do break down, service and spares are readily available for minimizing the downtime.

On the bases of these premises, this article aims to analyse and identify the benefits of using trilateral forklifts rather than traditional forklifts within distribution centres. In accordance with several studies (e.g., Saputro et al. 2015), through this paper the selection of MHEs at an intermediate level will be addressed; using simulative tools and with a multi-criteria selection logic we proceed in order to quantify the performance of the two machines in question, and the benefits that can be derived from them.

A technical-economic analysis of two forklifts, derived from interviews with three of the leading manufacturers on the market today, is initially presented. Next, a simulation model developed using MS Excel™ software package will be used to implement these two alternative solutions within a warehouse in order to evaluate their performance.

The remainder of the paper is structured as follows: as anticipated, section 2 is dedicated to a brief overview on the main existing forklifts solutions; section 3 follows by proposing the methodology, including the nomenclature and the assumptions made when developing the simulation tool, which is detailed as well; section 4 deals with the case study in which the tool is implemented. Results are presented in section 5, followed by a discussion and conclusions in section 6.

2. Forklifts Overview

Forklifts are just one possible solution when manufacturers are challenged with the choice of material handling machinery to purchase for their operations, whether production or logistics within warehouses. Kay (2012) highlights how there are multiple aspects that distinguish MEHs, including the products they handle, their capability to perform given operations, or their power supply (manual or powered). The main powered forklifts use electric power supply or fuel (diesel or LPG); specifically, while electric power poses questions about optimizing pickup routes by having battery range as a constraint, fuel power also needs to be evaluated from the perspective of fuel consumption and emissions generated, as the study by Ziółkowski et al. (2022) shows.

Thanks to their flexibility, Kay (2012) declares that the counterbalanced forklifts are considered the "workhorses" of material handling. The main characteristics of this machinery are the huge number of degrees of freedom in their movements, the high Load capacity (ranging within 454 kilograms and 45.4 Tons) and their lift height that can reach 12 metres. These data are confirmed also in a recent study by Vita et al. (2023) who use a standard range of load capacity for the development of an analytical method for assessing the stability of this material handling machinery.

Another important aspect that differentiates this equipment is the ability of rotating the forks sideways relative to their direction of travel rather than having them mounted frontally and devoid of movement. This aspect strongly impacts the dimensions of the warehouse aisles in which they will have to travel, which may be narrower if there is lateral handling of the forks; this is because the operator will not need to rotate the truck to place himself directly in front of the storage compartment.

Based on this preliminary information, we can provide a general overview of the main forklifts nowadays in market and explored in major detail in this study from a technical and economical point of view. The overview is presented in Figure 1 where it can be clearly seen the reason of the choice of traditional and trilateral forklifts for this study. In fact, these are two strongly different solutions both in terms of maximum load capacity and in terms of maximum lift heights. In the case of trilateral trucks, much greater heights can be used than with traditional forklifts, and lower width of the aisle; however, this is at the expenses of much lower maximum load capacities that can be transported.

Therefore, understanding the disadvantages and advantages of these solutions will be important to make the best decisions within real-world contexts.

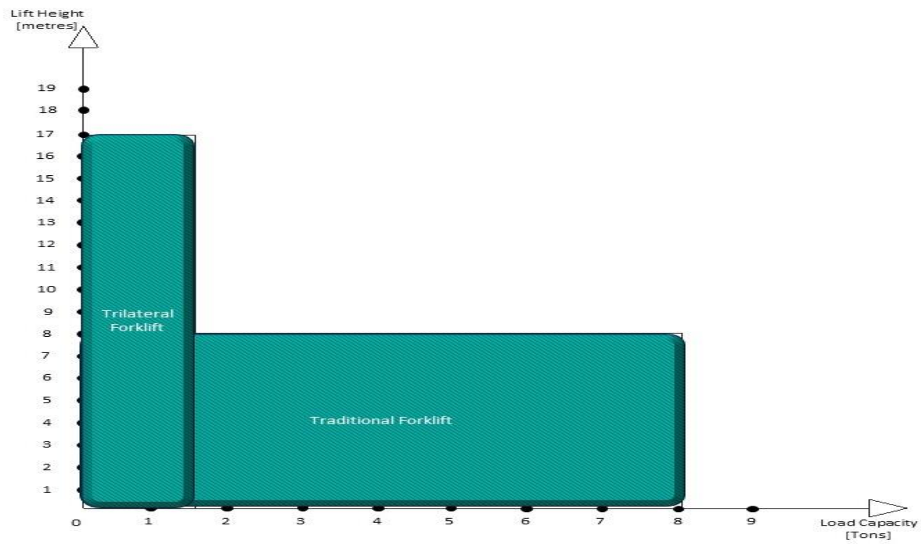


Figure 1. A general Forklifts' overview

3. Materials and Methods

3.1. Nomenclature

The nomenclature adopted in the present simulation study is proposed below in Table 1.

Table 1. Nomenclature

Symbol	Description
R	Storage Capacity
SL	Dimension of the Storage slot
Xf	Shape factor of the warehouse
I/O	Input/output position of pickers
EA	Aisles located in the front-part and in back-part of the warehouse
TA	Number of Cross-aisles into the warehouse
M_L	Number of different layout configuration considered for each scenario.
LO	Lines for every order
N_{LO}	Total number of different order size considered
O	Picking Order
Rout_Pol	Routing policy implemented during the picking activities
TRIL_F	Trilateral Forklift
TRAD_F	Traditional frontal Forklift
L_{EA}	Size of the Aisles located in the front-part and in back-part of the warehouse
L_{TA}	Size of the cross-aisles into the warehouse
d_m	Average of the distance travelled
SD(d)	Standard Deviation of the distance travelled
IPY	Number of different items processed in one year
D	Average of the Annual distance travelled for 300 000 items
%Red	Percentage of reduction of the distance travelled in the two different implementations
c_{picker}	Average cost per hour of a logistic operator
i	Interest rate
c_{saved}	Cost per year saved thanks to the implementation of Trilateral Forklift
n_{picker}	Number of pickers at work
t	Working time of a picker for picking operation
C	Investment Cost
PBP	PayBack Period

3.2. Preliminary Assumptions

This study will investigate two types of forklifts available on the market:

- Traditional frontal Forklift (TRAD_F)
- Trilateral Forklift (TRIL_F).

The two solutions were preliminarily analysed paying attention to their technical aspects. After a technical analysis, it was noted that for each type of forklift solution different warehouse layouts had to be considered in terms of minimum aisle width.

In particular, the implementation of TRIL_F involves a reduction in the width of the working aisles between different areas of the warehouse, but at the same time it requires a major width for those aisles designated for manoeuvring the forklift. These constraints are not present during the implementation of the TRAD_F, but the width aisle in this scenario is larger than the first scenario illustrated above.

In this context, it was therefore decided to adopt two different routing policies depending on the type of forklift used. Thus, with the utilization of the trilateral forklift, an S-Shaped Simple policy was adopted during which no cross-aisle are used, while in TRAD_F implementation, an S-Shaped Advanced was employed; this last policy allows the usage of the cross-aisle during the picking activities.

These policies were chosen in accordance with the model developed by Montanari et al. (2022), considering the constraints derived by the minimum width requested by the different forklifts. In particular, it is possible to assume that the advanced S-Shaped policy is the best routing for reducing the distances travelled by pickers in different warehouse configurations. However, the simple S-Shaped policy was preferred in this study for its simplicity of being implemented and capability to respond to constraints arising from aisle size.

Table 2 summarizes the preliminary conditions under which the simulation model was implemented.

Table 2. Preliminary assumptions.

Warehouse layout for TRIL_F		Warehouse Layout for TRAD_F	
Data	Value	Data	Value
L_{EA}	5 200 m	L_{EA}	5 200 m
L_{TA}	1 875 m	L_{TA}	5 200 m
Rout_Pol	S-Shaped Simple	Rout_Pol	S-Shaped Advanced

To complete the preliminary assumptions, the general characteristics of the warehouse are presented. More precisely, a single central picking (SCP) point was arbitrarily chosen for this study and kept unchanged for all the considered scenarios. The same logic was applied to the warehouse shape factor (Xf), set close to 1, in accordance with the geometric constraints, and the total storage capacity (R) of the warehouse, set at a fixed value of 640 picking locations.

Three different layouts, obtained starting with no cross corridors in the layout and then adding 1 and 2 cross corridors, respectively, were also included.

Figures 2a, 2b and 2c summarize the layout configurations considered for the implementation of TRAD_F. Similarly, the Figures 3a, 3b and 3c summarize the layout configurations considered for the implementation of TRIL_F. In this way, the analysis was performed on warehouses with 0, 1 or 2 cross-aisles.

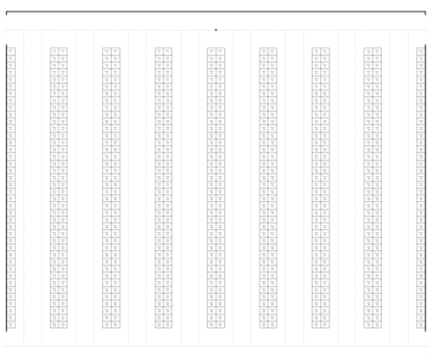


Figure 2a. Layout with 0 cross-aisle TRAD_F

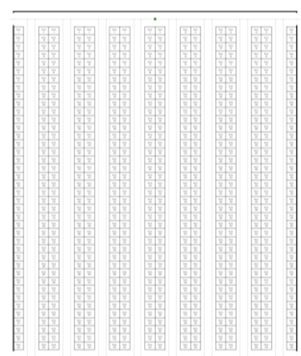


Figure 3a. Layout with 0 cross-aisle

TRIL_F

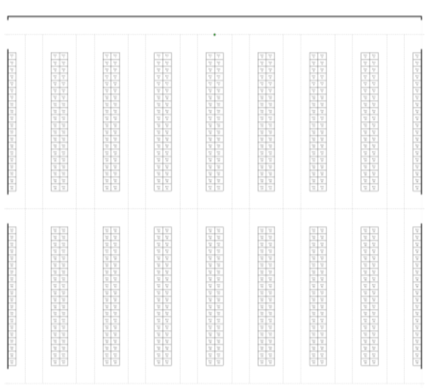


Figure 2b. Layout with 1 cross-aisle TRAD_F

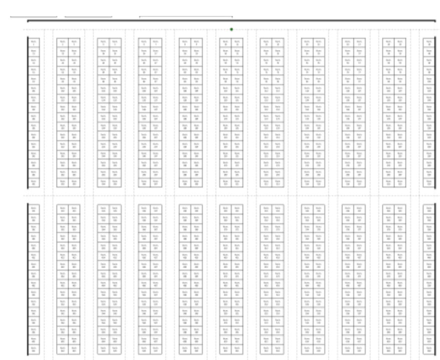
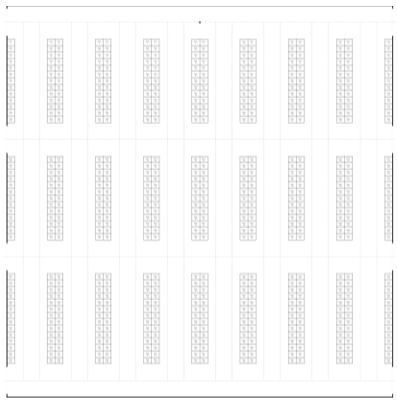


Figure 3b. Layout with 1 cross-aisle

TRIL_F



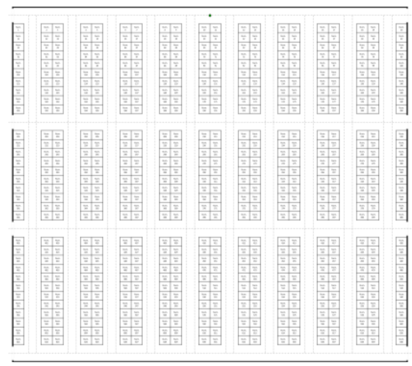


Figure 2c. Layout with 2 cross-aisle TRAD__F

Figure 3c. Layout with 2 cross-aisle

TRIL__F

3.3. Description of the simulation tool

The following is a concise scheme of the tool called "FORMULA 59" (depicted in gray in Figure 4) used for developing the simulation campaign. While only a limited set of features from FORMULA 59 were used in the simulation campaign, this section aims to provide a comprehensive description of all the potentialities of FORMULA 59, enhancing clarity for future extensions and developments.

Figure 4 illustrates the simulation model, which primarily consists of two interconnected parts.

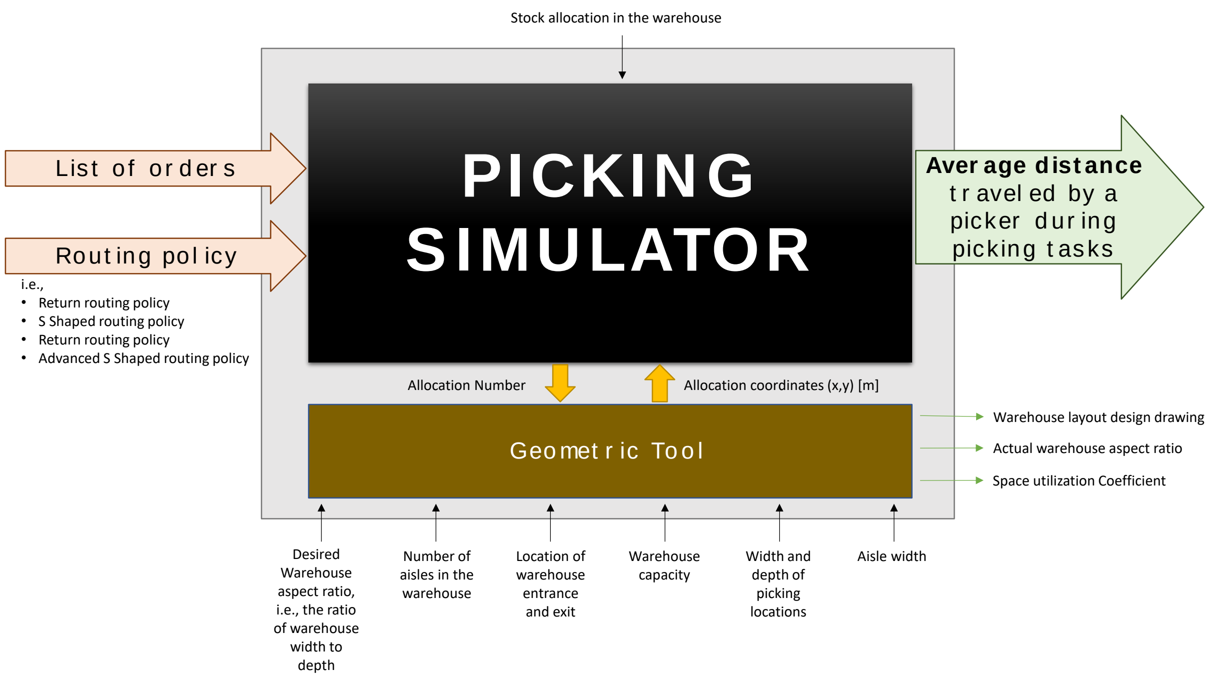


Figure 4. Work diagram of FORMULA 59

The first part, in brown, consists of the geometric tool. This tool constructs an abstract model of the warehouse and identifies the picking points for each allocation within the warehouse. To accomplish this, the tool employs various data inputs, including warehouse capacity, number of transversal corridors, allocation width and depth, corridor width, desired warehouse aspect ratio, as well as the input and output positions of the picker. By generating a virtual representation of the entire warehouse, the geometric tool determines the warehouse's size, shape factor, surface saturation coefficient, and, if needed, layout design. Notably, the warehouse's shape factor is subject to integer constraints, meaning that fractions of allocations or corridors cannot be considered. Consequently, the output and input shape factors may differ. Specifically, the output shape factor will be the one that most closely approximates the desired factor whilst satisfying the aforementioned integer constraints.

As previously stated, the geometric tool associates each allocation, in the virtual warehouse model generated, to the corresponding picking point, where the picker is positioned for order fulfillment operations. This model is used by the "picking simulator", black box in the previous Figure 4, whenever this information is required to calculate the distance for a picking mission in the warehouse.

Before being used, the picking simulator must be provided with instructions regarding the product allocation within the warehouse. In other words, it is necessary to define the product that will be stored for each allocation, along with its rotation index, which reflects the market demand for that specific item. In this paper the value of rotation index is fixed for all product and kept constant; future extensions can easily explore the impact of the rotation index on the results.

Once all the aforementioned data is available, the tool is employed to calculate the average distance covered by the picker during the picking mission. This is achieved by considering the list of orders requested by the market and selecting the desired routing policy within the warehouse.

There are several routing policies available to the user, including the Return Simple Routing Policy, the S-Shaped Simple Routing Policy, the Return Advanced Routing Policy, and the S-Shaped Advanced Routing Policy. As explained further below, in our study, we have adopted respectively, the Advanced S-Shaped Routing Policy and the Simple S-Shaped Routing Policy.

3.4. Simulation campaign

Based on the preliminary hypothesis, two different scenarios were considered: firstly, the implementation of TRAD_F and secondly the implementation of TRIL_F.

In each scenario, three layout variants (ML) were evaluated: no cross-aisles, 1 cross-aisle and 2 cross-aisles. Furthermore, four different picking list sizes (N_{LO}) were evaluated in terms of the total number of ordered lines (LO) for each pick list. Specifically, 10, 20, 50 and 100 LO were considered in this work.

The total number of simulations (N) carried out for each scenario is calculated by the Equation 1:

$$N = N_{LO} \cdot M_L = 4 \cdot 3 = 12 \quad (1)$$

Those twelve simulations are performed both for TRAD_F and for TRIL_F scenarios, and results are collected in terms of average distance travelled for completing one mission (dm) and its standard deviation (SD(d)). In terms of the replicates, 100 000 sample lists were randomly generated to guarantee the statistical validity of the results.

Based on this assumption, the simulations are conducted, and the results derived for a single mission are summarized respectively in Table 3 for TRAD_F scenario, and in Table 4 for TRIL_F scenario.

Table 3. Results for TRAD_F scenario.

TA	0				1				2			
LO	10	20	50	100	10	20	50	100	10	20	50	100
d_m [m]	342.13	450.47	523.93	589.92	309.96	430.82	553.94	631.18	317.77	443.83	579.95	670.73
SD(d) [m]	41.31	31.68	10.17	12.58	37.53	35.37	16.43	12.73	41.88	39.51	20.47	13.48

Table 4. Results for TRIL_F scenario.

TA	0				1				2			
LO	10	20	50	100	10	20	50	100	10	20	50	100
d_m [m]	309.62	385.41	415.99	439.67	308.47	402.78	454.57	478.83	321.02	419.79	473.31	497.58
SD(d) [m]	42.94	26.92	3.81	4.55	40.87	34.99	5.31	4.59	42.82	36.77	5.42	4.59

From the analysis of the listed above data, in both scenarios as LO increases, d_m also increases; this is due to a greater number of storage locations that must be visited to complete a mission. SD(d) is also affected by this factor, and, in this case, a decrease in the values is observed when LO increases.

4. Case Study

Based on the results described above, a case study was developed by implementing a TRAD_F solution and a TRIL_F solution in a warehouse with the same characteristics as specified above. A comparison of these two solutions has been performed and presented providing an initial reference for those real contexts that want to evaluate the implementation of these two types of MHE.

4.1. Technical Analysis

In the case study under examination, 300 000 different items (IPY) must be picked from a warehouse in one year.

The number of missions that need to be carried out turns out to vary depending on the LO to be included in each mission. The Table 5 summarizes the possible alternatives, calculated from Equation 2:

$$mission\ per\ year = \frac{IPY}{LO} \quad (2)$$

Table 5. Variable number of missions per year.

LO	Mission per year
10	30 000
20	15 000
50	6 000
100	3 000

All the three layout configurations (i.e., without cross-aisles, with 1 cross-aisles and with 2 cross-aisles) are used for both TRAD_F and TRIL_F. The remaining boundaries conditions and assumptions made for simulative campaign are kept unchanged for this case study.

Equation 3 illustrates the mathematical formula used to reach the total distance travelled in one year by operators to pick up 300 000 items:

$$D = mission\ per\ year \cdot d_m \quad (3)$$

In eq.3, d_m is taken from the results of simulations presented in Table 3 and Table 4. Whenever LO, the number of cross-aisle or the scenario analysed vary, d_m will change consequently.

As performance index, the percentage reduction (%Red) of the total distance travelled by pickers from the TRAD_F to TRIL_F scenario in one year is take, and computed as shown in Equation 4:

$$\%Red = \frac{(D_{m\_tril} - D_{m\_trad})}{D_{m\_trad}} \cdot 100 \quad (4)$$

The values of %Red obtained are presented in Table 6, and their trends illustrated in the Figure 5.

Table 6. %Red values.

	TA		
LO	0	1	2
10	-9.50%	-0.48%	1.02%
20	-14.44%	-6.51%	-5.42%
50	-20.60%	-17.94%	-18.39%
100	-25.46%	-24.14%	-25.82%

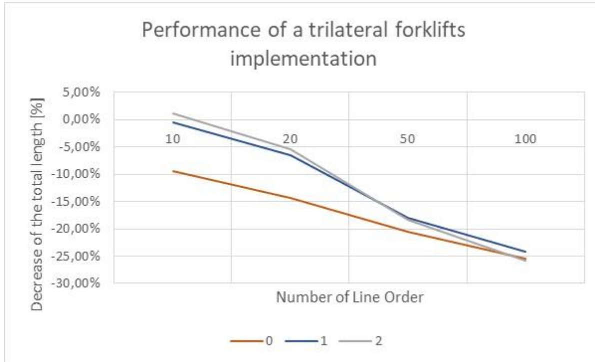


Figure 5. Trend of %Red, increasing the number of cross-aisles.

According to the results of the simulations, there is again a reduction in the distances travelled in a TRIL_F scenario as LO increases; accordingly, there is an increase in the %Red index.

Furthermore, in the case of LO equal to 100, it can be seen that the number of cross-aisles impacts on the overall performance in a negligible way. The reason is that an increase in the number of picking locations to be visited by the pickers reduces the differences in the tour resulting when applying different routing policies used.

4.2. Economic Analysis

Based on the %Red values in Table 6 above, an economic analysis was conducted for evaluating the PBP, i.e., the time horizon over which the purchase of a trilateral forklift is paid back based only on the savings resulting in the manpower cost.

Table 7 below shows the numerical values assumed for the analysis.

Table 7. Values of the parameters used in the economic analysis.

Parameter	Value
c_{picker}	35 €/h
C	60 000 €
i	5%
n_{picker}	5
t	1200 h/year

Equation 5 has been used for the evaluation of c_{saved} while the PBP was calculated using Equation 6:

$$c_{saved} = n_{picker} \cdot t \cdot (-\%Red) \quad (5)$$

$$PBP = \left\lceil \frac{C}{\frac{c_{saved}}{(1+i)}} \right\rceil \quad (6)$$

It should be noted that all terms entered in Equation 6 were used with the signs reversed.

5. Results

5.1. Results of the simulation campaign

The simulation campaign provided d_m values that increase with the increase in LO, regardless of the number of cross-aisles and of the scenario analysed (TRAD_F or TRIL_F).

A comparative analysis between TRAD_F and TRIL_F showed that in all three route variants, switching from the solution with a traditional forklift to a trilateral one leads to a reduction in the distances travelled; in particular, this effect is amplified as LO increases.

The Figures 6a, 6b and 6c illustrate these results.

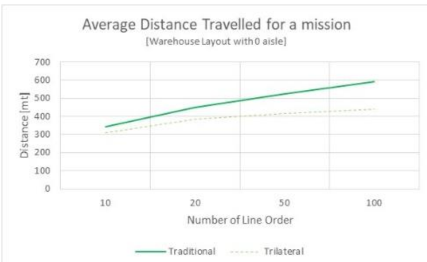


Figure 6a. Layout with 0 cross-aisles

Figure 6b. Layout with 1 cross-aisle

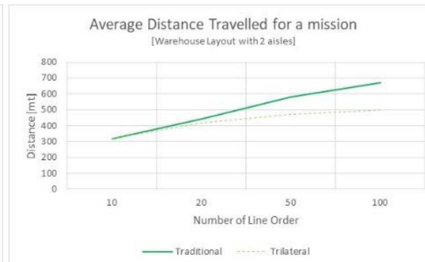


Figure 6c. Layout with 2 cross-aisles

In contexts with low values of LO there is almost no benefit from the implementation of trilateral forklifts. However, this is probably due to the design constraint of choosing a different picker routing policy. Indeed, with an S-Shaped Simple policy, the picker cannot use the cross-aisle. At the same time, there are not so many LOs to justify travelling completely through one aisle before entering the next one, as this type of routing would suggest. This disadvantage is not present in the TRAD_F scenario, in which an S-Shaped Advanced policy was involved. However, in a TRAD_F scenario there are much wider aisles, which means a greater distance between storage slots on opposite shelves and, consequently, among items.

Based on these considerations, for low LO values, the advantages of a TRIL_F scenario are not appreciable, but as LO increases, the number of storage slots to visit and the greater distance required to the aisles from a TRAD_F scenario impacts more on d_m making the TRIL_F scenario the best solution.

5.2. Results of the case study

In the technical analysis of the case study, 300 000 different items were used for generating a different number of picking missions per year depending on the different value of LO.

The total annual distance travelled by the pickers was computed and analysed in the two scenarios of TRAD_F and TRIL_F. As in the simulation campaign, three different layout conditions were studied: starting from no cross-aisle, passing to a configuration with only one cross-aisle and ending with two cross-aisles.

For each configuration the results are collected and presented in Table 8. Moreover, Figures 7a, 7b and 7c illustrate the trends of the total annual distance D.

Table 8. Comparison of the values of D[m], in the different contexts analyzed.

	TA					
	0		1		2	
LO	TRAD_F	TRIL_F	TRAD_F	TRIL_F	TRAD_F	TRIL_F
10	10 263.80	9 288.60	9 298.83	9 254.06	9 533.02	9 630.63
20	6 757.02	5 781.12	6 462.27	6 041.72	6 657.43	6 296.78
50	3 143.56	2 495.98	3 323.65	2 727.45	3 479.69	2 839.87
100	1 769.76	1 319.09	1 893.54	1 436.48	2 012.20	1 492.73

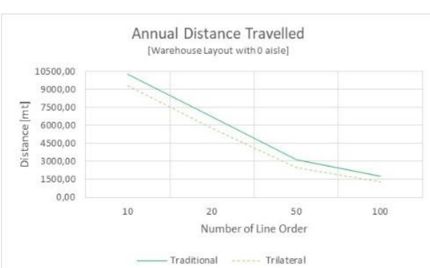


Figure 7a. 0 TA Layout **Figure 7b.** 1 TA Layout **Figure 7c.** 2 TA Layout

In all the analyzed cases, the implementation of the trilateral forklift allows to achieve a general increase in performance, reducing the total distance travelled by the picker. In the presence of cross-aisles in the warehouse layout, the impact of the different routing policies implemented is more evident when LO is low. The maximum reduction (%Red) in the distance travelled after the implementation of trilateral forklifts and under these conditions is 25%.

On the other hand, in the economic analysis it was assumed that 5 pickers work actively in picking operations for a total annual time of approx. 6 000 hours.

Based on the %Red values obtained from the technical analysis, and considering the assumptions described in Section 4.2, the c_{saved} for each scenario was estimated. Specifically, the cost derived from the amount of hours saved due to the implementation of the trilateral forklifts.

The next Table 9 illustrates the results obtained when varying LO and the number of cross-aisles of the warehouse.

Table 9. Values of c_{saved}.

	TA		
LO	0	1	2
10	19 952.76 €	1 011.07 €	-2 150.11 €
20	30 329.93 €	13 666.26 €	11 376.05 €
50	43 260.17 €	37 670.27 €	38 613.52 €
100	53 475.83 €	50 689.72 €	54 213.93 €

From these outcomes it is possible observe that for low values of LO, the cost saving is in general low and in one case, it is negative, meaning that an economic loss will result when choosing this type of MHE.

The PBP was thus evaluated to determine the number of years required for the investment to be paid back thanks to the benefits just described. Table 10 show the results:

Table 10. PBP values.

	TA		
LO	0	1	2
10	4	-	-
20	3	5	6
50	3	3	3
100	2	2	2

These results confirming what has just been observed in the case of low LO values; in fact, in these cases the investment cannot be repaid. On the other hand, for higher values of LO the investment is paid back in a reasonable time (3 years or less).

So, also from an economic point of view, the advantage of trilateral forklifts increases from low size of the picking list to wider ones and, more specifically the convenience of the choice is confirmed.

6. Discussion and conclusions

The correct choice of the MHE is crucial for improving the performance of the entire warehouse. The most important equipment nowadays into the market for this kind of activities are forklifts trucks, whose two main categories are traditional frontal forklifts and trilateral forklifts.

In the present manuscript, after a technical analysis of these two different solutions, it was noted that the main difference is in terms of minimum width of the aisle into the warehouse. Trilateral forklifts work with a minimum width of 1.875 meters of the work aisles, but the minimum width of the transit aisle increase up to 5.20 meters. On the other hand, traditional forklifts are a unique minimum width of 5.20 meters for all kind of aisles.

Under these conditions, a simulation campaign was carried out in which both the solutions were implemented in different layouts thanks to the variations of number of cross-aisles. In order to respect the constraints derived from the minimum width of the different solutions, it was decided to implement two different routing policies during the picking phase.

After simulating 100 000 picking lists for each configuration analyzed, it could be concluded that the implementation of trilateral forklifts increases warehouse performance by up to 25%. This means that the average value of the distance travelled by the pickers to complete a single mission is up to 25% lower if the use of trilateral forklift is implemented in the warehouse, compared to the traditional forklift. The only case in which the performance of these solutions is similar is when the number of lines populating the mission is low.

This result is due to the two different policies adopted to respect the minimum width constraint. Under these conditions, when the picking mission contains more order lines, the number of storage locations to be visited increases and the type of routing policy impacts to a lower extent on the length of the resulting tour. For small values of order lines, the maximum increase of performance of the trilateral forklifts is observed under the total absence of cross-aisles. In fact, under these conditions, both policies do not make use of cross-aisle, which represents the only difference between them.

The same results are confirmed after implementing the distance data obtained using the simulation into a case study, where during a year the picking of 300 000 different items is requested.

In this case study the same assumptions considered for the simulations are maintained, and the total distances covered by the pickers are calculated for the two different solutions. From these data the %Red in one year moving from traditional forklifts to trilateral forklifts is calculated. Even in this context, the implementation of the trilateral forklifts generates a reduction of the distance travelled in all the analysed cases with a maximum level of decreasing close to 25%.

From an economic perspective, it could be seen that the investment in these forklifts can be paid back around 3 years in all the most common cases, which are those characterized by intermediate values of LO. It should be emphasized that this solution is not effective if the picking missions consists in few LO. In that case, the warehouse configuration, under the conditions studied, plays instead a relevant role.

Finally, there are other positive aspects that have not been addressed in this work but that a trilateral forklift solution owns. The main one is the higher exploitation of the warehouse surface for storage; in fact, the lower width of the aisles admits a major surface covered by the storage slots. This involves two different possibilities: (i) a major storage capacity of the warehouse, or (ii) a smaller storage area required in the warehouse and, consequently a wider area available for other activities. The second important aspect is the higher value of the maximum height at which a trilateral forklift can work. Again, this aspect could further increase the storage capacity of the warehouse.

For future research developments, it would be interesting to evaluate other layout configurations with changes to the shape factor, for confirming the technical validity of the solution. In addition, performance could be assessed by implementing the same routing policies in both scenarios, checking whether the lowering of the surface saturation resulting from the increase in the size of the cross-aisles can be balanced by the possibility of using S-Shaped Advanced policy even with trilateral forklifts.

Furthermore, it would be interesting to extend the economic analysis by analysing all cost items affecting picking activities and MHE.

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