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AS/RS travel time with horizontal deployment in class-based storage areas: a new formula

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ABSTRACT

The enhancement of warehouse processes is pivotal in internal logistics activities and it is a lever of competitive advantage for companies that are operating in more turbulent business environment. Thus, this paper proposes a model for the accurate computation of travel time of automated warehouse systems under different configurations. The model is based on a simulation approach that is run with different levels of Input/Output (I/O) points, different shape factor values and rotational flows. The outcomes of the simulation are then analysed using regression analysis. The results obtained prove to be very accurate for a reliable calculation of travel times. Therefore, the proposed formula can be considered as an effective support for an accurate estimation of the travel time for a variety of automated warehouse configurations. The proposed work might be also supporting future studies focused on the warehouse design under different storage space shapes and operational conditions.

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Warehouse; AS/RS; travel time; class-based storage; simulation and regression analysis

1. Introduction

In recent decades, global supply chains have become an important part of all business sectors, and warehouses play a significant role in providing a continuous and reliable supply of goods to meet customer needs. Consequently, warehouse management is considered crucial to logistics operations and, as such, requires the effective design of warehouse facilities (Mangano & De Marco, 2014; Weber et al., 2023), as part of the design of optimized supply chain networks (Shahsavani & Goli, 2023).

Nowadays, the integration of warehouse management systems and Industry 4.0 technologies have stimulated the adoption of automation in the main warehouse activities, such as storing, picking, sorting, packaging, and shipping (Simic et al., 2023). In this context, Automated Storage and Retrieval Systems (AS/RSs) are considered highly valuable to businesses and are among the most critical solutions in the modern logistics

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industry. Moreover, they form the basis for advanced manufacturing automation solutions (Cagliano et al., 2021).

The estimation of the stacker crane travel time, also known as cycle time and defined as the time the automated handling machine takes to perform either a storage or retrieval task, is a key aspect in the design and operation of AS/RSs. In fact, it determines the warehouse responsiveness and in turn its throughput capacity (Azadeh et al., 2019). A lot of literature contributions addressing the evaluation of AS/RS travel times have been developed over time. Numerous research works are available that discuss many approaches to exploit empirical models (Schenone et al., 2020), simulation (Zammori et al., 2021), and analytical models to estimate travel time (Manzini et al., 2016). However, most of the literature considers warehouse configurations where the storage area has a vertical deployment. On the contrary, the present paper aims to propose a mathematical formulation for the estimation of the AS/RS travel time with the following characteristics, which are here considered simultaneously: horizontal warehouse deployment, where the travel time to reach the maximum length of the storage area is longer than the total vertical time, variable location of the Input/Output (I/O) point, dual command (DC) cycle, and class-based inventory policy. The novelty of the contribution lies in the combination of these features of the problem, as the literature mostly considers each of the above-mentioned aspects independently. Additionally, the focus on the class-based storage allocation policy and the DC cycle allows to overcome the limitations of the Bozer and White (1984)'s formula also in the case of warehouses with horizontal deployment.

The paper is structured as follows. First, an overview of the relevant literature is discussed, focusing on the approaches to calculating travel times in AS/RSs. After that, the methodology adopted to conduct this research is described, together with the assumptions of the proposed model. Then, the results are presented and discussed. Finally, implications and conclusions are traced.

2. Literature review

The impact of different design parameters and hypotheses on the performance of AS/RSs has been extensively studied for many years (Alnahhal et al., 2022; Borovinšek et al., 2017; Sternad et al., 2018; Yan et al., 2023). In particular, among the parameters, the estimation of the travel time of the stacker crane plays an important role in the assessment and analysis of the AS/RS throughput as it can improve the operational performance and handling capacity of a warehouse system (Metahri & Hachemi, 2018; Mirzaei et al., 2021; Rizqi et al., 2023). The earliest mathematical approach to calculate the travel time in AS/RSs is introduced by (Hausman et al., 1976). Later, Sarker and Babu (1995) provide a thorough assessment of various approaches to computing travel time, offering insight into research developments and advancements at the end of the last century. The authors suggest that more studies are needed to estimate travel times by considering the impact of the AS/RS design and operational characteristics, such as the rate at which orders arrive, the location of the orders, and the probability distribution of the ordered quantities, which can be a dominating factor in the physical design. In this section, the authors will go over the primary methods for calculating travel time in automated warehouses with various operational hypotheses and design characteristics. They are divided into two subsections, namely the travel time computation under different storage physical design configurations and warehouse allocation policies.

2.1. Calculating cycle time under different storage design configurations

A main reference approach in this field is that developed by (Bozer & White, 1984), who propose a model to estimate the cycle time in AS/RSs, focusing on single command (SC) and DC cycles. They propose travel time models for single-shuttle AS/RSs based on a rectangular rack configuration under a random storage allocation policy and with different positions of the I/O point. Bozer and White's work has been followed by several papers, such as Roodbergen and Vis (2009), which attempt to provide a complete picture of the state of the art in AS/RS travel time computation by conducting a comprehensive literature review focusing on warehouse design decisions and operational criteria. More specifically, they analyse the combination of different physical design aspects and operational strategies to optimise travel times. The key result is a proposal for further research utilizing analytical and simulation travel time models for single-aisle, multiple I/O point, and multi-shuttle AS/RSs.

Thus, based on the recommendations of Roodbergen and Vis, some researchers have conducted studies to introduce refined approaches for calculating travel times under various assumptions (Lehmann & Huβmann, 2022; Lerher et al., 2021). In particular, Ghomri and Sari (2017) present a simulation model relying on continuous mathematical functions to estimate the amount of time stacker cranes require for traveling in multi-aisle AS/RSs, considering both SC and DC cycles. The subsequent research is carried out by (Liu et al., 2018), where the authors introduce an evaluation model to estimate the expected travel time of storage and retrieval machines under DC cycles and different control parameters, such as I/O dwell point policies. Also, Xu et al. (2018) propose a travel time computation model for DC cycles by considering a lower midpoint I/O dwell point policy, where the input and output points are located at the bottom of the storage system. As a result, the DC cycle demonstrates superior travel time performance when compared to the SC cycle. Recently (Lerher et al., 2021), develop a travel time calculation model for SC and DC cycles of automated vehicle storage and retrieval systems under a fixed I/O point position and with multiple-level shuttle vehicles. Another recent development of AS/RS travel time computation models based on the S/R machine configuration is proposed by (Iç, 2022). This study aims to determine the expected cycle time of a unit-load AS/RS for both SC and DC cycles. It introduces the concept of diagonal speed, which represents the combined effect of the horizontal and vertical speed components of the storage/retrieval (S/R) machine. The proposed model is found to be more realistic and can be used as a suitable tool for the design of different variously sized AS/RSs.

As the AS/RS travel time depends on a number of heterogeneous physical design characteristics, some academics also address the effect of rack configuration on the calculation of AS/RS cycle time. For example (Vasili et al., 2007), present a statistical model for calculating the projected travel time of a specific type of AS/RS, namely a split-platform (SP) AS/RS, which has distinct mechanisms for horizontal and vertical movement. This design configuration can increase both throughput and handling capacity. The reliability of the proposed model has been confirmed through testing using Monte

Carlo simulation. Additionally, this work is extended by (Vasili et al., 2012), where the authors consider a SP AS/RS equipped with two I/O points located at the opposite ends of each aisle at floor level. Both stations can perform input and output functions. The most effective travel time model is achieved when the shape factor under the two I/O points is equal to 2. The shape factor is the minimum value between the ratios T_{height}/T_{max} and T_{length} /T_{max}, where T_{height} is the vertical stacker crane travel time, T_{length} is the horizontal time and T_{max} is the maximum time between them. Again concerning the shape factor, Schenone et al. (2019) present a revised formulation of the Meller and Mungwattana (1997) model to calculate AS/RS travel times. Their formula is designed using a simulation model and replaces the constant factor, which multiplies the travel between time, with a variable computed based on the rack features.

Other researchers build upon the previous work of (Xu et al., 2018) by examining four different I/O policies, namely I/O points on the two sides of the rack, I/O points on only one side in an elevated position, I/O points on the two sides in an elevated position, and finally I/O points in an elevated position at the midpoint of the rack height (Xianhao Xu et al., 2020). Among them, elevating the I/O points to the midpoint proves to be the most effective in minimizing travel time. Additionally, the square-in-time rack configuration is considered the optimal system structure. Alnahhal et al. (2022) aim to improve the travel and service time in AS/RSs by considering two alternative positions for the I/O station, which are at the lower left corner and below the centre of the storage rack height. In addition, at the beginning of each shift, they reallocate empty tote bins to reduce travel time by moving bins that will be needed in the next few hours closer to the I/O point. As a result, this combined strategy significantly increases the throughput rate by reducing the total stacker crane travel time. Recently (Lehmann & Huβmann, 2022), propose four travel time models for SC and DC cycles in multi-deep AS/RSs under an analytical continuous rack model, which is square in time, where the I/O point is fixed in place at the lower left corner of the storage system., Hoshimov et al. (2024) introduce a novel travel time calculation model for both SC and DC cycles, which aims to extend the' (Bozer & White, 1984)s equations under the following characteristics: variable vertical position of I/O stations and an allocation policy for storage based on classes. More recently, Oulhaci et al. (2024) have been proposed an optimization modelling of SC time by focusing on the unit load design parameters, namely applying one crane per aisle configuration in AS/RS.

2.2. Calculating cycle time with various storage assignment policies

In addition to the effects of physical design parameters, warehouse control policies also play a crucial role in determining the time performance of AS/RSs. Among them, storage assignment, batching, and dwell points policies are of paramount importance to improve warehouse operations through an accurate and more reliable estimation of the S/R machine cycle time (Roodbergen & Vis, 2009). To lay the foundation for the present work, this subsection reviews the AS/RS travel time computation models under different storage assignment strategies. In the next, the authors discuss the most commonly used ones, such as random, dedicated, and class-based storage.

The random storage allocation policy adopts an arbitrary approach to assigning locations to parts. The most suitable location is chosen from the accessible empty cells so that there is an effective use of space. However, it takes more time to identify the products to be picked and requires longer travel distances (Chackelson et al., 2011). The earliest travel time model considering random storage was introduced by (Bozer & White, 1984). Later (Koh et al., 2002),present a computational model for estimating the cycle time of AS/RSs for SC and DC cycles where the warehouse layout is circular and a tower crane S/R machine can move simultaneously in rotational and radial directions. Recently (Lehmann & Hußmann, 2021), present a model that calculates the travel time of multi-deep AS/RSs for SC and DC cycles along with a continuous storage rack approximation. The I/O point is fixed in the lower left corner of the racks.

Dedicated storage provides a fixed location for each stock-keeping unit (SKU) so that warehouse operators know where each product is located. On the other hand, this allocation is not the most advantageous storage strategy for C-class items, where hundreds or thousands of items with low turnover are stored (Chackelson et al., 2011). A few papers in the literature use a dedicated storage allocation policy to compute the AS/RS travel time. The oldest study is by (Mansuri, 1997) who discusses the significance of space, speed, and storage assignment policies. Some years later (Eldemir et al., 2004), introduce an analytical model to calculate the cycle time of the stacker crane for both SC and DC cycles by assuming a dedicated storage allocation policy without restricting the value of the shape factor to 1. Recently (Metahri & Hachemi, 2018), develop a continuous model, which is compared with a discrete model through simulations, to compute the retrieval time in AS/RSs equipped with free-fall flow racks. Their approach can be applied to different types of warehouses, including distribution centres and manufacturing warehouses.

Finally, the class-based storage assignment policy integrates several of the characteristics of both the random and dedicated methods discussed above. Under this strategy, SKUs are classified on the basis of their frequency of movement and inventory turns from an ABC analysis. Each product class is then assigned to a dedicated storage zone and the associated SKUs are randomly located within that zone so that the fastest-moving items are stored in more accessible locations (Khanorkar & Kane, 2023). In the last decade (Bortolini et al., 2015), present an analytical model to calculate the expected cycle time of the S/R machine in the standard ABC class-based environment. Again, the authors evaluate the average cycle time for both SC and DC cycles with different warehouse shape factors and determine the optimal assignment based on the values of skewness and shape factor. Furthermore, the most appropriate rack configuration under a class-based storage policy is addressed by (Ekren et al., 2015), to assess the travel time of shuttle-based AS/RSs in high-transaction environments. Later, a novel equation extending the formula of (Bozer & White, 1984) is proposed by (Schenone et al., 2020), which combines simulation with regression analysis. They aim to calculate the travel time in AS/RSs under class-based storage by focusing on the shape factor and different turnover rates of the stored goods. More recently, Hoshimov et al. (2024) extend the work of (Schenone et al., 2020) by considering a not-fixed vertical location of the I/O point along with both SC and DC cycles. Finally, Yu (2024) has presented a travel time estimation modelling and optimization under two class based storage policy for multi aisle AS/RSs. As a result of this work, optimized contour-shaped class boundary has been applied with class-based storage that can improve notably the average expected cycle time of multi-aisle AS/RSs.

The literature review shows that AS/RS travel time calculation has attracted the interest of many researchers over time. However, approaches that consider both SC and DC cycles and integrate different physical warehouse design characteristics, including variable vertical position of the I/O point and horizontal deployment of the storage area, are still lacking when it comes to class-based storage assignment policy. In this context, a limited number of contributions develop extensions of the Bozer and White (1984) equation by taking into account the physical flow of stored parts and how long they remain stored. Finally, the joint application of simulation and statistical methods, allowing the use of simulation results to derive mathematical models that are easily applicable to warehouse environments, is an area that deserves further exploration.

This work advances the research of (Schenone et al., 2020) and (Hoshimov et al., 2024) by focusing on a horizontal deployment of the storage area and not a vertical one as in the two aforementioned contributions and in most of the available literature works on travel time calculation. A simulation model and regression analysis are integrated to allow for estimating the traveling time of stacker cranes within AS/RS. The main objective is to expand upon the findings achieved by (Bozer & White, 1984) for DC cycles with a horizontal deployment of the storage area, a class-based storage policy, and a not fixed vertical location of the I/O point.

3. Methodology

The research has been developed according to the following steps. First, a simulation model was developed able to represent the warehouse space considering three different rotation areas, according to the ABC policy, by varying a set of identified crucial factors. The model was validated, in order to obtain consistent outcomes. Finally, a regression analysis was carried out so that to get to a formulation for computing the travel time.

3.1. Description of the simulation model

In the study of logistics and warehousing systems, the simulation approach has been extensively considered as a powerful tool to investigate the behaviour of the related processes by developing different scenarios (Cagliano et al., 2014; Hoshimov et al., 2021; Mangano et al., 2019).

The simulation approach is here chosen because it is deemed to be the best way to analyse the complexity of the addressed system. A mathematical modelling approach to determining the stacker crane travel time would require a statistical evaluation of the average times for each of the three phases of a combined storage and retrieval cycle (from the I/O point to the storage point; transfer of the stacker crane from the storage point to the picking point; and from the picking point to the I/O point) with storage areas characterized by different turnover rates. Mathematical models are usually associated with storage areas with the same access probability and have limited applicability in the case of an I/O point that might be at a given height from the floor. Additionally, the complexity of the mathematical problem is because the areas that can be associated with the different turnover rates can assume completely different shapes depending on the warehouse configuration considered (shape factor, I/O point, flow rates, and days of supply). Such variability does not allow the definition of a single mathematical model that can always be applied. These different shapes, which cannot always be traced back to basic geometric figures, have a significant impact on the evaluation of the travel time, together with the probability that the storage and the picking points are located in the high, medium, or low rotation area, thus generating multiple scenarios to be considered.

The present research creates a simulation model running on Microsoft Excel®. Its two worksheets contain the input and output data, and the simulation runs. Following an ABC storage allocation policy, this study divides the warehouse storage area into three distinct zones dedicated to storing high, medium, and low turnover SKUs, respectively.

Then, a number of variables are identified that are expected to influence the travel time of the stacker crane in a class-based storage system. These are the days of supply and the product flow rate for each storage area. The latter is calculated as the percentage of items moved in a given area out of the total number of items moved in the warehouse. These two variables make it possible to calculate the third variable considered, which is the physical space allocated to each storage area as a proportion of the total warehouse area, according to Equation (1). The days of supply represent the duration for which the inventory in the warehouse can meet demand needs without new incoming deliveries (Praharsi et al., 2022). The quantity of pick-up and delivery services for the products belonging to a specific class determines the product flow for each area (Ang & Lim, 2019). In particular, the flow rate and the days of supply are here defined as follows:

- High rotation flow rate: HRf
- Medium rotation flow rate: MRf
- Low rotation flow rate: LRf
- Days of supply for high rotation area: HRd
- Days of supply for medium rotation area: MRd
- Days of supply for low rotation area: LRd.

Also, when HRf and MRf are given, LRf can be obtained as 1- (HRf+MRf).

All the defined quantities can be used to express the storage space associated with each product class as per Equation (1)

$$\mathrm{X}_{area}\% = \frac{XRf*XRd}{HRf*HRd + MRf*MRd + LRf*LRd} \tag{1}$$

where X is H (high), M (middle), or L (low).

It can be stated that the division of storage space into various areas is not determined by the days of supply but is instead based on the daily flow of unit loads (Hoshimov et al., 2024). For this reason, HRd is fixed at a constant value of 1 and has not been considered in the analysis. In the same way, LRf can be derived from HRf and MRf as stated above. Finally, one additional variable is considered: the shape factor Height Length (h_l) which is obtained as the ratio between the horizontal and vertical travel time values. Thus, it is equal to 1/b, where b is the parameter in the Bozer and White's formula (Bozer & White, 1984). h_l ranges between 1 and 2. When it is equal to 1, the storage area is squared in shape. When it is equal to 2, the width is double the height.

Table 1. Simulation variables.

	Acronym	Min	Max	Step Increase
Shape Factor	h_l	1	2	0.2
I/O Point	$T_{i/o}$	0 %	50 %	12.5 %
High Rotation Flow	HRf	60 %	76 %	4 %
Medium Rotation Flow	MRf	10 %	20 %	3.3 %
Days of Supply for Medium Turnover	MRd	3	6	1
Days of Supply for Low Turnover	LRd	10	20	3.3

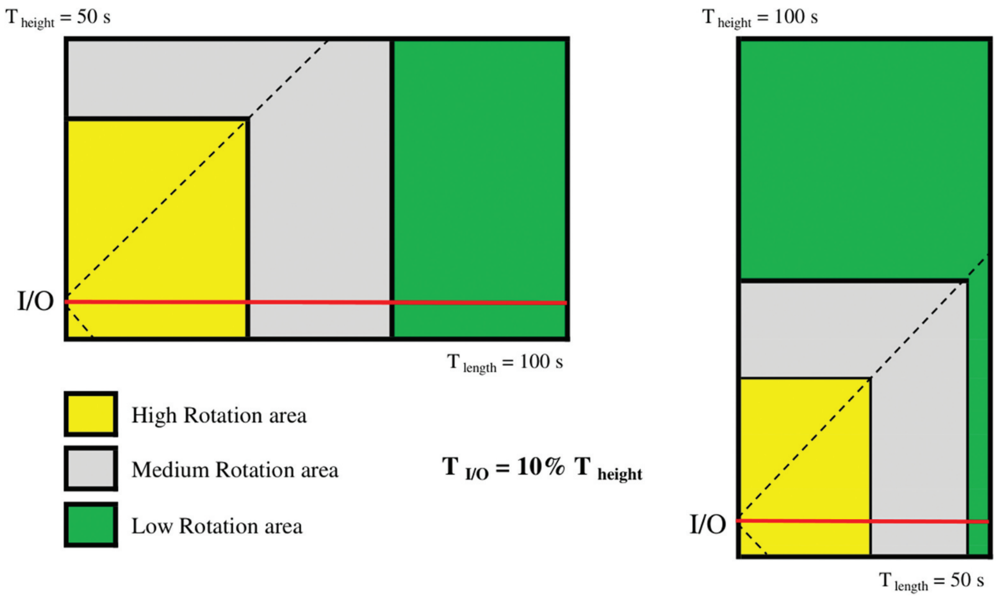

Figure 1. Classification of class-based storage space for horizontal and vertical warehouse.

Table 1 summarizes the ranges of possible values of the variables relevant to the simulations in order to obtain the stacker crane travel time values.

As h_l ranges between 1 and 2, the warehouse storage area under study is horizontal in shape. A dedicated travel time calculation model needs to be designed just for this situation. In fact, the shape of the three good rotation areas (High, Medium and Low) is significantly different compared with the vertical configuration of the storage space, as illustrated by Figure 1.

The developed simulation model generates random positions of warehouse locations to be visited for both storing and picking unit loads. A dedicated Microsoft Excel® macro has been created to compute the stacker crane travel time associated to each performed cycle according to the assumptions made, the different warehouse configurations as per Table 1, and a DC cycle.

In particular, 9,600 different warehouse configurations are considered and each of them is simulated five times. In turn, each travel time obtained is the average value out of 1,000 simulation runs. Such a high computational complexity is introduced to minimize the random error, thus increasing the reliability of the outcomes (Ives, 2022). Therefore, the output is constituted by 48,000 travel time values coming from 48 million simulation runs computed by the aforementioned macro.

The simulation returns three values for each warehouse configuration:

- T: the average stacker crane travel time for each performed cycle according to the warehouse configuration considered.
- Std.dev (T): the standard deviation of the travel time calculated over the 1,000 simulation runs that are carried out.
- T/T_{max}: the average travel time normalized by the maximum travel time according to the considered storage area deployment, which is T_{length}. This will be the response variable in the development of the regression model.

The simulation outputs are validated based on both literature and real case studies. To this end, the authors focus on the relevant existing works, mainly considering the I/O point situated at ground level (Bortolini et al., 2015), since few contributions addressing a not fixed vertical location of the I/O point are currently available (Hoshimov et al., 2024). In addition, a first field validation attempt is made by comparing the simulation results with some real automated warehouse settings.

Table 2 presents an excerpt from the simulation summary table. The columns on the left provide the input values of the shape factor h_l, the I/O point position as a percentage of T_{height}, the high and medium rotation flow rates (HRf and MRf respectively), and the days of supply for the medium and low rotation areas (MRd and LRd respectively). The number of days of supply associated with the high rotation area is assumed to be equal to 1 coherently with the previously discussed relationship among HR, MR, and LR. The three final columns on the right show the simulation outcomes: T, Std.dev (T), and $T/T_{max.}$

3.2. Description of the empirical approach (regression analysis)

Regression analysis is an empirical approach designed to investigate whether a set of independent variables can have a positive or negative impact on a dependent response

Table 2. Excerpt from simulation input and output values.

DUAL CYCLE COMMAND								
Input/Variable						Output/Variable		
h_l	$T_{i/o}$	HRf	MRf	MRd [day]	LRd [day]	T [s]	Std.dev(T) [s]	T/T_{max}
...	...	...	...	...	...	...	...	...
1	12.5%	60%	10%	3	10	110.96	52.22	1.1096
1	12.5%	64%	10%	6	16.6	102.24	54.42	1.0224
1.4	25%	64%	16.6%	4	13.3	94.61	48.22	0.9461
1.4	25%	68%	20%	5	13.3	94.84	46.06	0.9484
...	...	...	...	...	...	...	...	...
1.6	37.5%	68%	13.3%	3	20	77.79	50.42	0.7779
1.6	37.5%	72%	16.6%	4	10	92.15	43.05	0.9215
2	50%	60%	13.3%	5	16.6	82.62	55.52	0.8262
2	50%	76%	20%	6	20	79.42	40.15	0.7942
...	...	...	...	...	...	...	...	...

variable (here T/T_{max}) (Ferrari et al., 2023). This method was selected since it is broadly adopted for capturing dependencies between a dependent variable and a set of other independent continuous predictors. A positive influence shows that an increase (or decrease) of the independent factors brings an increase (or decrease) in the dependent one and vice versa. The degree of significance attributed to each independent factor is quantified by the p-value. If the value in question is below a critical threshold, typically equal to 5%, the relationship can be considered to be significant (Zenezini et al., 2022). The notion of significance can be associated with the reliability of the relationship instead of its strength. As the relationship between the independent factors and the response variable might exist but it could be not linear, quadratic factors have been also included in the analysis. The reference regression model is given by Equation (2).

$$\begin{aligned} T/T_{max} = {} & \beta_0 + \beta_1{*}h_l + \beta_2{*}T_{i/o} + \beta_3{*}HRf + \beta_4{*}MRf + \beta_5{*}MRd + \beta_6{*}LRd + \beta_7{*}h_l^2 \\ & + \beta_8{*}T_{i/o}^2 + \beta_9{*}HRf^2 + \beta_{10}{*}MRf^2 + \beta_{11}{*}MRd^2 + \beta_{12}{*}LRd^2 + \beta_{13}{*}h_l{*}T_{i/o} \\ & + \beta_{14}{*}h_l{*}HRf + \beta_{15}{*}h_l{*}MRf + \beta_{16}{*}h_l{*}MRd + \beta_{17}{*}h_l{*}LRd \\ & + \beta_{18}{*}T_{i/o}{*}HRf + \beta_{19}{*}T_{i/o}{*}MRf + \beta_{20}{*}T_{i/o}{*}MRd + \beta_{21}{*}T_{i/o}{*}LRd \\ & + \beta_{22}{*}HRf{*}MRf + \beta_{23}{*}HRf{*}MRd + \beta_{24}{*}HRf{*}LRd + \beta_{25}{*}MRf{*}MRd \\ & + \beta_{26}{*}MRf{*}LRd + \beta_{27}{*}MRd{*}LRd \end{aligned} \tag{2}$$

HRd is not here considered as its value has been set equal to 1.

A total of 28 regression coefficients (β_i) have been considered. As this number is quite high, the model is complex to be understood, together with the related outcomes. Thus, after the regression has been completed, both the total standard error and the t-student value for each coefficient have been observed. The t-student value is a relevant indicator, since the lower its value, the lower the influence of the associated coefficient on the regression model (Shah et al., 2014). Thus, the factors with the lowest t-student values were iteratively removed one by one from the regression model. After 17 iterations, the level of error associated with the regression increased dramatically, meaning that the level

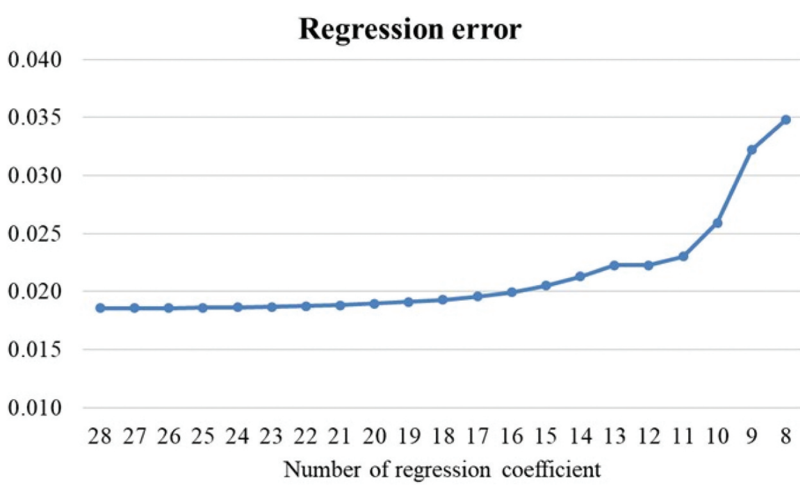

Figure 2. Total standard error for each regression carried out.

of precision of the regression decreased. As a consequence, the iteration process of discarding coefficients stopped. The behaviour of the error for each regression is presented in Figure 2.

Equation (3) shows the final regression model; a total of 12 regression coefficients, including the constant value β_0, have been considered.

$$\begin{aligned} \boldsymbol{T/T_{max}} = {} & 4.4505 - 0.4747 * \boldsymbol{h_l} - 0.9014 * \boldsymbol{T_{i/o}} - 7.0850 * \boldsymbol{HRf} - 5.0533 * \boldsymbol{MRf} \\ & - 0.0138 * \boldsymbol{LRd} + 0.1436 * \boldsymbol{h_l}^2 + 0.6879 * \boldsymbol{T_{i/o}}^2 + 4.7551 * \boldsymbol{HRf}^2 + 0.1973 \\ & * \boldsymbol{h_l} * \boldsymbol{T_{i/o}} - 0.3037 * \boldsymbol{h_l} * \boldsymbol{HRf} + 7.9739 * \boldsymbol{HRf} * \boldsymbol{MRf} \end{aligned} \tag{3}$$

4. Results analysis

Preliminary to the discussion of the outcomes of the regression analysis, it is worth pointing out that it was performed by focusing on the ratio T/T_{max} and did not directly rely on the absolute physical warehouse sizes. In fact, it was based on the ratio of length to height of the storage area within the warehouse, measured in terms of time. As a consequence, it might be stated that the stacker crane travel time is expressed as a share of T_{max}.

The results of the regression analysis indicate that the developed formula is capable of achieving a good level of precision in the computation of the travel time, as proved by the regression error in Figure 2.

In general terms, all the independent factors included in the regression equation show a negative linear relationship with T/T_{max}. On the contrary, most of their quadratic

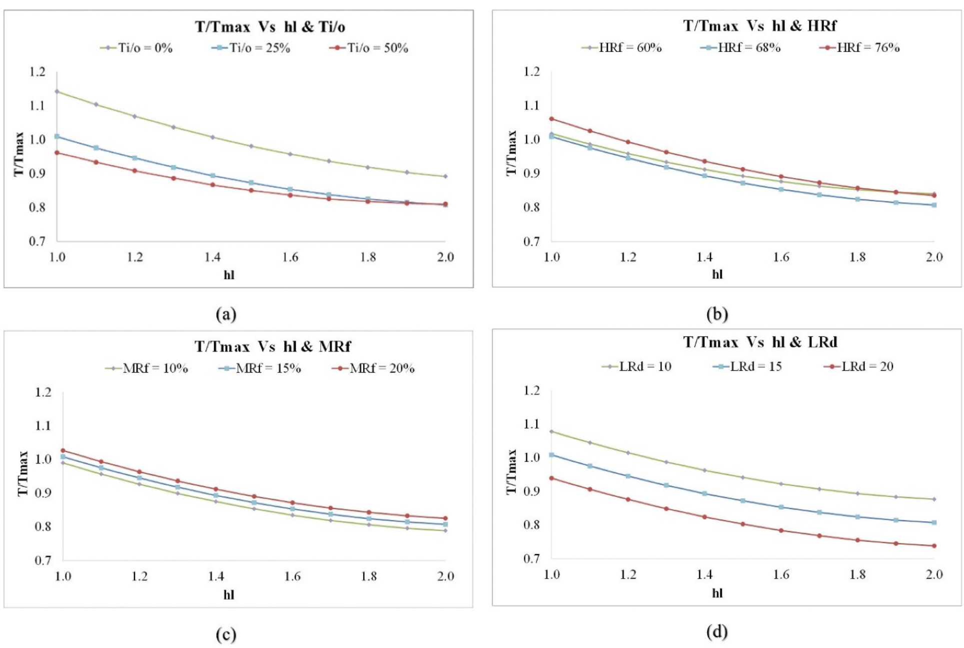

Figure 3. T/T_{max} behaviour as main independent factors change.

coefficients have a positive influence on T/T_{max}. This result is confirmed by the shapes of the graphs in Figure 3, which are similar to negative asymptotic curves. Such graphs have been obtained by plotting the developed computation formula for T/T_{max} in the ranges of the numerical values of the main independent factors shown in Table 1. Here it can be first noted that when h_l increases T/T_{max} decreases, since T_{length} becomes pretty much greater than T_{height}, and in a horizontal storage area deployment T_{max} is equal to T_{length}. Figure 3(a) depicts that, being h_l the same, T/T_{max} shows a relevant decrease when the I/O point is located in an elevated position, and already when $T_{i/o}$ is equal to just 25%$T_{height.}$ However, when $T_{i/o}$ doubles to 50% T_{height}, the associated decrease in T/T_{max} is less significant and becomes 0 when $h_l = 2$. Moreover, according to Figure 3(b), T/T_{max} does not show any relevant variation as the percentage of the total stored items assigned to the high rotation area changes in a limited range. Again, T/T_{max} increases in a very small range as the percentage of the total stored items assigned to the medium rotation area increases (Figure 3(c)). Finally, being h_l the same, T/T_{max} decreases as LRd increases (Figure 3(d)). In fact, from Figure 1 it can be seen that an increase in the low rotation area, which is proportional to an increase in LRd, determines a change in the size of the three different storage areas. In particular, the increase in LRd results in an increase in the low rotation area and, keeping the total warehouse space constant, the average distances travelled by the crane in each of the three areas are lower. Thus, as a consequence, T/T_{max} is reduced.

5. Discussions and conclusions

This work focuses on studying travel times in AS/RSs with horizontal storage area deployment. In addition, the warehouse space is here divided into three different rotation areas. As such, the proposed analysis advances the previous works by (Hoshimov et al., 2024) and (Schenone et al., 2020), wherein simulation outcomes are then processed via a regression model. As a result, it has been possible to obtain a mathematical formulation for computing T/T_{max} that can be easily adopted when the main warehouse input parameters are known. Since different configurations of a horizontally developed warehouse have been analysed both in physical (shape factor and I/O point) and in managerial (flow rates and days of supply for different areas) terms, the obtained formula for calculating T/T_{max} allows its applicability to warehouses of different types and sizes, as long as the conditions of the problem are met.

The present study adds value to the existing literature works, by considering together the following warehouse features in the travel time model: horizontal deployment, class-based storage policy, variable I/O point, and DC cycle. In fact, most of the available models to calculate the travel time do include just one or a few of these characteristics (Lehmann & Huβmann, 2022; Oulhaci et al., 2024). Furthermore, by considering the DC cycle and implementing a class-based inventory policy, the limitations of the Bozer and White (1984)'s formula, especially in the context of warehouses with horizontal deployment, can be addressed.

Thus, from a theoretical perspective, the proposed mathematical formulation refines the existing approaches already available in the literature. In particular, it extends the' (Bozer & White, 1984)s equation for travel time computation by considering a class-based storage allocation policy as well as physical material flows and good days of inventory. Thus, it can be considered a pillar for future studies that investigate the warehouse design process under different storage space shapes and operational conditions. Additionally, the present contribution can foster the integrated use of simulation and statistical analysis to develop approaches to estimate the stacker crane travel time that are enough general but at the same time consistent with real warehouse configurations and the associated processes. The combination of different methodologies to model the behaviour of a physical warehouse can also support the effective integration with innovative approaches, such as Machine Learning, Artificial Intelligence, and Digital Twin, that seem to be quite promising in the analysis of intra-logistics processes.

The proposed paper originates practical implications too. For instance, the proposed model can be used by warehouse design companies for more accurate projects. In addition, the obtained travel time calculation formula might be used as a pillar for the evaluation of the integration in warehouse systems of innovative 4.0 technologies (such as Internet of Thing sensors). This is a crucial aspect for practitioners that are currently working in a more and more competitive environment, with increasing levels of complexity that need to be managed. In fact, the demand pressure determined by the COVID-19 pandemic and the Russia-Ukraine war is calling for the exploitation of innovative and efficient logistics solutions. Furthermore, customer expectations are driving the demand for agile and responsive warehouses, while maintaining fully automated activities (Khan et al., 2022). Such an aspect becomes crucial in specific sectors like the pharmaceutical, automotive, and food ones, where automated storage and material handling equipment has long been employed successfully. Furthermore, the expansion of e-commerce on a global scale has prompted the rapid diffusion of AS/RSs in response to the increasing demand for a greater range of products, with a reduction in the associated volume and a shorter response time (Lupi et al., 2024).

In this context, being able to design automated warehouse systems more accurately might have a beneficial effect on inventory management activities, which in turn could have positive impacts on supply chain resilience. In fact, automated storage systems significantly improve resilience by strengthening warehouse capabilities, improving efficiency, and providing the flexibility and visibility needed to effectively manage and recover from disruptions.

However, the work suffers from some limitations. The validation of simulation results was performed based on literature evidence and a limited number of real automated warehouse environments. Moreover, the present paper does not compare the travel time behaviour in horizontal and vertical storage area deployments to understand the associated different warehouse performance.

Thus, future research will be focused on extending the validation of the simulation results by performing a large number of tests in real automated warehouses of different sizes, shapes, and belonging to various industries. Attention will be paid not only to the business sectors that traditionally base their supply chain operations on automated warehouses but also to those that might benefit from AS/RSs and similar storage systems as a consequence of the recent changes in customer demand. In such a way, it would be possible to explore how the kinds of products that are managed in warehouses and the related replenishment and delivery processes might influence stacker crane travel time estimates. Finally, the impact of the optimization of AS/RS travel time on supply chain resilience will be investigated in order to improve the reliability of warehouse operations to better address supply chain risks and the related disruptions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Alnahhal, M., Salah, B., & Ahmad, R. (2022). Increasing Throughput in Warehouses: The Effect of Storage Reallocation and the Location of Input/Output Station. *Sustainability*, *14*(8), 1–16 doi: https://doi.org/10.3390/su14084611.

Ang, M., & Lim, Y. F. (2019). How to optimize storage classes in a unit-load warehouse. *European Journal of Operational Research*, *278*(1), 186–201. https://doi.org/10.1016/J.EJOR.2019.03.046

Azadeh, K., De Koster, R., & Roy, D. (2019). Robotized and automated warehouse systems: Review and recent developments. *Transportation Science*, *53*(4), 917–945. https://doi.org/10.1287/trsc.2018.0873

Borovinšek, M., Ekren, B. Y., Burinskienė, A., & Lerher, T. (2017). Multi-objective optimisation model of shuttle-based storage and retrieval system. *Transport*, *32*(2), 120–137. https://doi.org/10.3846/16484142.2016.1186732

Bortolini, M., Accorsi, R., Gamberi, M., Manzini, R., & Regattieri, A. (2015). Optimal design of AS/RS storage systems with three-class-based assignment strategy under single and dual command operations. *The International Journal of Advanced Manufacturing Technology*, *79*(9–12), 1747–1759. https://doi.org/10.1007/s00170-015-6872-1

Bozer, Y. A., & White, J. A. (1984). Travel time for automated storage/retrieval systems. *IEE Transactions*, *16*(4), 329–338. https://doi.org/10.1080/07408178408975252

Cagliano, A. C., Gobbato, L., Tadei, R., & Perboli, G. (2014). ITS for e-grocery business: The simulation and optimization of Urban logistics project. *Transportation Research Procedia*, *3*, 489–498. https://doi.org/10.1016/j.trpro.2014.10.030

Cagliano, A. C., Mangano, G., & Rafele, C. (2021). Determinants of digital technology adoption in supply chain. An exploratory analysis. *Supply Chain Forum: An International Journal*, *22*(2), 100–114. https://doi.org/10.1080/16258312.2021.1875789

Chackelson, C., Errasti, A., Cipres, D., & Álvarez, M. J. (2011, March). Improving picking productivity by redesigning storage policy aided by simulations tools. *V International Conference on Industrial Engineering and Industrial Management* Cartagena, Columbia. 306–313.

Ekren, B. Y., Sari, Z., & Lerher, T. (2015). Warehouse design under class-based storage policy of shuttle-based storage and retrieval system. *IFAC-Papersonline*, *28*(3), 1152–1154. https://doi.org/10.1016/j.ifacol.2015.06.239

Eldemir, F., Graves, R. J., & Malmborg, C. J. (2004). New cycle time and space estimation models for automated storage and retrieval system conceptualization. *International Journal of Production Research*, *42*(22), 4767–4783. https://doi.org/10.1080/00207540412331281953

Ferrari, A., Mangano, G., Cagliano, A. C., & De Marco, A. (2023). 4.0 technologies in city logistics: An empirical investigation of contextual factors. *Operations Management Research*, *16*(1), 345–362. https://doi.org/10.1007/s12063-022-00304-5

Ghomri, L., & Sari, Z. (2017). Mathematical modeling of the average retrieval time for flow-rack automated storage and retrieval systems. *Journal of Manufacturing Systems*, *44*, 165–178. https://doi.org/10.1016/j.jmsy.2017.05.002

Hausman, W. H., Schwarz, L. B., & Graves, S. C. (1976). Optimal storage assignment in automatic warehousing systems. *Management Science*, *22*(6), 629–638. https://doi.org/10.1287/mnsc.22.6.629

Hoshimov, A., Cagliano, A. C., Mangano, G., Schenone, M., & Grimaldi, S. (2024). AS/R system travel time in class-based storage with different input-output point levels: A proposed formula. *Journal of Facilities Management*, *22*(1), 108–123. https://doi.org/10.1108/JFM-11-2021-0145

Hoshimov, A., Mahdavisharif, M., & Cagliano, A. C. (2021). Impacts of digital technologies on supply chain performance: A system dynamics approach. *Proceedings of the International Conference on Industrial Engineering and Operations Management, Singapore* (pp. 5303–5314).

Iç, Y. T. (2022). A simplified throughput model for a unit-load AS/RS considering dynamics principles. *Journal of Advanced Manufacturing Systems*, *21*(1), 125–142. https://doi.org/10.1142/S0219686721500451

Ives, A. R. (2022). Random errors are neither: On the interpretation of correlated data. *Methods in Ecology and Evolution*, *13*(10), 2092–2105. https://doi.org/10.1111/2041-210X.13971

Khan, M. D., Schaefer, D., & Milisavljevic-Syed, J. (2022). Supply chain management 4.0: Looking backward, looking forward. *Procedia CIRP*, *107*, 9–14. https://doi.org/10.1016/j.procir.2022.04.002

Khanorkar, Y., & Kane, P. V. (2023). Selective inventory classification using ABC classification, multi-criteria decision making techniques, and machine learning techniques. *Materials Today: Proceedings* (Vol. 72. pp. 1270–1274). https://doi.org/10.1016/j.matpr.2022.09.298

Koh, S. G., Kim, B. S., & Kim, B. N. (2002). Travel time model for the warehousing system with a tower crane S/R machine. *Computers and Industrial Engineering*, *43*(3), 495–507. https://doi.org/10.1016/S0360-8352(02)00122-5

Lehmann, T., & Hußmann, J. (2021). Travel time model for multi-deep automated storage and retrieval system with a homogeneous allocation structure. *Logistics Research*, *14*(1). https://doi.org/10.23773/2021_5

Lehmann, T., & Huβmann, J. (2022). Travel time model for multi-deep automated storage and retrieval systems with different storage strategies. *International Journal of Production Research*, *61*(16), 5676–5691. https://doi.org/10.1080/00207543.2022.2110536

Lerher, T., Ficko, M., & Palčič, I. (2021). Throughput performance analysis of automated vehicle storage and retrieval systems with multiple-tier shuttle vehicles. *Applied Mathematical Modelling*, *91*, 1004–1022. https://doi.org/10.1016/j.apm.2020.10.032

Liu, T., Gong, Y., & De Koster, R. B. M. (2018). Travel time models for split-platform automated storage and retrieval systems. *International Journal of Production Economics*, *197* (February 2017), 197–214. https://doi.org/10.1016/j.ijpe.2017.12.021

Lupi, G., Accorsi, R., Battarra, I., Manzini, R., & Sirri, G. (2024). Space efficiency and throughput performance in AVS/RS under variant lane depths. *The International Journal of Advanced Manufacturing Technology*, *131*(3–4), 1449–1466. https://doi.org/10.1007/s00170-024-13160-3

Mangano, G., & De Marco, A. (2014). The role of maintenance and facility management in logistics: a literature review Facilities 32 5/6 241–255 0263-2772 doi:https://doi.org/10.1108/F-08-2012-0065.

Mangano, G., Zenezini, G., Cagliano, A. C., & De Marco, A. (2019). The dynamics of diffusion of an electronic platform supporting city logistics services. *Operations Management Research*, *12* (3–4), 182–198. https://doi.org/10.1007/s12063-019-00147-7

Mansuri, M. (1997). Cycle-time computation, and dedicated storage assignment, for AS/R systems. *Computers and Industrial Engineering*, *33*(1–2), 307–310. https://doi.org/10.1016/S0360-8352(97)00099-5

Manzini, R., Accorsi, R., Baruffaldi, G., Cennerazzo, T., & Gamberi, M. (2016). Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS). *International Journal of Production Research*, *54*(14), 4286–4304. https://doi.org/10.1080/00207543.2016.1144241

Meller, R. D., & Mungwattana, A. (1997). Multi-shuttle automated storage/retrieval systems. *IIE Transactions (Institute of Industrial Engineers)*, *29*(10), 925–938. https://doi.org/10.1080/07408179708966412

Metahri, D., & Hachemi, K. (2018). Retrieval-travel-time model for free-fall-flow-rack automated storage and retrieval system. *Journal of Industrial Engineering International*, *14*(4), 807–820. https://doi.org/10.1007/s40092-018-0263-9

Mirzaei, M., Zaerpour, N., & de Koster, R. (2021). The impact of integrated cluster-based storage allocation on parts-to-picker warehouse performance. *Transportation Research Part E: Logistics & Transportation Review*, *146*(January), 102207. https://doi.org/10.1016/j.tre.2020.102207

Oulhaci, A., Ghomri, L., Rimouche, A., & Kahouadji, H. (2024). On minimizing the expected travel time in a unit load AS/RS. *2024 ASU International Conference in Emerging Technologies for Sustainability and Intelligent Systems, ICETSIS 2024* (pp. 1709–1712). https://doi.org/10.1109/ICETSIS61505.2024.10459591

Praharsi, Y., Jami'in, M. A., Suhardjito, G., Reong, S., & Wee, H. M. (2022). Supply chain performance for a traditional shipbuilding industry in Indonesia. *Benchmarking: An International Journal*, *29*(2), 622–663. https://doi.org/10.1108/BIJ-05-2020-0232

Rizqi, Z. U., Chou, S.-Y., & Choon, S. S. (2023). Performance of dual stacker automated storage and retrieval system (AS/RS) with double-deep configuration. *2023 IEEE 5th Eurasia Conference on IOT, Communication and Engineering, ECICE 2023* (pp. 683–687). https://doi.org/10.1109/ECICE59523.2023.10383137

Roodbergen, K. J., & Vis, I. F. A. (2009). A survey of literature on automated storage and retrieval systems. *European Journal of Operational Research*, *194*(2), 343–362. https://doi.org/10.1016/j.ejor.2008.01.038

Sarker, B. R., & Babu, P. S. (1995). Travel time models in automated storage/retrieval systems: A critical review. *International Journal of Production Economics*, *40*(2–3), 173–184. https://doi.org/10.1016/0925-5273(95)00075-2

Schenone, M., Mangano, G., Grimaldi, S., & Cagliano, A. C. (2019). Estimating travel times in dual shuttle AS/RSS.: A revised approach. *International Journal of Industrial Engineering Computations*, *10*(3), 405–420. https://doi.org/10.5267/j.ijiec.2018.12.002

Schenone, M., Mangano, G., Grimaldi, S., & Cagliano, A. C. (2020). An approach for computing AS/R systems travel times in a class-based storage configuration. *Production and Manufacturing Research*, *8*(1), 273–290. https://doi.org/10.1080/21693277.2020.1781703

Shah, A., Wilson, A. G., & Ghahramani, Z. (2014). Student-t processes as alternatives to Gaussian processes. *Journal of Machine Learning Research*, *33*, 877–885 doi:https://doi.org/10.48550/arXiv.1402.4306.

Shahsavani, I., & Goli, A. (2023). A systematic literature review of circular supply chain network design: Application of optimization models. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-023-03362-2

Simic, V., Dabic-Miletic, S., Tirkolaee, E. B., Stević, A., Amirteimoori, A., & Ala, A. (2023). Neutrosophic LOPCOW-ARAS model for prioritizing industry 4.0-based material handling technologies in smart and sustainable warehouse management systems. *Applied Soft Computing*, *143*, 143. https://doi.org/10.1016/j.asoc.2023.110400

Sternad, M., Lerher, T., & Gajsek, B. (2018). Maturity levels for logistics 4. 0 based on nrw ' S. *18th International Scientific Conference Business Logistics in Modern Management* (pp. 695–709. https://hrcak.srce.hr/ojs/index.php/plusm/article/view/7920

Vasili, M., Hong, T. S., Homayouni, S. M., Ismail, N., & Samin, R. (2007). Travel time analysys of SP-AS/RS with an alternative configuration for the input/output station 37th International Conference on Computers and Industrial Engineering 2007 Alexandria, Egypt. , *3*), 2036–2045.

Vasili, M., Vasili, M., Raminfar, R., & Matoorian, P. (2012). A closed form model for travel time of split-platform automated storage and retrieval system equipped with two input/output stations. *9th International Conference on Modeling, Optimization & SIMulation* Bordeaux, France.

Weber, G. W., Goli, A., & Tirkolaee, E. B. (2023). Logistics and operations modelling and optimization for sustainable supply chain. *Sustainability (Switzerland)*, *15*(17), 2–4. https://doi.org/10.3390/su151712727

Xu, X., Gong, Y., Fan, X., Shen, G., & Zou, B. (2018). Travel-time model of dual-command cycles in a 3D compact AS/RS with lower mid-point I/O dwell point policy. *International Journal of Production Research*, *56*(4), 1620–1641. https://doi.org/10.1080/00207543.2017.1361049

Xu, X., Zhao, X., Zou, B., Gong, Y., & Wang, H. (2020). Travel time models for a three-dimensional compact AS/RS considering different I/O point policies. *International Journal of Production Research*, *58*(18), 5432–5455. https://doi.org/10.1080/00207543.2019.1659519

Yan, Q., Lu, J., Tang, H., Zhan, Y., Zhang, X., & Li, Y. (2023). Travel time analysis and dimension optimisation design of double-ended compact storage system. *International Journal of Production Research*, *61*(20), 6718–6745. https://doi.org/10.1080/00207543.2022.2136283

Yu, H. (2024). Modeling and optimization of expected travel time for multi-aisle AS/RSs with two-class-based storage policy. *Naval Research Logistics (NRL)*, *71*(8), 1073–1091. https://doi.org/10.1002/nav.22202

Zammori, F., Neroni, M., & Mezzogori, D. (2021). Cycle time calculation of shuttle-lift-crane automated storage and retrieval system. *IISE Transactions*, *54*, 1–31. https://doi.org/10.1080/24725854.2020.1861391

Zenezini, G., Mangano, G., & De Marco, A. (2022). Experts' opinions about lasting innovative technologies in city logistics. *Research in Transportation Business & Management*, 45. https://doi.org/10.1016/j.rtbm.2022.100865