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AS/R system travel time in class-based storage with different Input-Output point levels: A proposed formula

Abstract

Purpose – This paper proposes a simulation model integrated with an empirical regression analysis to provide a new mathematical formulation for Automated Storage and Retrieval System (AS/RS) travel time estimation under class-based storage and different Input/Output (I/O) point vertical levels.

Design/methodology/approach – A simulation approach is adopted to compute the travel time under different warehouse scenarios. Simulation runs with several I/O point levels and multiple shape factor values.

Findings – The proposed model is extremely precise for both Single Command (SC) and Dual Command (DC) cycles and very well fitted for a reliable computation of travel times.

Research limitations/implications – The proposed mathematical formulation for estimating the AS/RS travel time advances widely applied methodologies existing in literature. As well as, it provides a practical implication by supporting faster and more accurate travel time computations for both SC and DC cycles. However, the regression analysis is conducted based on simulated data, and can be refined by numerical values coming from real warehouses.

Originality/value – This work provides a new simulation model and a refined mathematical equation to estimate AS/RS travel time.

Keywords AS/RS, Warehousing systems, Travel time, Simulation, Class-based storage, Regression Analysis

Paper type Research paper

Introduction

Automated Storage and Retrieval Systems (AS/RSs) are one of the warehousing systems most extensively used in production facilities and distribution centers (Liu *et al.*, 2018). AS/RSs are more efficient than traditional systems when storing a large amount of parts to be moved with a high frequency.

Sari *et al.* (2007) demonstrate that AS/RSs can reduce inventory level and respond to customers' needs in a timely manner, as well as improve space utilization and equipment. This has also positive impacts on enhancing material flows and on properly supporting production processes (Rose *et al.*, 2021). AS/RSs are composed of storage racks, input/output (I/O) stations, and storage/retrieval (S/R) machines, namely automated stacker cranes, to handle unit loads without human intervention under the supervision of a computerized control system. In general, they are classified according to their design characteristics and storage assignment policies. In particular, the rack configuration and the type of command cycles performed by stacker cranes have a significant impact on the AS/RS efficiency. Furthermore, AS/RSs can be either single-shuttle or multi-shuttle systems. Single-shuttle systems allow to move only one unit load at a time, while in the multi-shuttle configuration cranes are able to carry multiple unit loads simultaneously. Moreover, AS/RSs can perform both single command (SC) and dual command (DC) cycles according to the operational properties of the S/R machine. In a SC cycle, either a storage or a retrieval operation is performed between two consecutive S/R machine travels from/to the I/O point. In a DC cycle, the S/R machine consecutively performs a storage, it travels empty to a retrieval location, and finally it performs a retrieval operation (Schenone *et al.*, 2020).

AS/RSs can help companies achieving substantial cost reduction by minimizing direct and indirect labor, energy, maintenance, and building expenses, together with improving control on goods (Sarker and Babu, 1995). This allows enhancing efficiency, which is the reason why AS/RSs have received increased attention by both scholars and practitioners in the last decades (Faber *et al.*, 2013).

Numerous researches address different aspects of AS/RSs including configurations, characteristics, design, and operational management (Hamzaoui and Sari, 2020). The stacker crane travel time is one of the potential key indicators to assess the storage system performance. The travel time depends on the AS/RS throughput rate, which defines the maximum number of unit loads that can be moved to and from the system during a specific time interval. Thus, travel time estimation plays a significant role in AS/RS design. In order to achieve high operational excellence in storing and retrieving goods, it is needed to reduce the expected travel time of S/R machines. One of the first computational travel time models was established in the Eighties by Bozer and White (1984). Since the technologies and business environments have changed over the decades, several research works have been developed to update the existing travel time models. In order to decrease the expected S/R machine travel time, many scholars have introduced approaches based on various AS/RS characteristics (Dörr, 2018; Schenone *et al.*, 2019). The available contributions can be broadly divided into three streams. The first one addresses how the AS/RS travel time changes according to different warehouse design features, such as layouts, rack systems, and location of I/O points (e.g. Roodbergen and Vis, 2009). The second group of works, instead, looks at warehouse management and proposes travel time computation approaches under different storage policies, such as random, dedicated or class-based ones, and retrieval strategies, like for instance sequencing of different orders into a batch (Gu *et al*., 2010; Lee, 2014) . Finally, a number of authors discuss travel time estimation by taking into account both the topics mentioned above (Singbal and Adil, 2019; Schenone *et al.,* 2020).

However, in this context few studies have been conducted about the computation of travel time in AS/RSs that simultaneously take into account the following characteristics: both SC and DC cycles, class-based storage configurations, and variable vertical position of I/O points. In order to fill such a research gap, the present paper puts forward a simulation model combined with an empirical regression analysis to provide a new mathematical formulation for travel time estimation.

The reminder of the paper is organized as follows. The next section discusses the reference literature background about AS/RS travel time computation. The assumptions and the development of the simulation model are described in Section 3, while in Section 4 the regression analysis is presented together with its results. Finally, Section 5 discusses the research findings and conclusions.

Literature review

This section discusses the literature background constituting the theoretical foundation of the present work, which includes two streams.

AS/RS travel time calculation under different design characteristics

Research on the computation of travel time in AS/RSs has been a challenging area during the past decades because the expected travel time of an S/R machine is considered as a key factor when assessing the storage system performance (Metahri and Hachemi, 2018). Modelling and computing the travel time are topics that have been extensively studied since the Seventies *(*Hausman *et. al.*, 1976; Vasili *et.al.*, 2007) and many investigations have been carried out by several academicians. Some authors, such as Sarker and Babu, (1995), Kosanić *et al*. (2018), performed literature reviews and confirmed that the travel time is crucial to increase efficiency. Sarker and Babu (1995) conduct a critical review on travel time models under different design aspects and their impacts on the computation of the throughput rate. Moreover, they also propose to develop travel time computation studies by considering heterogeneous demand parameters and inventory management policies. For instance, the order arrival rate, the probability distribution of order quantity, and the geographical location of customers greatly affect the expected travel time and, in general, the physical design of AS/RSs. After a period of time, Roodbergen and Vis (2009) perform another literature review on AS/RSs focusing on the combination of different physical design issues and control problems, such as batching, dwell-point rules, and I/O point decisions, in order to improve stacker crane travel time. In addition, they state that detailed researches should focus on the combination of single and multiple aisles with more than one I/O point, as well as different storage assignment policies.

Literature about travel time calculation can be addressed based on the main storage system characteristics considered by each work.

A number of authors focus on SC and DC cycles. Among them, Bozer and White (1984) put forward an approach to calculate the AS/RS travel time that is a reference in the field. They develop both SC and DC cycle travel time models of a rectangular rack configuration under random storage and for different I/O point positions. Moreover, various dwell-point strategies for the S/R machine are assessed. However, some operational characteristics, such as acceleration and deceleration, are not considered by this work and are integrated in subsequent researches (Chang *et al.*, 1995). To this end, the travel time is considered again for both SC and DC cycles but with multi-shuttle and multi-aisle systems as well as different rack configurations (Lerher *et al.*, 2021; Hamzaoui *et al.*, 2021). In particular, Ghomri *et al.* (2009) propose a simulation model based on continuous mathematical functions, which aim to be fairly easy to compute, in order to calculate SC and DC cycle times of a multi-aisle AS/RS. Lee (2014) introduces travel time models for a single machine flow rack with different sized rack systems under random storage policy. Later on, Liu *et al.* (2018) propose a model to assess the expected travel time of AS/RSs for the DC cycle under I/O dwell point policies. Recently, Hamzaoui and Sari (2020) also address flow rack AS/RSs, and in particular bidirectional ones, by developing an accurate mathematical model for computing dual cycle times. Finally, Lerher *et al.* (2021) consider one of the latest evolutions of AS/RSs, namely the Automated Vehicle Storage/Retrieval Systems (AVS/RS), and propose travel time models for both SC and DC cycles with multiple-tier shuttle vehicles as well as fixed position of the I/O station at the beginning of the first tier of storage racks.

In the last decade, single and multi-shuttle systems have been also investigated with the aim of minimizing the travel time. Lerher *et al.* (2010) improve previous works (e.g. Potrč *et al.*, 2004) by putting forward an analytical model for automated storage with aisle transferring S/R machines. This model considers both the S/R machine movements in picking and crossing warehouse aisles. Innovative travel time models for dual-shuttle AS/RSs are developed by Azzi *et al.* (2011), who conducted Monte Carlo simulations for the purpose.

By moving from stacker cranes features to rack characteristics, several design parameters can impact travel time. For example open-rack structured unidirectional-upward mobile loads in Miniload AS/RSs are addressed by Vasili (2016). In order to compute the travel time, such an author assumes the stacker crane can perform just retrieval operations, while storage operations are completed by a dedicated platform. Ghomri and Sari (2015) propose a mathematical model extending the work by Bozer and White (1984) for determining the average travel time in particular AS/RS configurations such as the flow-rack ones. This work considers an AS/RS with two machines on the two opposite sides of the racks, one for storage and another one of retrieval. The average retrieval travel time is calculated by considering a continuous rectangular area and fixed I/O point positions. The authors use simulation to validate their new formulation. Again relying on simulation, Schenone *et al.* (2019) address Meller and Mungwattana's formulation (1997) and propose a revised formula by replacing the constant factor multiplying the travel between time with a variable value depending on the rack configuration. A fixed vertical position of the I/O station is considered in this work. A simulation model is also proposed by Singbal and Adil (2019) in order to discuss more in depth multi-aisle AS/RSs with different storage policies. This model describes the impact of storage policies and different design parameters, such as the number of aisles, the shape factor b, and the skewness parameter, on the computation of the expected travel time of S/R machine. Finally, very recently, Lehmann and Hußmann (2021) focus on multi-deep racks by proposing a travel time computation model under continuous rack approximation and reallocation probability of goods.

Computing AS/RS travel time under different storage assignment polices

Storage assignment strategies profoundly affect many warehouse operational aspects and performances, in particular the travel distance and time in AS/RSs as well as the throughput rate among the key aspects (Manzini, 2012). The available literature shows that several ways to assign products to AS/RS storage locations have been proposed by both academicians and practitioners (Singbal and Adil, 2019). Hausman *et al.* back in 1976 presented a research describing the impacts on the travel time computation of the following three main storage assignment policies: Random Storage, Dedicated Storage, and Class-Based Storage.

The random storage policy allows a product to be stored anywhere in warehouse racks. Under such a condition, all the empty locations have an equal probability of having an incoming unit load assigned. It is easy to use and in general requires a smaller area than other storage polices, providing a better utilization level of all the picking aisles (Petersen and Schmenner, 1999). Koh *et al.* (2002) develop mathematical models for SC and DC cycles under randomized storage assignment policies with the S/R crane that can move in radial and circumferential directions simultaneously. Later on, Lerher *et al.*, (2010) put forward a model that computes the travel time of multi-aisle AS/RSs under randomized storage assignment policy with horizontally fixed I/O stations. Lee (2014) addresses an additional issue in travel time computation and proposes a model with different rack sizes, besides considering randomized storage policy for each warehouse zone.

The dedicated storage policy assigns specific locations to each Stock Keeping Unit (SKU), which can be occupied by only that product. Thus, the replenishment of a given product always occurs at the same locations (Mansuri, 1997). Only two works applying the dedicated storage policy are relevant to the present research. Mansuri *et al.* (1997) study both the combined and the individual role of space, speed, and storage allocation on AS/RS operational performance. In particular, a computerized algorithm to compute the cycle time is developed by exploring dedicated storage allocation. Some years later, Metahri and Hachemi (2018) introduce a continuous retrieval time calculation model based on the free-fall flow rack design, which can be used in different applications ranging from distribution centers to manufacturing warehouses. This model is validated by means of computer simulation.

The class-based storage policy partitions products among a number of classes and reserves a storage area for each class defined according to the inventory turnover value of individual SKUs. Several contributions address travel time computation under class-based storage. Ashayeri *et al.* (2001) propose an algorithmic approach to compute the expected travel time of the S/R machine with both single and multiple I/O stations. They prove that a class-based storage layout contributes to a significant travel time reduction with two I/O points located at the floor level at opposite aisle ends. Moreover, the best rack design configuration is addressed for shuttle-based storage and retrieval systems with stations at the first tier of each aisle (Ekren *et al.*, 2015). The joint application of the class-based storage policy and an appropriate rack design results in a more efficient utilization of warehouse areas characterized by relevant heights. Later on, Schenone *et al.* (2020) enlarge the application fields of the Bozer and White's (1984) formula to class-based storage by developing numerical equations to compute the travel time by taking into account the warehouse shape factor and the turnover of the stored products. Recently, Mirzaei *et al.*

(2021) perform a research on the impacts on AS/RS travel time estimation of combining the class-based storage policy with the part-to-picker approach.

Additionally, there are some works that focus on the travel time calculation when multiple storage policies are applied in an integrated way. Already Hausman *et al.* (1976) address random storage together with full turnover and class-based assignment policies to estimate the one-way travel time. Another relevant contribution is given by Van den Berg (2002) who develops an analytical expression to optimize the expected travel time of S/R cranes under randomized and class-based storage policies. According to his assumptions, the input station should be located at the lower-left corner of the racks. However, the class-based storage policy can also be explored by using other configurations of the input station and this makes more general the approach of integrating different storage policies.

In the last years, the AS/RS travel time has also been computed with new storage policies different from the three classical ones discussed before. For example, Singbal and Adil (2019) develop a simulation model that describes the impact of rack design under random and across aisle full-turnover (AAFT) storage policies. In the AAFT storage policy the highest frequency item is assigned to the first locations in the first aisle. The next highest frequency one is assigned to the first locations in the second aisle and so on. As a result, the benefits of the AAFT storage policy are minimal when the number of aisles increases because the travel in the cross-aisle increases together with associated time.

The performed literature review reveals that further approaches for calculating the AS/RS travel time applying to both SC and DC cycles still need to be developed in class-based storage, focusing in particular on different storage system design configurations in terms of the I/O point position. In addition, there are few works that address the extension of Bozer and White's (1984) formula under class-based storage policy by considering both material flows and days of inventory as input data, together with variable I/O point vertical position. Moreover, simulation is often adopted to validate analytical models but a limited number of contributions relies on it to derive mathematical formulations that can be directly implemented in real cases in a straightforward way and based on the main warehouse design and flow parameters.

The present work advances the studies by Schenone *et al.* (2019, 2020) by proposing a simulation model, combined with an empirical regression analysis, to calculate the S/R machine travel time. To be more precise, the aim is extending the results obtained by Bozer and White (1984) related to SC and DC cycles under a class-based storage policy. Additionally, the S/R machine travel time is computed by assuming a variable vertical position of the I/O point.

Model Assumptions

The objective of the present work is extending the results obtained by the previous studies of Bozer and White (1984) related to SC and DC cycles in a configuration of random storage policy. In particular, the authors refer to AS/RSs that handle entire unit loads and apply the class–based storage policy with three classes determined according to the turnover criterion, which is here defined in terms of flows (Figure 1). This means that an SKU in the developed model is classified based on its level of inventory turnover (Van Donselaar *et al.*, 2021). In order to define all the remaining features of the model the authors mainly refer to the assumptions (Hi) provided by Gagliardi's review (2012):

<u>Crane group: H2, H6, H8</u>

<u>Rack group: H1, H3, H5, H13, H16, H26</u>

- The warehouse length, measured in seconds, is greater that the height

<u>Handling policy group: H7, H19. Additionally,</u>

- The input and output points are located in the same position at the end of an aisle (Bozer and White, 1984)
- The I/O point is located over the floor and different possible vertical heights are analyzed in the present study
- The system handles entire unit loads
- A pure random storage policy is adopted within each class, so each SKU is stored anywhere in the space associated with its class
- Each unit load of an SKU has an equal probability of being picked for each class

All these assumptions are very important in travel time computation, although they can be considered strict and they are static in nature. Therefore, the conclusions drawn from them may be questionable for real life scenarios. Nevertheless, models proposing some forms of simulation are often very precise and quite able to integrate dynamic behaviors. For this reason, the methodology proposed in this work relies on a simulation technique based on the previous assumptions.

Methodology

Description of the Simulation Approach

Simulation is adopted as the main methodology in the present research because it allows to create different scenarios to deeply investigate dynamic processes in complex and uncertain systems like supply chains and warehouses (Cagliano *et al.*, 2011). An Excel®-based simulator is developed: it is composed by two sheets, namely "Data Generation", wherein input and output data are displayed, and "Data Elaboration", where simulations are run.

The class-based storage condition is ensured by performing an ABC analysis of the products stored in a warehouse, which classifies them in three groups according to their inventory turnover values. The products with the highest turnover values are assigned to the most readily accessible warehouse storage locations (Mirzaei *et al.*, 2021). Products belonging to the same ABC class are randomly assigned to the storage locations associated with that class (Yang *et al.*, 2017). As a result of locating fast moving products very close to the I/O point, the ABC policy is a lever for reducing the travel time to reach the frequently requested items. According to these considerations, the warehouse storage space has been subdivided in three areas accommodating products with high, low, and medium turnover values respectively. After that, the factors supposed to have an impact on the time performance of AS/RSs implementing a class-based storage policy are identified by analyzing real warehouse case studies. They include the product flow for each area (% of total item), the physical space associated with each area (% of total warehouse area), and the days of supply for each area. The product flow for each area depends on the number of pick-up and delivery activities that are carried out for the products belonging to the associated class (Li *et al.*, 2016). The space measures the amount of available space, out of the total warehouse floor area, that is assigned to the products in each of the three different classes (Zhang *et al.*, 2021). Finally, the days of supply assess for how many days the demand for the products in the three classes faced by the warehouse can be fulfilled by the goods stocked in the related areas. Besides these three main variables, the following ones are also defined:

- High rotation flow rate: HR_f
- Medium rotation flow rate: MR_f
- Low rotation flow rate: LR_f
    - Days of supply for high rotation area: HR_d
    - Days of supply for medium rotation area: MR_d
    - Days of supply for low rotation area: LR_d.

These quantities can be used to define an equation linking together the product flows, the storage area, and the days of supply:

- Given HR_f and MR_f, LR_f is calculated as 1- (HR_f+MR_f)
- HR_d, MR_d, and LR_d are also defined as stated above
- Therefore, the associated space for each product class can be defined as:

$$X_{area}\ \% = \frac{XR_f * XR_d}{HR_f * HR_d + MR_f * MR_d + LR_f * LR_d} \tag{1}$$

where X can assume the following values: high (H), medium (M), or low (L).

It can be proved that partitioning the storage space in different areas does not directly depend on the days of supply but on the daily unit load flow (Schenone *et al.,* 2020). This is why HR_d is conventionally set as a constant equal to 1 and has not been taken into account. Similarly, LR_f can be obtained from HR_f and MR_f as per Equation 1.

Moreover, two other important variables are considered. On the one hand, the shape factor b (Bozer and White, 1984) is obtained by the ratio between T_{height} and T_{lenght}, which are the maximum vertical travel time and the maximum horizontal travel time from the I/O point respectively. On the other hand, the I/O point level is computed as a percentage of T_{height}.

The simulator generates random positions of possible storage and pickup locations in the warehouse. Table I summarizes the factors that are assumed to be relevant for the travel time computation, together with their ranges of numerical values. They represent the conditions under which simulations are run.

Variable	**Acronym**	**min**	**max**	**range**
Shape Factor	b	0.5	1	0.1
I/O Point	Ti/o	0	50%	12.5%
High Rotation Flow Rate	HRf	60%	76%	4%
Medium Rotation Flow Rate	MRf	10%	20%	3,3%
Days of Supply for Medium Rotation Area	MRd	3	6	1
Days of Supply for Low Rotation Area	LRd	10	20	3.3

Table I. Variables influencing travel time computation

The variables in Table I play a key role in assessing the travel time in AS/RSs. In fact, when HR_f and MR_f increase, the travel time decreases due to the fact that a larger quantity of products is stored close to the I/O point. Conversely, the higher MR_d and LR_d, the longer the travel time because of products with limited inventory turnover values. The shape factor b has been set just ranging between 0.5 and 1, in order to avoid high computational complexity. Furthermore, values of b higher than 1 bring to a warehouse shape that is completely different. In fact, as shown in Figure 1, when $T_{lenght} > T_{height}$, so b > 1, the rotation areas are placed one next to the other. On the contrary, when $T_{lenght} < T_{height}$, and b < 1, the areas are located one over the other. Therefore, just a single mathematical model would not be able to describe both the two warehouse shapes. In the proposed model T_{fixed} is not taken into account since it is constant and it does not influence the output of the analysis.

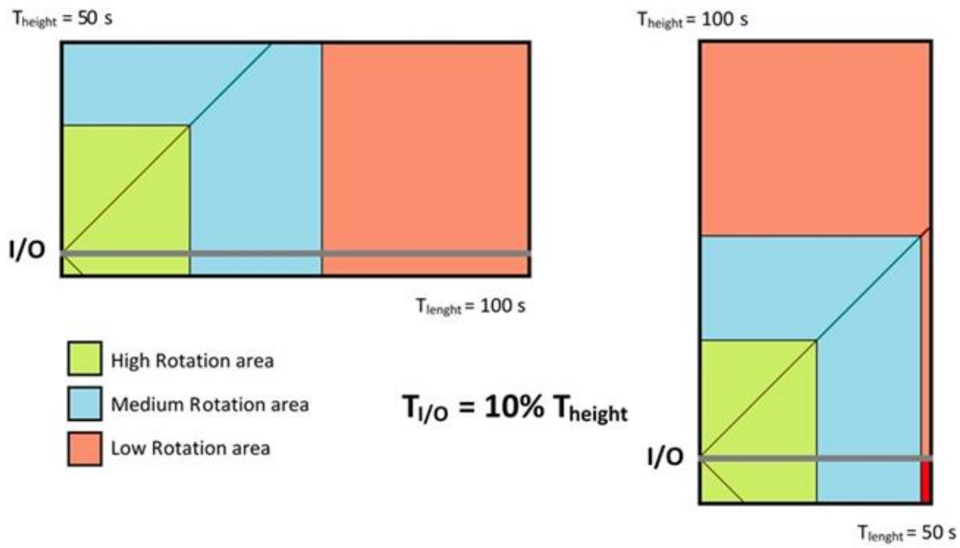

Figure 1. Benchmark between horizontal and vertical warehouses

In the present research, simulations are carried out by means of a Microsoft Excel® macro in order to calculate the travel time under the assumptions detailed in Section 3 as well as heterogeneous warehouse conditions.

The simulation approach is corroborated based on literature, in particular the contributions by Schenone and others (2019, 2020) considering both the Bozer and White's (1984) and the analytical approach. The validation is carried out for the main possible operational warehouse situations, in particular when the I/O point is located on the floor since there are few available works relying on variable I/O point height. A further step of validation is performed by comparing the simulation outcomes with the performance of a limited number of cases from real warehouse systems, currently without the possibility of carrying out a more extensive validation campaign.

With the final aim to propose a mathematical model for travel time evaluation, 19,200 warehouse configurations are investigated, each of them characterized by a different combination of the values of the significant factors for travel time computation presented in Table I. Out of these configurations, 9,600 are based on the SC cycle and 9,600 refer to the DC cycle. As already mentioned, a number of possible values are associated to each variable in Table I. For example, the shape factor can assume six values ranging from 0 to 0.5 in steps of 0.1; thus, its possible values are 0, 0.1, 0.2, 0.3, 0.4, and 0.5. Similarly, five values for the I/O point level are considered: 0%, 12.5%, 25%, 37.5%, and 50% of T_{height}. The same approach is coherently applied to all the other variables. Simulations are replicated five times for each warehouse configuration in order to minimize the random error (Koehler, *et al.*, 2009). Therefore 96,000 tests are performed in total. The output of each single test is the average value obtained from 2,000 crane cycle times computed by the Microsoft Excel® macro. The next section details the characteristics of the simulator.

Simulations

Table II reports the outputs of some simulations. The columns refer respectively to the shape factor b, the percentage defining the I/O point height in terms of time, the percentages of items associated with the high rotation (HR_f) and medium rotation (MR_f) flow rates, the days of supply for medium (MR_d) and low rotation (LR_d) areas, and the response variable T/T_{max}, the travel time, related to both the SC and the DC cycle.

SINGLE COMMAND										
Variable						**Output SC test/run/replication – T/T_{max}**				
b	**Ti/o**	**HRf**	**MRf**	**MRd**	**LRd**	#1	#2	#3	#4	#5
0.5	12.5%	0.6	0.1	3	13.33	….	….	…..	0.5158	0.4975
0.5	12.5%	0.6	0.1	3	16.67	0.4938	0.4873	0.4896	0.4813	0.4714
0.5	12.5%	0.6	0.1	3	20.00	0.4711	0.4661	0.4515	0.4641	0.4504
0.5	12.5%	0.6	0.1	4	10.00	0.5493	0.5348	…..	…..	….

DOUBLE COMMAND										
Variable						**Output DC – test/run/replication – T/T_{max}**				
b	**Ti/o**	**HRf**	**MRf**	**MRd**	**LRd**	#1	#2	#3	#4	#5
0.5	12.5%	0.6	0.1	3	13.33	….	….	…..	0.7697	0.7800
0.5	12.5%	0.6	0.1	3	16.67	0.7672	0.7611	0.7745	0.7737	0.7868
0.5	12.5%	0.6	0.1	3	20.00	0.7459	0.7538	0.7257	0.7212	0.7693
0.5	12.5%	0.6	0.1	4	10.00	0.8597	0.8435	…..	…..	….

Table II. Examples of simulations

Regression analysis

The regression analysis aims to test if the independent variables taken into account are significant factors and whether they have a negative or positive impact on the response variable. It is a widely used tool for explaining relationships among variables within a dataset. In order to take into account even squared relationships with response variable both squared terms have been considered (De Marco et al., 2010). In fact, linear regression models are able to capture just first order relationships among factors.

The results of the regression analysis are shown in Table III, where the columns report the regression coefficient estimate for each kind of simulation that was completed. The Analysis of Variance (ANOVA) is also reported.

Results show that the obtained models are very precise. As a matter of fact, the sum squared of residuals appear to be very low, namely 6.587 for the SC cycle and 9.190 for the DC cycle, with associated values of R-Squared higher than 99%. The squared error computed with 27 factors is 0.0117 for the SC cycle and 0.0138 for the DC cycle. Although these models fit very well, they are not so simple to be easily used for a quick computation of travel time. Therefore, the choice has been the reduction of interaction coefficients of the combinations of the first variables at issue, so that to reduce the level of complexity. The terms have been removed according to the values of the T-test. The lower the absolute value out of the T-test, the lower the importance of the coefficient, and therefore the coefficient can be removed. The iterations are carried out monitoring the values of the squared errors as shown in Figure 2

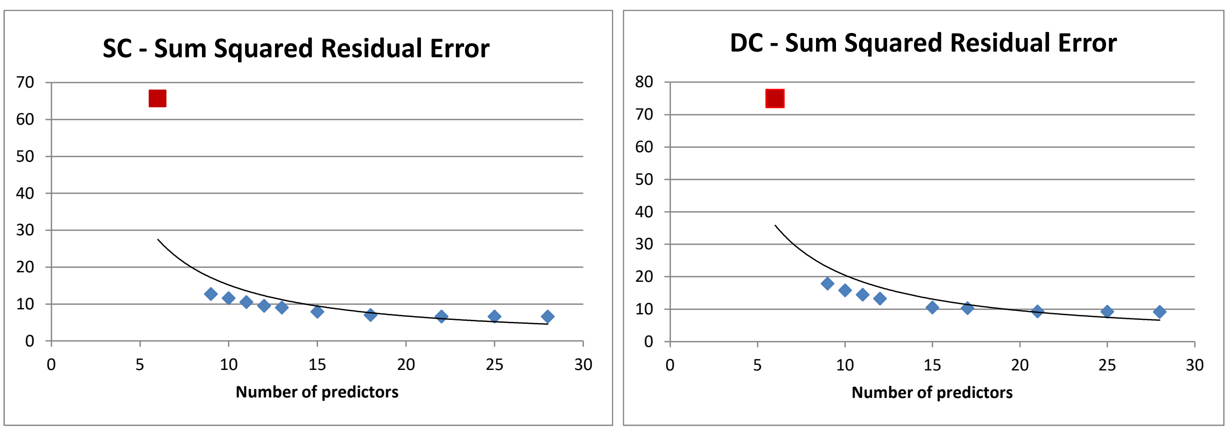

Figure 2. Sum Squared Residual Errors Vs Number of Predictors

Figure 2 highlights huge errors in case of regression analysis conducted just based just on first order terms (6 coefficients). The models also including second order coefficients (9 coefficients) represent a good trade-off between the level of error and the related computational complexity. In Table III the selected coefficients are reported together with the values of the errors.

S I N G L E   C O M M A N D

SC – Complete Model

Predict\or	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*
Constant	2.3197	b^2	0.023	b*HRf	0.2611	Ti/o*LRd	0.0070
b	0.2877	Ti/o^2	1.1472	b*MRf	0.3258	HRf*MRf	5.3110
Ti/o	-0.8392	HRf^2	3.3061	b*MRd	0.0025	HRf*MRd	-0.0770
HRf	-4.7710	MRf^2	2.8306	b*LRd	-0.0072	HRf*MRd	0.00
MRf	-4.0702	MRd^2	0.00007	Ti/o*HRf	-0.3064	MRf*MRd	-0.0631
MRd	0.0537	LRd^2	0.0003	Ti/o*MRf	-0.3524	MRf*LRd	0.0091
LRd	-0.0192	b*Ti/o	0.00578	Ti/o*MRd	0.0030	MRd*LRd	0.0003

	SS	**DF**	**MS**	
ANOVA Analysis of Variance	638.06	27	23.63	**R^2 = 0.9898**
	6.58	47,972	1.4E-4	
	644.64	47,999		

SC – Final Model

Predictor	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*
Constant	2.3560	HRf	-4.9828	LRd	-0.0096	HRf*MRf	5.31219
b	0.4190	MRf	-3.2111	Ti/o^2	1.1472		
Ti/o	-0.9768	MRd	-0.0026	HRf^2	3.3061		

	SS	**DF**	**MS**	
ANOVA Analysis of Variance	631.95	9	70.22	**R^2 = 0.9803**
	12.69	47,990	2.6E-4	
	644.64	47,999		

D U A L   C O M M A N D

DC - Complete Model

Predictor	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*
Constant	3.4120	b^2	0.0602	b*HRf	0.2388	0.0057	0.0070
b	0.3940	Ti/o^2	1.0697	b*MRf	0.3619	7.5477	5.3110
Ti/o	-1.2098	HRf^2	4.5734	b*MRd	-0.0015	-0.1043	-0.0770
HRf	-6.8013	MRf^2	4.1112	b*LRd	-0.0082	-0.0020	0.00
MRf	-5.9482	MRd^2	0.00002	Ti/o*HRf	0.1121	-0.0669	-0.0631
MRd	0.0750	LRd^2	0.0004	Ti/o*MRf	-0.0786	0.0067	0.0091
LRd	-0.0237	b*Ti/o	0.1539	Ti/o*MRd	-0.0029	0.0004	0.0003

	SS	**DF**	**MS**	
ANOVA Analysis of Variance	976.19	27	36.16	**R^2 = 0.9907**
	9.19	47,972	1.9E-4	
	985.38	47,999		

DC – Final Model

Predictor	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*	*Predictor*	*Coefficient*
Constant	3.4137	**HRf**	-7.0937	**LRd**	-0.0131	**HRf*MRf**	7.5477
b	0.6003	**MRf**	-4.6779	**Ti/o^2**	1.0709		
Ti/o	-0.9572	**MRd**	-0.0012	**HRf^2**	4.5734		

	SS	**DF**	**MS**	
ANOVA Analysis of Variance	967.52	9	107.50	**R^2 = 0.9819**
	17.86	47,990	3.7E-4	
	985.38	47,999		

Table III. Outputs of the regression in the complete and final models

The new values of errors are 0.0163 and 0.0193 for the SC and the DC cycle respectively.

The next step is to make more exploitable the mathematical function obtained through the regression analysis via the definition of new simpler coefficients. Following the Equations 2 and 3 for travel time computation in both SC and DC cycles.

$$T/T_{max}\,(SC) = 2.4 + \frac{2}{5}b - T_{i/o} - 5HR_f - 3MR_f - \frac{3}{1000}MR_d - \frac{1}{100}LR_d + \frac{10}{9}{T_{i/o}}^2 + \frac{10}{3}{HR_f}^2 + 5HR_f * MR_f \quad (2)$$

$$T/T_{max}\,(DC) = 3.4 + \frac{3}{5}b - T_{i/o} - 7HR_f - \frac{14}{3}MR_f - \frac{1}{800}MR_d - \frac{1}{80}LR_d + {T_{i/o}}^2 + \frac{9}{2}{HR_f}^2 + \frac{15}{2}HR_f * MR_f \quad (3)$$

The proposed formulas imply a lower precision for the calculation of the travel time. However, the errors associated with their expected values are very low, 0.0168 for the SC cycle and 0.025 for the DC cycle. Knowing that the mean error of T/T_{max} for the SC cycle, associated with to 48,000 simulations, is equal to 0.589, with a level of confidence of 95% it can be assumed that the error is lower than 6% of the expected value. Similarly, the mean error for the DC cycle is equal to 0.896, which corresponds to the 6% of the expected value.

Discussion and Conclusions

This paper focuses on SC and DC cycle AS/RSs. In particular, the aim of the present study is to put forward a new approach to calculate the stacker crane travel time under different vertical levels of the I/O point. In addition, a class-based storage assignment policy is applied according to the inventory turnover values of the stored products. The proposed methodology has been motivated by Bozer and White (1984), who provide a mathematical formula for travel time calculation in an environment with equal probability of access to goods. However, the Bozer and White's (1984) approach cannot be directly applied when a class-based storage policy is adopted. Therefore, the present work enlarges the perspective by addressing different inventory turnover levels. The approach relies on a simulation model and advances the previous works by Schenone *et al.* (2019, 2020) in the case of different I/O point levels. Simulation is integrated with an empirical regression analysis to provide a numerical formulation of the travel time that can be used once the main parameters of the warehouse and of the associated material handling equipment are known. The model is based on several coefficients that make it reliable from the error perspective. At the same time, the high number of coefficients does not allow to propose a concise formula that is straightforward to be adopted. For this reason, two formulas are given, for both the SC and the DC cycle, in order to provide a simpler tool to be easily used in the travel time computation, without a significant increase of the errors due to the rounding of the numerical values of the parameters.

This study offers some implications to academicians and practitioners. From a theoretical point of view, the refined mathematical formulation for estimating the AS/RS travel time advances existing methodologies already widely applied and it can be used as a basis for further investigations about warehouse design and management. For example, the present study can provide a framework to analyze the time performance of automated material handling systems when new digital technologies are introduced in warehouses. Additionally, the proposed simulation model and regression analysis approach might be applied to assess other warehouse systems and their operational performance. From a practical point of view, a proper travel time computation allows a better monitoring of the efficiency of warehouse operations and it can support practitioners in the choice of the configuration, not only in terms of kind of cycle but also from a policy assignment perspective. As well as, the proposed mathematical formulation to compute the travel time for both the SC and the DC cycle is well fitted to support precise calculations requiring a short time to be carried out. This is of particular value in current competitive markets, where organizations should provide fast and customized deliveries (Guimarães *et al.*, 2021), and in some industry sectors, such as the food and pharmaceutical ones (Zaerpour *et al.*, 2014), where automated storage systems have been applied for a long time. In fact, they face the need to further improve the efficiency of their warehouse processes due to the increasing demand pressure introduced by Covid-19 pandemic. Moreover, the present contribution can support setting appropriate service levels in warehouses serving the last mile urban distribution, as a new application field of automated storage systems.

However, this work suffers from some limitations. Crane acceleration and deceleration are neglected. Moreover, the shape factor range is limited between 0.5 and 1. Additionally, regression analysis is based on warehouse data coming from a simulation model that would benefit from a more extensive validation in real settings. This in turn might improve the estimate of the coefficients of the proposed formulas.

Future research will be addressed to the investigation of travel time formulas for shape factors ranging from 1 to 2. Moreover, acceleration and deceleration will be included in the proposed model. Finally, according to what already stated, the approach will be applied to real warehouse configurations to validate and further improve it.

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