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An approach for computing AS/R systems travel times in a class-based storage configuration

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ABSTRACT

This study provides an approach to compute the travel time for AS/R systems in a class-based storage environment. A regression analysis is completed in order to define the importance of the key predictors taken into account and to propose a formulation of travel times. The results show the reliability of the model and allow to evaluate the travel time through the identification of a complete list of predictors. The proposed approach supports managers in theex-ante definition of travel times for a warehouse. A correct evaluation of travel times enables a better monitoring of the performance of warehouse operations and can support practitioners in the choice of the configuration not only in terms of kind of cycle, but also from a policy assignment perspective. From a theoretical point of view, this work can be considered as an attempt to refine the existing methods to compute travel times.

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Warehousing system; simulation; as/RS; class-based storage; regression analysis

1. Introduction

AS/RSs are warehousing systems used for the storage and retrieval of products in both distribution and production environments. The basic components of AS/RSs are storage racks, I/O locations, and S/R machines or automated stacker cranes with computerized control to store and retrieve unit loads without human interference. The effective and efficient management of a warehouse has become more and more a challenging task (Faber et al., 2013) and a lever for competitive advantage (Choy et al., 2014) in global markets wherein companies attempt to minimize activities that do not add value to products, such as inventory management, warehousing (Voordijk, 2010), transport, and material handling. Fundamental to any warehouse strategy and design is the minimization of costs while achieving the desired level of customer service (Moynihan & Padmanabhan, 2006). AS/RSs are widely used in many industries for their numerous advantages: efficient utilization of warehouse space, reduction of damages and of shirking of goods, increased control upon storage and retrieval tasks, and decreased number of warehouse workers.

A large number of system options exist in the application of AS/RSs. They mainly differ in the rack configuration and in the potentiality of command of automated stacker cranes. On the one hand, based on the load capacity of S/R machines, single-shuttle and multi-shuttle

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systems can be identified. The traditional design is characterized by a single shuttle that allows handling one unit load at a time. In multi-shuttle systems the cranes move more than one unit load during each cycle. On the other hand, according to the unit load capacity and the operational characteristics of the S/R machine, SCs and DCs can be considered. In SC either a storage or a retrieval is performed between two consecutive visits of the I/O. In DC the S/R machine consecutively performs a storage, it travels empty to a retrieval location, and finally it performs a retrieval.

AS/RSs have been the subject of many investigations according to the several structural, functional, and operational aspects distinguishing these systems (J.P. Gagliardi et al., 2012; Petersen et al., 2005; Roodbergen & Vis, 2009). The main feature of the different reviews is the throughput capacity of the system, that appears to be a crucial performance measure (Shah & Khanzode, 2017). Such an indicator is the reciprocal of the average transaction time. This is the expected amount of time required for the S/R machine to store and/or retrieve a transport unit load. As a result, estimating travel times is very important in designing AS/RSs (Khojasteh & Son, 2016). In this context the formula proposed by Bozer and White (1984) is largely used for computing the travel times for both SC and DC shuttles. However, their approach cannot be adopted in the case of warehouse areas with different inventory turnover values. In such a configuration, the Analytical approach can be exploited (Lerher et al., 2010), but it suffers from the limitation that it is not feasible with DC shuttles. Also, most of the research in the field typically focuses on specific aspects such as crane movements, demand rate, and storage methods (Jauhari & Saga, 2017) that can fit for simple model buildings, but it turns out to be deficient in real-life applications (Moon et al., 2009).

Therefore, there is a lack of methodologies for the computation of travel times that can be applied to both SC and DC systems in warehouses characterized by storage areas with different inventory turnover values. In order to bridge this research gap, the present paper proposes a simulation approach to estimate travel times in case of multiple turnover areas (class-based storage).

The manuscript is structured as follows. First, an analysis of pertinent literature about the existing studies addressing the calculation of AS/RS travel times and storage assignment policies is developed. Then the approach is provided together with the assumptions of the model and the description of the simulator. After that the output of the simulations are presented and the regression analysis is described. Finally, future research directions and conclusions are discussed.

2. Literature background

2.1. Research on computation of travel time

AS/RSs have been the subject of many researches over the past few decades. The first studies related to travel time models for single-aisle AS/RSs were conducted by Graves et al. (1977).

Some years later Bozer and White (1984) developed a model for computing the travel times of SCs and DCs. Their model is based on randomized storage and retrieval with different I/O configurations. Lerher et al. (2010) put forward an analytical travel time model relying on case studies of AS/RSs operating according to both SCs and DCs and using a randomized assignment policy.

Muppani and Adil (2008) developed a model based on the Branch and Bound algorithm aimed at minimizing the total picking travel distance and in turn defining a proper and effective class-based storage location policy. The model proposed by Taylor and Gue (2009) is based on heuristics for travel time estimation in complex configurations including different demand levels and heterogeneous layouts. The heuristic approach has been also used by Hwang et al. (2003) for optimizing travel distances. With a similar goal, Bessenouci et al. (2012) developed two metaheuristic algorithms applied to the control of a flow rack automated storage retrieval system. Hamzaoui and Sari (2015) presented a model relying on an enumeration technique for optimizing the dimensions of a flow rack AS/RS based on the minimum travel time. Hamzaoui et al. (2019) used continuous and discrete cycle time models to introduce exact and heuristic approaches to optimize the design of bi-directional flow-rack AS/RSs.

Travel time is one of the major issues in warehouse design for determining the most proper layout and for determining the item locations (Zhang et al., 2017). Cao and Zhang (2017) used a simulation approach for globally optimizing the travel time by implementing a genetic algorithm performing an efficient scheduling of all the travels that need to be completed. A simulation approach has been also adopted by Liu et al. (2016) for computing travel times for DC shuttles under an I/O dwell policy. They demonstrated that square-in time racks bring to the shortest expected travel-time. More recent studies use simulation to validate analytical models developed to compute travel time under specific AS/RSs configurations and conditions. Liu et al. (2018) addressed DC split-platform AS/RSs and put forward travel time models in case of both dedicated lifts per rack and dedicated lifts per job type. Simulation results proved that dedicated lifts per rack better perform in case of rack shape factor less than 1, while dedicated lifts per job are to be preferred when the shape factor is greater than 1. Xu et al. (2018) extended to DCs the travel time calculation for AS/RSs with lower mid-point I/O dwell point policy. Xu et al. (2019) developed an analytical model to determine travel times in multi-deep AS/RSs with both random and class-based storage policies. Finally, 2019) investigated travel times when different I/O positions are considered, namely at one or both the sides of the AS/RS and elevated. Their results proved that the travel time is minimized when the I/O is elevated and located at the mid-point of the storage system.

Lerher et al. (2010) proposed analytical travel time models for unit-load double-deep AS/RSs in order to achieve good design performances. Also Singbal and Adil (2019) focused on warehouse design and applied simulation to estimate the effects on travel time of different warehouse parameters and storage policies. A single crane multi-aisle AS/RS performing SCs is addressed. By looking at the material handling equipment operations, Boysen and Stephan (2016) presented a study for classifying crane scheduling algorithms according to the AS/RSs layout shape.

Simulation is often used in research about AS/RSs because it enables to perform extensive experiments under various conditions (Salah et al., 2017). However, several available studies just provide simulation results without translating them into models that can be directly implemented in real situations.

2.2. Defining storage assignment policies

A storage assignment policy can be defined as a method to assign items to storage locations (Lee & Elsayed, 2005).

Both practitioners and scholars have developed numerous ways to assign products to storage locations in AS/RSs (Graves et al., 1977). The class-based storage policy has been taken into account by Yu and De Koster (2009) who proposed a model for determining the optimal storage zone boundaries. This issue is particularly relevant since a limited warehouse space leads to storage constraints and calls for a better volume utilization (Pasandideh, et al., 2014). In such a context, storage management plays an important role in reducing the inventory costs (Bakeshlu et al., 2014). According J.-P. Gagliardi et al. (2014), a correct way of performing storage and retrieval operations is a key determinant of efficiency. These authors propose a mathematical formulation that addresses such a topic. However, their model is based on only static location in the sense that each location can be devoted to pick up or storage activity. Yang et al. (2017) apply a metaheuristics methods exploiting integer quadratic programming model in order to solve the location assignment and sequencing problems simultaneously. Their study is developed under a random storage environment. Thus it cannot be applied in class-based storage spaces. Huh et al. (2019) presented an algorithm for route optimization in AS/RSs that allows decreasing the computation time without affecting its reliability. However, their study does not take into account the actual physical distances between locations.

Storage assignment strategies heavily affect many warehouse aspects, such as distances, travel times, and administration efforts, in turn impacting on the overall performance. Hausman et al. (1976) presented three storage location assignment policies:

1. Random Storage.
2. Dedicated Storage.
3. Class-Based Storage.

In random storage policies SKUs are randomly assigned to the first available location in the rack. All empty locations have an equal probability of having an incoming unit load to be assigned. If the closest open location storage is applied, the first empty location that is encountered will be used to store products. This typically leads to AS/RSs where racks are full around the I/O and gradually emptier towards the back.

The dedicated storage policy assigns specific locations to each SKU, which may only be occupied by that product. Thus, the replenishments of one SKU always occur at the same locations. For each product type sufficient space should be reserved to accommodate the maximum inventory level that is actually needed, therefore the main disadvantages of this policy are its high space requirements and consequent low space utilization.

The class-based storage policy partitions the products among a number of classes, based on different criteria such as the number of items, the demand level, and the value, and reserves a specific rack region for each class (Guo et al., 2016). Accordingly, an incoming unit load is stored at an arbitrary open location within the area associated with its class. Therefore, randomized and dedicated storage policies can be seen as extreme cases of the class-based one. Randomized storage considers a single class and, on the contrary, dedicated storage considers one class for each product. Petersen et al. (2005)

proposed a formula for calculating SC cycle times in a two class-based configuration by taking into account access frequencies and storage areas.

The performed literature review reveals that approaches for calculating the AS/RS travel time that apply to both SCs and DCs are still scarce in class-based storage. Moreover, simulation is often adopted to validate analytical models but few works rely 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 first develops a new simulation approach to compute AS/RS travel time in class-based storage configurations and under both SCs and DCs. Then, moving steps from it, uses regression analysis to propose two mathematical equations computing the travel time according to the warehouse shape factor and the turnover characteristics of the stored products.

3. The proposed simulation approach

3.1. Methodology

The research has been conducted through three different approaches for the evaluation of travel times, namely the Bozer and White's formula, the Analytical methodology, and a new simulation approach proposed by the authors, named the Class-Based Travel Time Simulation (CBT^{2}Sim) approach. The Bozer and White's formula can be applied just with one turnover area and an equal probability access configuration. However, its validity is extended to SC and DC, as Equations (1) and (2) show (Bozer & White, 1984):

$$E(Single\ Command) = T_{max}\left(1 + \frac{1}{3}b^2\right) + 2 \cdot T_{fix} \tag{1}$$

$$E(Dual\ Command) = T_{max}\left(\frac{4}{3} + \frac{1}{2}b^2 - \frac{1}{30}b^3\right) + 4 \cdot T_{fixed} \tag{2}$$

where b is equal to:

$$b = \min\left(\frac{T_{height}}{T_{max}}, \frac{T_{length}}{T_{max}}\right)\ T_{max} = \max\left(T_{height}, T_{length}\right) \tag{3}$$

It is worth highlighting that AS/RSs are able to move SKUs both vertically and horizontally simultaneously. For this reason, T_{max} is the maximum value between T_{length} and T_{height}.

On the contrary, the Analytical methodology can be adopted only in the SC but with both no class-based and class-based environments.

Indeed, with the CBT^{2}Sim approach a simulator has been developed building up a macro in Microsoft Excel®. Then simulations are run in order to evaluate travel times. This will be described in Section 4.

All the fields of application for each of the methods described above have been summarized in Figure 1.

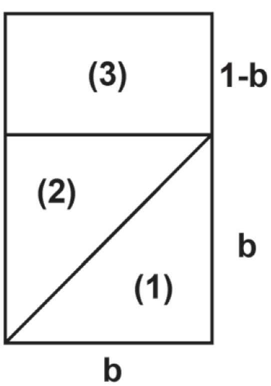
The 'Allowed ' labels in the Bozer and White column have been demonstrated and largely validated by literature (Bozer & Cho, 2005; Ekren et al., 2014; Hur & Nam, 2006). The 'Allowed' labels associated with the Analytical method are just referred to

SYSTEM CONFIGURATION \ APPROACH	B&W	ANALYTICAL	SIMULATION
Single Command - no class based	Allowed	1 Allowed	3 Allowed
Single Command - class based	Not allowed	2 Allowed	4 Allowed
Dual Command - no class based	Allowed	Not allowed	5 Allowed
Dual Command - class based	Not allowed	Not allowed	Allowed

Figure 1. Overview of system configurations and associated approaches.

the SC but this approach is suitable also with different turnover areas. In the Analytical methodology the travel time is evaluated starting from a rectangle in terms of time of the AS/RS (Figure 2).

The entire area served by the AS/RS is viewed as the sum of two areas divided by the diagonal line. In this way a triangle and a rectangular trapezoid are generated. In particular, for the triangle T_{max} is equal to T_{length} and for the polygon T_{max} is equal to T_{height} because in the lower triangle the horizontal time is always longer than the vertical time. On the other hand, in the trapezoid the vertical time is always longer respect to the horizontal one. In particular, the trapezoid can be also divided into two areas, via the bisector, the lower one (1) and the upper one (3). The triangle (1) is equal to the triangle (2). The present method is based on an empirical approach and the resulting travel time is computed as the average value of the integrals of the travel times weighted by the value of the associated subarea. To this end, the travel time computation can be performed through the identification of the areas in Figure 2. Thus, the following formulas as a function of T_{max} can be obtained. $T(SC)_{mean\text{-}one\ way}$ (Equations (4) and (5)) is the average travel time of the stacker crane when it moves from the I/O to one storage location or viceversa, while $T(SC)_{round\ trip}$ (Equation (6)) is the time required to move from the I/O to one storage location and then back to the initial crane position.



Zone	Area	Average Travel Time
(3)	$b*(1-b)$	$(b+1)/_2$
(2)	$b^2/_2$	$^2/_3\, b$
(1)	$b^2/_2$	$^2/_3\, b$

Figure 2. Identification of areas and travel times.

$$T\ (SC)_{mean-one\ way} = \frac{2*\left(\frac{2}{3}b*\frac{b^2}{2}\right) + \frac{b+1}{2}*b*(1-b)}{b} \tag{4}$$

$$T(SC)_{mean-one\ way} = \frac{2}{3}b^2 + \frac{1-b^2}{2} =$$

$$\frac{4b^2+3-3b^2}{6} = \frac{b^2+3}{6} = \frac{b^2}{6} + \frac{1}{2} \tag{5}$$

$$T(SC)_{round\ trip} = 2\ T(SC)_{mean-one\ way} = 2*\left(\frac{b^2}{6}+\frac{1}{2}\right) = \frac{b^2}{3}+1 \tag{6}$$

With this simple demonstration, it can be stated that the Analytical model provides the same results given by Bozer and White (as highlighted by the arrow 1 in Figure 1).

If multiple turnover areas are taken into account, it is possible to work with rectangles only considering the differences among their areas. In particular, the area related to the high rotation zone is a rectangle by itself. Then, the travel times associated with the medium rotation and low rotation areas are derived as the algebraic difference among rectangle areas, as detailed in Figure 5 in Section 3.3. Thus, based on these assumptions, the travel time is computed as the weighted average of the integrals of the travel times considering the different probabilities of access to each area. The probability of access is evaluated as the percentage flow of SKUs in each area. This statement is highlighted in Figure 1 by the arrow number 2 and it allows to apply the Analytical model to warehouses characterised by different inventory turnovers and related flows. The four 'Allowed' labels in the Simulation column in Figure 1 are validated in terms of difference between the results of the simulator and the outcomes of the Bozer and White's formula and the Analytical model. The comparison with the two methodologies appears to be necessary because the Bozer and White's formulation refers to both SC and DC but different rotation areas cannot be considered (column B&W in Figure 1). At the same time the Analytical model also fits with warehouses with different turnover areas but it does not work with DC systems (columns Analytical in Figure 1).The arrows labelled as 3, 4, and 5 in Figure 1 are related to simulation founded on the outcomes of the Bozer and White's formula and the Analytical model.

3.2. Approach description

Simulation allows to generate different scenarios in order to get an exhaustive idea of the system under analysis (Marin et al., 1998). It is a well-known technique for investigating dynamic processes in complex and uncertain systems (Jansen et al., 2001). Furthermore, simulation models a system and exercises this system to predict its operational performance (Smith, 2003).

In the present work the CBT^{2}Sim approach has been developed based on a macro in Microsoft Excel® that is able to evaluate the travel time for both SC and DC. A detailed description of the assumptions underlying the proposed approach is provided in Section 3.3. The simulator file is composed by two different sheets. In the first one, named 'Data Generation', input and output data are shown. In this sheet the definition of the pickup and delivery points for each simulation is carried out. These points are randomly assigned for every rotation area of the available space. In order to define the size of each area, the flow level is here multiplied by the days of supply. The whole area is then obtained via a normalization of the three products for the three rotation areas. The second sheet is named 'Data Elaboration' and runs simulations gathering travel time data for every single simulation computed.

It is very common to categorize products based on ABC analysis. This is why the warehouse space under analysis has been divided in three different areas according to such a classification. The factors that are likely to have an impact on an AS/RS with class-based storage are the product flow for each area (% of total item), the space related to each area (% of total warehouse area) and the days of supply associated with each area. Thus, for the three different turnover areas the identified variables are: area, flow, and days of supply.

Besides them, other several variables have been defined:

High rotation flow: HRf.

Medium rotation flow: MRf.

Low rotation flow: 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.

The three main variables (flow, area, and days of supply) are connected through the following relationships:

Once HRf and MRf are set, LRf is obtained as 1- (HRf + MRf).

HRd, MRd, and LRd are defined;

In turn the associated space for each area equals to:

$$Xarea\% = \frac{XRf \cdot XRd}{HRf \cdot HRd + MRf \cdot MRd + LRf \cdot LRd} \tag{7}$$

where X is equal to high (H), medium (M) or low (L).

As it can be demonstrated, the partitioning of the different areas does not depend merely on the days of supply, but also on the daily SKU flow. That is why the days of supply for high rotation areas are conventionally equal to 1 and they have not been taken into account. As well as, the low rotation flow is not considered in the analysis because it is got from the flow of high and medium rotation.

The simulator allows the generation of random data about possible storage and pickup locations. To be more precise, in order to ensure randomized access to warehouse locations with non-rectangular areas, such as when class-based storage is considered, three cases have been defined (Figure 3). In this way it is possible to guarantee an equal access probability in each case at issue. The probability of being in one of these three cases is coherent with both warehouse flows and physical areas.

Figure 3 highlights that the access to the high rotation area is possible in all the three cases, while the access to the low rotation area is possible only in case 1.

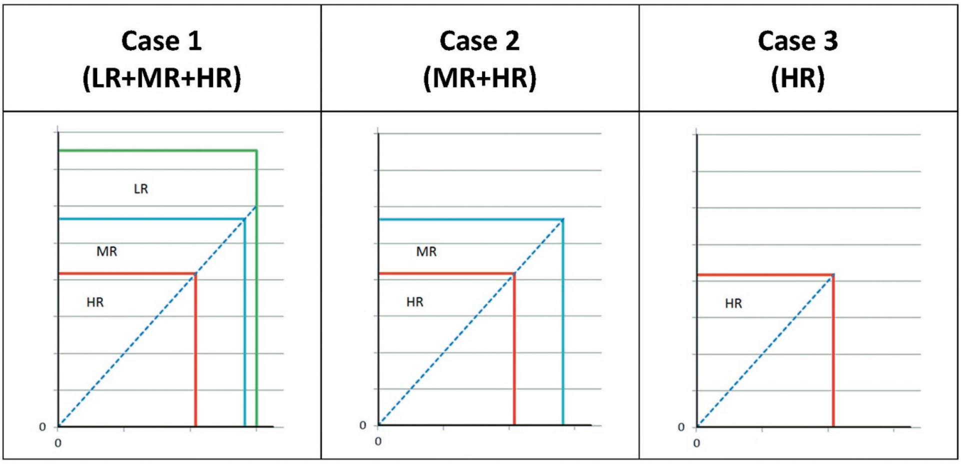


Figure 3. Randomized access to warehouse locations: case definition.

Simulations are run under the following conditions that have been defined based on the analysis of several real warehouse observations. 16,600 tests have been completed for different levels of the shape factor and for each test 2,000 simulations have been carried out. For each configuration 5 replications have been conducted in order to minimize the random error. Simulations have been completed for different warehouse configurations depending on characteristics such as the shape factor and the different rotation rates. In each simulation, a casual storage/retrieval point is extracted and for that point the travel time is computed. The data obtained through the simulations can be considered as random since the Random Function in Microsoft Excel® has been adopted for both T_{height} and T_{length}. However, these two parameters have been independently taken into account. Furthermore, the identification of the point takes place in sub-areas of the warehouse that are rectangular in shape. In particular, the first one is given by the sum of HRf, MRf, and LRf, while the second one is computed by adding HRf to MRf, and finally the last rectangular area is related only to HRf.

Table 1 summarizes the factors that are supposed to be significant for travel time computation. Table 2 shows the different values of the shape factor that have been taken into account.

Table 1. Description of the variables.

Variable	Acronym	min	max	step
Shape Factor (provided by Bozer and White)	b		see Table 2	
High Rotation Flow Rate	HRf	60%	76%	4%
Medium Rotation Flow Rate	MRf	13%	20%	3.3%
Days of Medium Rotation	MRd	3	6	1
Days of Low Rotation	LRd	10	20	3.3

Table 2. The shape factor.

$b^* = \frac{T_{lenght}}{T_{height}}$	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0
0.5	0.6	0.7	0.8	0.9	1.0	0.83	0.71	0.63	0.56	0.5	
			$b = b^*$						$b = {}^{1}/_{b^*}$		

These variables appear to be crucial in travel time evaluation. If HRf and MRf increase, the travel time is supposed to decrease, since there are more items that are closer to the I/O. On the contrary, the higher the number of days of stock for both MRd and LRd, the longer the travel time because of the increased number of items that do not turn.

The CBT^2Sim approach has been validated through different perspectives. First, the simulation results have been compared with the output of the Analytical approach for a SC with different turnover values. Then, the outcomes of the CBT^2Sim approach have been compared with the results provided by the Bozer and White's formula in a DC configuration with a unique inventory area. Finally, the simulation results have been compared in a SC configuration with just one single area of inventory turnover. In fact, in this situation all the methodologies can be used. Figure 4 shows that the results provided by the CBT^2Sim approach are comparable with the outcomes of the Bozer and White's formula and the Analytical model.

3.3. Approach assumptions

First of all, a space with different turnover areas is considered as per Figure 5.

Then, in order to define the key features of the simulation model the authors refer mainly to the assumptions (Hi) provided by J.P. Gagliardi et al. (2012). These are conveniently classified into three groups according to the different AS/RS elements (Roodbergen & Vis, 2009): rack, crane, and handling policy.

Rack group

The system is a unit-load AS/RS and each unit load holds just one SKU (H1).

All the storage locations have the physical capability to store any item (H3).

The distance (i.e. travel time) from rack location i to rack location i' is symmetrical and does not change over time (H5).

Racks are considered to be continuous and rectangular-in-time (H13).

Rack utilization is 100% (H16).

The number of SKUs in the system is constant (H26).

Crane group

The crane simultaneously moves both vertically and horizontally (Chebyshev displacement), enabling to circulate on two horizontal axes (depth on the serving aisle and on the common aisle) and on a vertical axis (the columns) (i.e. the travel time follows a Chebyshev distance metric) (H2).

The crane acceleration and deceleration are assumed instantaneous and are ignored (H6).

A single crane serves a single two-sided aisle (H8).

Handling policy group

The I/O is fixed and located on the floor level.

The system handles entire unit loads.

Pickup and storage times are assumed constant and are ignored (H7).

A pure random storage policy is used wherein each class, then one unit load is stored anywhere in the space associated with its class.

Each unit load of a SKU has a same probability of being selected for each class.

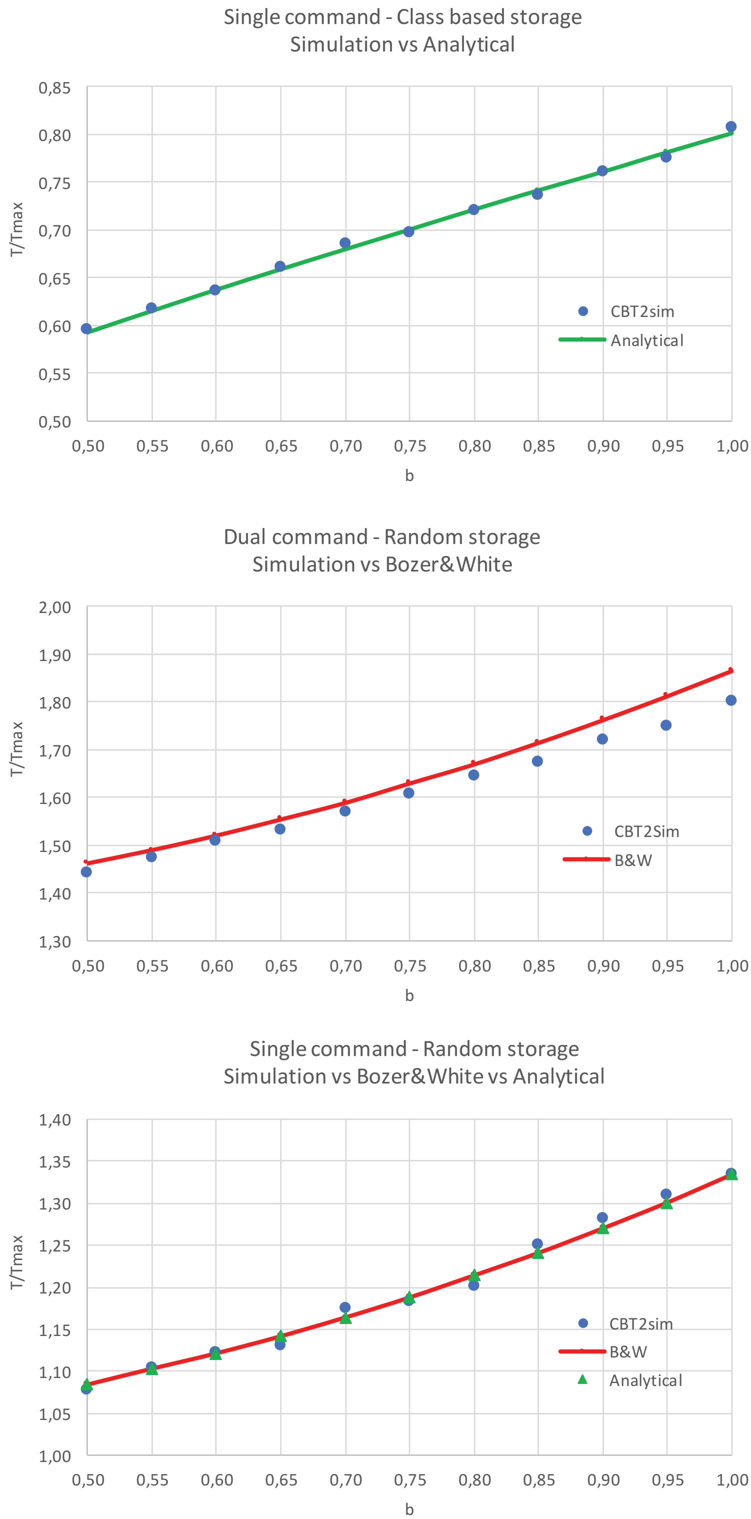


Figure 4. Comparison among the CBT^{2}Sim, bozer and white, and the analytical approach.

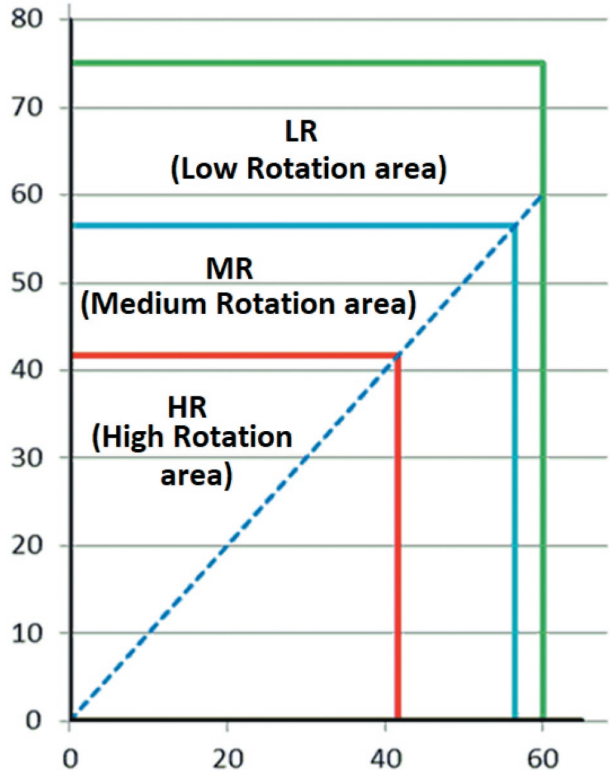


Figure 5. A space with different turnover areas.

4. Numerical computations and mathematical formulation of travel time

As mentioned in Section 3.2, for each warehouse configuration 2,000 iterations have been performed and then the average value of the associated travel times has been considered (T/T_{max}). Furthermore, the simulation of each configuration has been replicated 5 times. Simulations have been computed for both SC and DC.

Table 3 reports the output of some simulations. The columns refer respectively to the shape factor b, the percentage of high rotation and medium rotation items, the days of supply for medium and low rotation, the response variable T/T_{max}, the travel time resulting from the Bozer and White's formula, and the CRTT that is equal to the ratio between the time got through the simulation and the time obtained using the Bozer and White's formula. This coefficient actually represents another way of computing the travel time starting from the Bozer and White's formula instead of using the direct proposed formula.

A regression analysis is then performed to test if the independent variables taken into account as input data for the simulation are statistically significant factors and whether they have a negative or positive impact on the response variables, namely the travel time and CRTT.

A positive influence indicates that an increase (or decrease) in the independent variable determines an increase (or decrease) in the dependent variable, while a negative effect produces opposite direction between independent and response variable variations. The

Table 3. Example of simulation.

Input Variables					OUTPUT		OUTPUT
b	HRf	MRf	MRd	LRd	T/T_{max}	T/T_{max} (Bozer and White's formula)	CRTT
0.5	0.6	0.1	3	10	0.958299	1.454167	0.659002
0.5	0.6	0.1	3	10	0.982558	1.454167	0.675685
0.5	0.6	0.1	3	10	0.954569	1.454167	0.656437
0.5	0.6	0.1	3	10	0.972041	1.454167	0.668452
0.5	0.6	0.1	3	10	0.969318	1.454167	0.66658
0.5	0.6	0.1	3	13.3	0.93297	1.454167	0.641584
0.5	0.6	0.1	3	13.3	0.918608	1.454167	0.631708
0.5	0.6	0.1	3	13.3	0.918557	1.454167	0.631672
0.5	0.6	0.1	3	13.3	0.925437	1.454167	0.636404
0.5	0.6	0.1	3	13.3	0.895633	1.454167	0.615908
0.5	0.6	0.1	3	16.7	0.902125	1.454167	0.620373
0.5	0.6	0.1	3	16.7	0.895684	1.454167	0.615943
0.5	0.6	0.1	3	16.7	0.882518	1.454167	0.606889
0.5	0.6	0.1	3	16.7	0.900503	1.454167	0.619257
0.5	0.6	0.1	3	16.7	0.87568	1.454167	0.602187
0.5	0.6	0.1	3	20	0.88345	1.454167	0.60753
0.5	0.6	0.1	3	20	0.85511	1.454167	0.588042
0.5	0.6	0.1	3	20	0.860163	1.454167	0.591516
0.5	0.6	0.1	3	20	0.863678	1.454167	0.593933
0.5	0.6	0.1	3	20	0.861089	1.454167	0.592153
0.5	0.6	0.1	4	10	0.968919	1.454167	0.666305
0.5	0.6	0.1	4	10	0.983021	1.454167	0.676003
0.5	0.6	0.1	4	10	0.956323	1.454167	0.657643
0.5	0.6	0.1	4	10	0.967309	1.454167	0.665198
0.5	0.6	0.1	4	10	0.980217	1.454167	0.674075
0.5	0.6	0.1	4	13.3	0.913932	1.454167	0.628492
0.5	0.6	0.1	4	13.3	0.953434	1.454167	0.655657
0.5	0.6	0.1	4	13.3	0.961637	1.454167	0.661298
0.5	0.6	0.1	4	13.3	0.919449	1.454167	0.632286

level of significance is associated to the p-value, which ranges from 0 to 1 and is obtained from the observed sample. It represents the probability of incorrectly rejecting the null hypothesis. The smaller the p-value, the lower the probability that rejecting the null hypothesis is wrong. If it is less than a predetermined critical value, usually equal to 5%, the null hypothesis is rejected. In the regression analysis the null hypothesis states that the coefficient equals zero (Montgomery & Runger, 1999). In other words, the notion of significance is not related to the strength of the relationship but to its reliability. Thus, it is possible to assume as true the impact of a predictor that is significant, with an associated p-value lower that 5%. This value is widely used in experiments and decision processes (Hryniewicz, 2018). The results of the regression analysis are shown in Table 4, where the columns report the estimates of the regression coefficients, the associated standard errors (SE Coeff), and the p-values.

Results show that for both T/T_{max} and CRTT all the factors taken into account have a significant impact. For this reason, the previous simulations allow to define a mathematical model for estimating travel times based on the defined variables and using the coefficients given by regression. Equations (8) and (9) show the obtained formulas for both T/T_{max} and CRTT.

$$^{T}/_{T_{max}} = 0.62 + 0.555\mathrm{b} + 0.223\mathrm{HRf} + 0.456\mathrm{MRf} - 0.0005\mathrm{MRd} - 0.0144\mathrm{LRd} \quad (8)$$

$$\mathrm{CRTT} = 0.59 + 0.0076\mathrm{b} + 0.146\mathrm{HRf} + 0.285\mathrm{MRf} - 0.0003\mathrm{MRd} - 0.0091\mathrm{LRd} \quad (9)$$

Table 4. Regression analysis.

T/T_{max}			
Variable	Coefficient	SE Coeff	p – value
Constant	0.6207	0.003	0
b	0.5549	0.001	0
HRf	0.223	0.003	0
MRf	0.4564	0.006	0
MRd	−0.0005	0.0002	0.003
LRd	−0.01439	0.00006	0
R-Square	0.929		
R-Square Adj	0.929		
CRTT			
Constant	0.5879	0.002	0
b	0.0076	0.008	0
HRf	0.1376	0.002	0
MRf	0.2851	0.0037	0
MRd	−0.0003	0.0001	0.009
LRd	−0.0091	0.00003	0
R-Square	0.814		
R-Square Adj	0.814		

Thus, when calculating AS/RSs travel times, in case of storage policies not depending on the inventory turnover value the Bozer and White (1984) formula (Equations (1) and (2)) can be applied.

The contribution of this work is developing an approach, the CBT^2Sim, to estimate travel times in class-based storage configurations. In particular, two formulations are proposed: Equation (8) as a direct approach to travel time computation and Equation (9) as an indirect method that moving steps from the Bozer and White's formula introduces the correction coefficient CRTT.

5. Implications and conclusions

The proposed study aims at providing an approach for the evaluation of travel times for AS/RSs in warehouses characterised by different inventory turnover values. In particular, attention has been paid to class-based storage policy divided into three rotation classes. The rotation rate has been taken into account based on the SKU turnover in terms of physical flows. The CBT^2Sim approach has been inspired by Bozer and White (1984) who provide a formula for the computation of travel times in an environment with equal access probability. The proposed CBT^2Sim model is based on simulation and integrates the previous studies related to both SCs and DCs through the introduction of new predictors associated with crucial variables of warehouse operations. The simulation approach is often used in the case of process time computation (Heydarian & Jolai, 2018). The reliability of the CBT^2Sim approach has been tested through the comparison with the analytical travel time computation in SCs, so that it has been possible to extend the simulation to DCs. The simulation results have been processed with a regression analysis, wherein the travel time and the CRTT were the response variables taken into account. Thanks to regression the coefficients related to each crucial operational predictor have been identified.

This work originates some theoretical and practical implications. From a theoretical perspective, the proposed approach offers a basis for further studies aimed at refining the

Bozer and White's formula, and in turn enlarging its application fields. As well as, the developed simulation framework might be used in other warehousing systems for evaluating their performance. From a practical point of view, a proper computation of travel times allows to better monitor the performance of warehouse operations. Additionally, this study can support practitioners in the choice of an appropriate AS/RS configuration not only in terms of kind of cycle, but also from a policy assignment perspective. However, the mathematical formulation derived from the regression model still presents a certain level of error. For this reason, future research will be addressed to its refinement in order to reduce the level of uncertainty in the prediction.

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Acronyms

(in the same order as they appear in the paper)

AS/RSs: Automated Storage and Retrieval Systems
I/O: input/output point
S/R: storage/retrieval
SCs: single command cycles
DCs: dual command cycles
SKUs: Stock Keeping Units
b: shape factor according to Bozer and White
T_{fixed}: constant related to acceleration and deceleration time
T_{length}: maximum horizontal travel time from the I/O point
T_{height}: maximum vertical travel time from the I/O point
CRTT: coefficient of reduction of travel time

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