A simulation approach for computing travel times of warehousing systems: Application for AS/RS in a class-based storage configuration

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Abstract- This paper aims to provide with a methodology suitable to compute the travel time for a AS/RS system in case of class-based storage assignment policy. A literature review is carried out to emphasize the importance of the computation of travel times that is one of the most crucial indicator to define the performance of the system. A simulator has been developed in order to create different scenarios. A regression analysis is then completed to define the importance of the key predictors taken into account. Results show the reliability of the model and allow to evaluate the travel time through the definition of a complete list of predictors. The identified predictors are the turnover of items in the different areas of rotation and the shape factor of the warehouse. This study integrates a formula for travel times computation that has been widely validated by both scholars and practitioners suitable for a random storage environment. However, our extension is oriented to the application in a class-based storage configuration.

Keywords –Warehousing System, Simulation, AS/RS, Class-based storage, Regression Analysis

I. Introduction

Automated Storage and Retrieval Systems (AS/RSs) are warehousing systems that are used for the storage and retrieval of products in both distribution and production environments. The basic components of AS/RS are storage racks, input/output (I/O) locations and storage/retrieval machines (S/R machines) or automated stacker cranes with computer control to store and retrieve warehouse stock without human interference. The effective and efficient management of a warehouse has become more and more a challenging task [1], in a global competitive market wherein companies attempt to minimize activities that do not add value, especially in the warehouse processes. AS/RSs are widely used in industry for the numerous advantages of application: efficient utilization of warehouse space, reducing of damages and of loose of goods, increased control upon storage and retrieval of goods, and decreasing the number of warehouse workers.

A large number of system options exist in the application of AS/RS system. They especially differ in the rack configuration and in the potentiality of command of the automated stacker cranes. On the one hand, based on S/R machine's load capacity the operational characteristics are limited to single-shuttle and multi-shuttle systems.

The traditional design is characterized by a single shuttle that allows one load at the time. In multi-shuttle system the cranes move more than one load during each cycle. On the other hand, its unit-load capacity and the operational characteristics of the S/R machine are limited to single command cycles and dual command cycles. In a single command cycle either a storage or a retrieval is performed between two consecutive visits of the input and output station. In a dual command cycle 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 a subject of many investigations according to the many structural, functional, and operational aspects distinguishing these systems. Therefore, in recent years the need to properly map and contextualize the various existing research literature has arisen; in particular structured reviews are crucial, since they support researchers and industrial users in their research for the best modeling approach for a specific problem.
The main feature of the different reviews is the throughput capacity of the system, that appears to be an
important measure of system performance. This indicator is the inverse of the mean transaction time.
This is the expected amount of time required for the S/R machine to store and/or retrieve a Transport Unit Load (TUL). As a result, estimating travel times is very important in designing AS/RSs.

[2] present a short review and a comparative study of some design aspects of automated storage/retrieval systems. In particular, the examined models are categorized into three groups: models based on random storage, models based on retrieval sequencing, wherein the schedule and sequence of storage that minimizes are defined to minimize the the shuttle travel time, and models based on order batching, wherein the orders are grouped into batches in an optimum manner.

[3] highlight two aspects which together determine the physical configuration of the system: first, the AS/RS type (unit load, multi-shuttle, miniload) and then the way through the specific chosen system must be configured. For example, by deciding the number of aisles and the rack dimensions (system configuration). This analysis has originated an overview of research about design
models that can support the decision making into physical design related to control issues. Furthermore, they overview travel time models for different types of AS/RS for different layouts, racks, location of I/O-points, storage assignment methods, scheduling approaches and operational characteristics.

[4] propose an examination of the published research related to warehouse design, and classified papers based on the main addressed issues (overall structure, department layout, operation strategy selection, equipment selection, sizing and dimensioning). [5] develop a heuristic analysis for puzzle-based storage systems as feasible way to compute the travel time. In particular, they summarize the research on travel time models for aisle based systems (randomized storage, dedicated storage and class-based storage). In this context few studies about the computation of travel times for AS/RS in a class- based configuration have been carried out. In order to fill this research gap, the paper a model that based on simulation provides a tool for the evaluation of travel times in a class-based environment. The manuscript is structured as follow. First the analysis of pertinent literature about storage assignment policies and of the assumptions for the operations of the system is proposed. Then the description of the model is provided. Finally, future research directions and conclusions.

II. STORAGE ASSIGNMENT POLICES

Both practitioners and scholars have developed In the literature numerous ways to assign products to storage locations with AS/RSs [6]. The storage assignment strategies heavily affects many warehouse aspects, such as distances, travel times, and administration effort and in turn the whole performance of a warehouse. [7] present three storage location assignment policies:

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

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

The dedicated storage policy assigns specific locations to each product, which may only be occupied by that product. The replenishments of that product always occur at this same location. For each product type sufficient space must be reserved to accommodate the maximum inventory level that is actually needed, therefore the main disadvantage of this policy are its high space requirements and consequent low space utilization. The class based storage policy partitions the products (N_i) among a number of classes (C_i) and reserves a region within the rack for each class. For instance [8], propose a formula for single command cycle time in a two class-based configuration, that takes into account the access frequencies and the storage areas. Accordingly, an incoming load is stored at an arbitrary open location within its class. Therefore, randomized and dedicated storage are extreme cases of the class-based storage policy. Randomized storage considers a single class and, on the contrary dedicated storage considers one class for each product. Hence Class- Based Storage appears to be Random Storage if $C_i=1$, and if $C_i=N_i$ the policy becomes the Dedicated Storage. In particular

- if C_i tends to 1 travel times increase and the utilization warehouse coefficients are enhanced;
- if C_i tends to N_i travel times decrease and the utilization warehouse coefficients get worse [10];

In Table 1 the main features for the different storage assignment solutions are shown with the associated strengths and weaknesses.

Table -1 Characteristics of storage assignment policies

Storage assignment polices	Strengths	Weaknesses
Random Storage (Koster et al.,2007; Petersen, 1999)	• better utilization of the space • less congestion in the corridors	• leak of structured organization • increased travel times.
Dedicated storage (Heskett, 1964)	• the management of products with different characteristics is facilitated • it can be integrated with random policy	• high space requirements • low space utilisation coefficient • not efficient management of warehouse operations
Class-based storage (Graves et al.,1977; Petersen et al., 2004; Roodbergen et al.,2009)	• reduction of travel time • an increased efficient operations thanks to the storage of fast moving items close the I/O-point • lower storage space requirements and flexibility	• complex solution due to the choice to the indicator associated with the classification of the items • class-based storage requires more rack space compared with randomised storage

With class-based storage configuration a relatively small number of classes, usually less than 10, is to be preferred to get most of the potential savings in terms of travel time as compared to full turn over storage [11]. Based on the described characteristics, a proper tradeoff between travel times and the utilization coefficient suggests to identify three different classes for the class-based storage policy [3]. This classification is carried out through a criteria with an associated indicator that is identified *ex ante*. The rule establishes a ranking that allocates the items firstly considering the most crucial class, and then it assigns less convenient positions. However the choice of the indicator for the classification of the items is not univocal. As a matter of fact it depends on the activity that has to be performed in a warehouse in terms of handling of Storage Keeping Units (SKU), or single products after the picking [12].

Several slotting measures are available to warehouse managers, such as popularity, turnover, volume, pick density, and cube-per-order index (COI) [13- 14].

- Popularity. This parameter indicates the number of requests received for a given SKU , and as a first step, can be considered as the number of times a picker must visit allocations wherein each item is stored and this is the most commonly used slotting measure in practice.
- Turnover. In this case it is used as a discriminating criterion for the products classification, based on the total quantity of a reference shipped a given period of time Usually the requested products get the easiest accessible locations, usually near the I/O-points. Slow-moving products are located farther away from the

I/O-point.

- Volume. The demand for a SKU multiplied by the cube (volume) of the SKU, sometimes called the cube movement of a SKU.
- Pick density. The ratio of the popularity of a SKU to the cube (volume) of the SKU.
- COI. The ratio of the cube of a SKU to the turnover of the SKU with SKUs ranked in ascending order of the index. The Cube-per-Order index COI of a load is defined as the ratio of the load's required storage space to the number of request for this product per period. The COI rule assigns loads with the lowest COI to the locations closest to the I/O-point in terms of time [15].

The analysis of current literature shows that the most proper indicators associated with the handling of SKUs are turnover and volume, and in turn the COI.

III. Model Assumptions

According to the previous literature research, it results that it is very important to define the environment of application for the model under analysis. Through this model, the objective is to integrate the results obtained by previous studies of [16] related to single and dual command cycles in a configuration of random storage policy. In particular, we refer to AS/RS systems that handle entire SKUs and that are able to improve the throughput, by using the storage assignment policy of class– based storage with 3 classes based on the turnover criteria, that here is defined in terms of flows (see Figure 1). This means that an item in our model is classified according its level of requests in a given period of time.

In order to define all the remaining features of the model we refer mainly to the assumptions (Hi) provided by [17]. These are conveniently classified into three groups according to the different AS/RS system option [3]: rack, crane and handling policy.

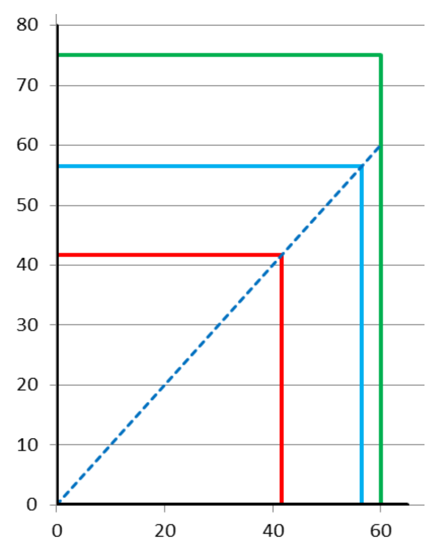


Figure 2. A space with different area of rotations

Rack group

- The system is a unit-load AS/RS and each SKU holds only one part number or item type (H1).
- All 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).
- The rack is considered to be continuous and rectangular-in-time (H13).
- The length measured in seconds of the warehouse is greater that the height.
- Rack utilization is 100% (H16).
- The number of SKUs in the system is constant (H26).

Crane group

- The cranes moves, simultaneously, 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. travel time follows a Chebyshev distance metric) (H2).
- Crane acceleration and deceleration are assumed instantaneous and are ignored (H6)
- A single crane serves a single two-sided aisle (H8).

Handling policy group

- Input and Output are constant and are on the floor level.
- The system handles entire SKUs.
- Pickup and deposit times are assumed constant and are ignored (H7).
- A pure random storage policy (PRS) is used wherein each class, then the SKU is stored anywhere in the space associated with its class.
- Each SKUs of an item has an equal probability of being selected for each class.

All these assumptions are very important in the computation of travel times, even if they can be considered strict and they are static in nature. Therefore on the one hand, the conclusions drawn from those assumptions may be questionable for real life scenarios. On the other hand, models proposing some form of simulations are often more precise and quite able to integrate dynamic behaviors. For this reason our proposed methodology is based on the simulation technique coached on the previous assumptions.

IV. METHODOLOGY

After the analysis of the exiting literature, the research focuses on the evaluation of travel times and in turn of the throughput capacity for an AS/RS system in a class-based storage environment. The research has been conducted through three different approaches for the evaluation of the travel times have been taken into account, namely the Bozer & White formula, the Analytical methodology and the Simulations. Bozer and White's formula is applicable just with one area of turnover, then with an equal probability access configuration, but the Bozer and White applicability is extended to Single and dual command cycle, as following formula shows:

E(Single Command) = $T_{max}(1 + \frac{1}{3}b^2)$ + 2 T_{fixed} [16]

E(Dual Command) = $T_{max}(\frac{4}{3} + \frac{1}{2}b^2 - \frac{1}{30}b^3)$ + 4 T_{fixed} [16]

Where b is defined as the shape factor and it is equal to:

b = min ($\frac{T_{height}}{T_{max}}$, $\frac{T_{length}}{T_{max}}$); Tmax = Max ($T_{height,}$ T_{lenght})

It is worth to highlight that the systems under study are able to move SKUs both vertically and horizontally simultaneously. For this reason the travel time between two different points of the warehouse is the maximum between the horizontal travel time and the vertical travel time.

On the contrary, the Analytical methodology is usable only in the Single Command but with both no class-based and class based environments. Indeed with the third approach a simulator has been developed building up a macro in excel. Then we run simulations in order to evaluate travel times.

The all fields of application for each method have been summarized in the following table.

Table -2 Combination between approaches and configurations

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

In the Bozer and White column, the "YES"s have been demonstrated by the authors and largely validated by the literature [18-19-20]. The "YES"s associated with the Analytical Method are just referred to the Single Command cycle, but they be suitable also with different turnover areas.

In the Analytical methodology the travel time is evaluated starting from, a rectangular in terms of time of the AS/RS [15-21]. After that, the entire area served by the AS/RS system is viewed as the sum of two areas divided by the segment I/O-B. In this way a triangle and a polygon are generated and they are both based on the same Tmax. In particular, for the triangle Tmax is T_{lenght} and for the polygon Tmax is $T_{height.}$. As a matter of fact, in the lower triangle, the horizontal times are always greater than the vertical times. On the other hand, in the upper polygon the vertical times are always greater respect to the horizontal ones. In particular, the polygon is divided into two areas, via the bisector, the lower one (1) and the upper one. In this polygon, two areas (2;3) are identified namely a triangle (2) – that is equal to the other one previously defined - and a rectangular (3) by the two triangles are defined by a diagonal segment. In this way, the following formula can be identified.

This method is based on an empirical approach and the travel time resulted is computed as weighted mean of the integral of the travel times associated with every subarea. To this end, the computation of travel time can be got through the identification of the three different areas. Thus, the following formula can be obtained.

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

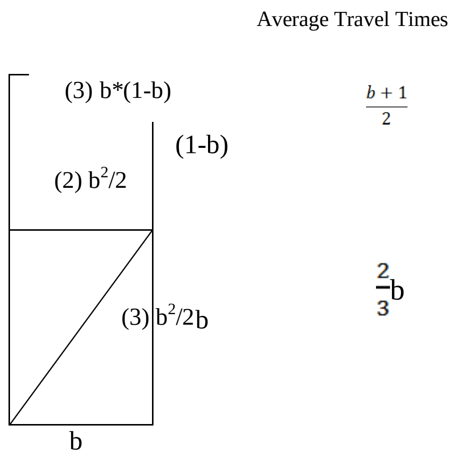
$$T(SC)_{mean-one\,way} = \frac{2}{3} b^2 + \frac{1-b^2}{2} = \frac{4b^2+3-3b^2}{6} = \frac{b^2+3}{6} = \frac{b^2}{6} + \frac{1}{2}$$

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

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

If different areas of turnover are taken into account, it is possible to work with rectangles only considering the differences among their areas. In particular, the area of high rotation is a rectangle by itself. Then, the travel times associated with the medium rotation and low rotation areas are derived as algebraic difference of areas of rectangles. Thus based on these assumptions, the travel times is computed as weighted mean of the integral of the travel times considering the different probabilities of access to each area. The probability of access is considered as the percentage of flow of SKUs in each area. This statement is highlighted in Table 2 by the arrow number 2 and it allows to validate the Analytical model in the spaces with different inventory turnovers and related flows. The four "YES"s of the Column of the Simulation are validated in terms of errors by comparing the Simulation and both Bozer and White and the Analytical model. The comparison with the two methodologies appears to be necessary, because Bozer and White refers to both Single Command and Dual Command but different areas of rotation cannot be considered. At the same time the Analytical model fits with also space with different turnovers but it does not work with Dual Command system.

Figure 2. Identification of areas and travel times



The simulator has been validated through different perspectives. First for a Single Command cycle with different turnovers, the results of simulations have been compared with the output of the analytical approach. Then the simulator has been compared in a Dual Command configuration with a unique area of inventory with the results provided by the formula of Bozer and White. Finally, the results of the simulator have been compared in a Single Command configuration with just one single area of inventory turnover. As a matter of fact, in this situation the all methodologies can be used.

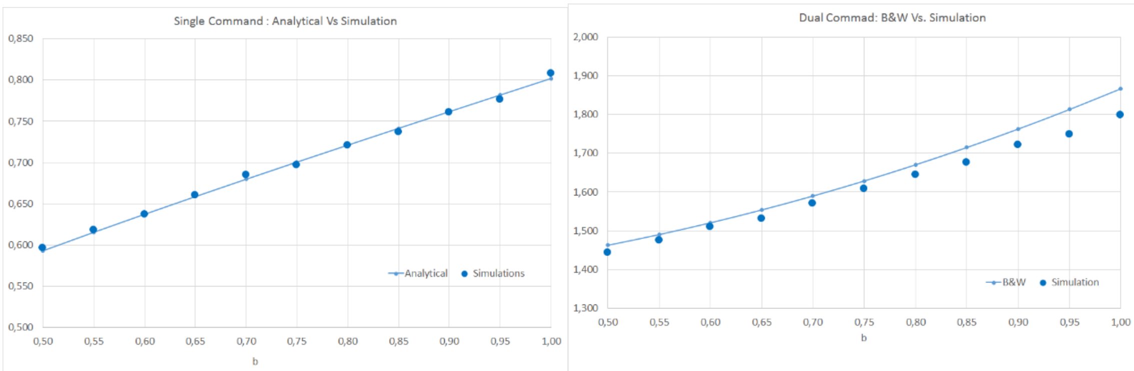
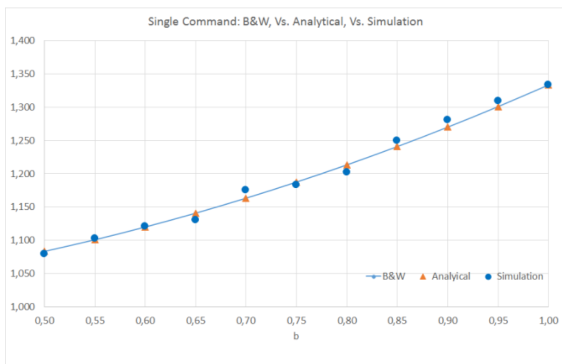


Figure 3. Comparison between the Simulation, Bozer and White and the Analytical approach



The results shown in Figure 3 highlight that the simulator is always reliable, since the outputs of the simulations are always comparable with the outputs of the Analytical method and Bozer and White's ones. These outcomes validating the robustness of the Simulator bring to affirm that the simulator can be used in the all proposed situations (see arrows number 3,4 and 5 figure). In this way it can be stated that the simulator is also suitable in the Dual Command Cycles in class based storage environment. This is a crucial aspect since neither the Analytical method, neither Bozer and White are able to compute the times in this kind configuration.

Spaces with different rotation areas are able to reduce travel times therefore the purpose is to propose a coefficient that reduces the time computed through the formula of Bozer and White. This has been defined as the Coefficient of Reduction for Travel Time (CRTT). Both T/Tmax and CRTT have been considered as response variables and a regression analysis has been performed in order to capture the impact of each factor on the travel time.

A. Description of the simulator

Through the simulation it is possible to generate different scenarios in order to get an exhaustive idea of the system under analysis [22]. It is a well-known technique for the investigation of dynamic processes in complex and uncertain systems [23]. Furthermore simulations model a system and exercise this system to predict its operational performance [24]. The simulator has been developed with a macro in excel that, is able to evaluate travel time for both single and dual command. The simulator is composed by two different sheets, namely "Data Generation" wherein output and input data are shown and "Data Elaboration" that runs the simulations. It is very common to classify products based on ABC analysis [15]. This is why the space under analysis has been divided in three different areas. Factors that are likely to have an impact on an AS/RS system with class-based storage are the product flow for each area (% of total item) and the space related each area (% of total area). Thus for the three different turnover areas, the identified variable are: area, flow, and days of supply Thus the selected variables are: area, flow and days of supply.

Thus, several variables have been identified.

- High rotation flow: HRf;
- Medium rotation flow: MRf;
- Low rotation flow: LRf;
- Days of supply for high rotation area: HRday;
- Days of supply for medium rotation area: MRdays;
- Days of supply for low rotation area: LRdays

The three components (flow, area, days of supply) are related through the following relationships.

- once HRf flow and MRf are set LRf is obtained as 1- (HRf+MRf);
- HR days, MR days, and LR days are defined;
- In turn the associated space for each area equals to: Xarea % = (XRf * XR days)/ (HRf * HR days+ MRf * MR days+LRf * LRdays), wherein 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 *per se*, but also on the flow of the daily SKUs. That is why conventionally, Days of supply for high rotation areas are equal to 1 and it has not taken into account. As well as, 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 and simulations are run under the following conditions that have been extrapolated based on the analysis of several real case studies. 16,600 tests have been completed for different level of the shape factor and for each test, 2000 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 configuration of the warehouse depending on its characteristics. In each simulation, a casual point is extracted and for that point the travel time is computed.

Table 3 summarizes the factors that are supposed to be significant for the computation of travel times. Table 4 shows the different values of shape factor that have been taken into account.

Table -3 Description of the variables

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

Table -4 The shape factor

$b^* = T_{lenght}/T_{height}$	0.5	0.6	0.7	0.8	0.9	1	1.2	1.4	1.6	1.8	2
b (Bozer)	0.5	0.6	0.7	0.8	0.9	1	0.83	0.71	0.63	0.56	0.5
	b = b*						b = 1/b*				

These variables appear to be crucial in the evaluation of travel times. As a matter of fact if HRf and MRf increase the travel time is supposed to decrease, since there are more items that are closer to the input output point. On the contrary the higher the number of days of stock for both MRd and LRd, the higher the travel time because of the increased number of items that do not turn.

B. Simulations

For each configuration of warehouse 2000 iterations have been performed and then the average value has been considered. Furthermore the simulation of each configuration has been replicated 5 times. Simulations have been computed for both single and dual command. 35,200 simulations have been totally performed.

Table -5 Example of Simulation

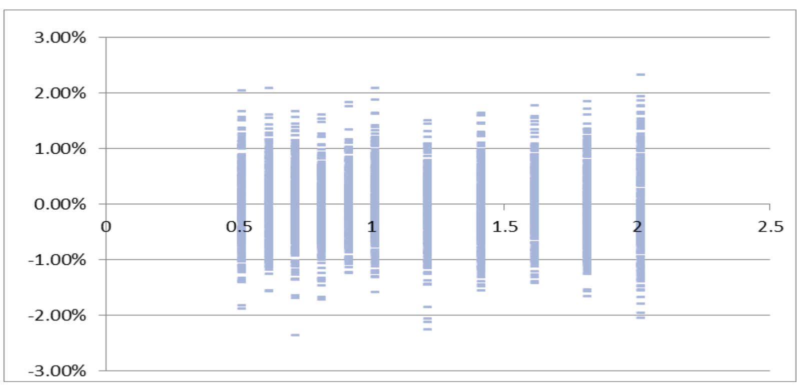
Variable					**OUTPUT**	**T/Tmax (Bozer formula)**	**OUTPUT**
b	**HRf**	**MRf**	**MRd**	**LRd**	**T/Tmax**		**CRTT**
0.5	0.6	0.1	3	10	0.958299	1.454167	0.659002
0.5	0.6	0.1	3	10	0.982558	1.454167	0.675685
0.5	0.6	0.1	3	10	0.954569	1.454167	0.656437
0.5	0.6	0.1	3	10	0.972041	1.454167	0.668452
0.5	0.6	0.1	3	10	0.969318	1.454167	0.66658
0.5	0.6	0.1	3	13.33333	0.93297	1.454167	0.641584
0.5	0.6	0.1	3	13.33333	0.918608	1.454167	0.631708
0.5	0.6	0.1	3	13.33333	0.918557	1.454167	0.631672
0.5	0.6	0.1	3	13.33333	0.925437	1.454167	0.636404
0.5	0.6	0.1	3	13.33333	0.895633	1.454167	0.615908
0.5	0.6	0.1	3	16.66667	0.902125	1.454167	0.620373
0.5	0.6	0.1	3	16.66667	0.895684	1.454167	0.615943
0.5	0.6	0.1	3	16.66667	0.882518	1.454167	0.606889
0.5	0.6	0.1	3	16.66667	0.900503	1.454167	0.619257
0.5	0.6	0.1	3	16.66667	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	13.33333	0.913932	1.454167	0.628492
0.5	0.6	0.1	4	13.33333	0.953434	1.454167	0.655657
0.5	0.6	0.1	4	13.33333	0.961637	1.454167	0.661298
0.5	0.6	0.1	4	13.33333	0.919449	1.454167	0.632286

Table 5 reports the output of some simulations. Columns refer respectively to the shape factor b, the percentage of high rotation and medium rotation items, the days of medium and low rotation and the response variable T/Tmax. the travel time resulting from the formula of Bozer and White, and the coefficient of reduction that is equal to the ratio between the time got through the simulation and the time obtained using the Bozer and White formula.

The simulator has been validated with the travel time analytically computed compared with the results of the simulation in case of a single command (SC) configuration. The time resulted by the analytical model is computed as weighted mean of the integral of the travel times for the three different areas of rotation. As shown in Figure 4 for different levels of the shape factor b* the differences between the time that is obtained analytically and the time got through the simulations are always lower than 3%. This proves the reliability of the simulator. The error ranges from -2.49% to 2.45%. Its mean equals -0.02% and its standard deviation is equal to 0.526%.

Figure 4. Comparison between the analytical model and the simulator



C. 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 reflecting relationships between variables within dataset [25]. In order to take into account even squared and cubic relationship with response variable both squared and cubic terms have been considered.
The results of the regression analysis are shown in Table 6, where the columns report the estimate of the regression coefficient, for each kind of simulation that has been completed. At the bottom the Analysis is reported.

Table 6. Outputs of the regression analysis

Predictor	Coefficient			
	SC		DC	
	T/Tmax	CRTT	T/Tmax	CRTT
Constant	-1.44840	-1.25400	-2.38410	-1.41420
b	0.06968	0.38126	0.14644	0.19085
b^2	not sign.	-0.51817	not sign.	-0.34733
b^3	not sign.	0.14086	not sign.	0.08228
HRf	11.80200	10.20200	18.56400	11.77130
HRf^2	-20.72600	-17.79300	-32.26700	-20.47000
HRf^3	11.76090	10.11230	18.08860	11.51090
MRf	-10.98400	-9.61100	-18.28000	-12.04600
MRf^3	67.13000	58.55000	105.60000	68.86000
MRd	0.06464	0.05423	0.08348	0.05260
LRd	-0.03241	-0.03020	-0.04192	-0.02927
LRd^2	0.00098	0.00082	0.00158	0.00100
LRd^3	-0.00001	-0.00001	-0.00002	-0.00002
b*HRf	0.55369	0.34169	0.63941	0.34276
b*MRf	0.50302	0.26360	0.63313	0.27604
b*MRd	-0.00588	-0.00386	-0.00615	-0.00370
b*LRd	-0.00567	-0.00086	-0.00624	not sign.
HRf*MRf	32.35000	28.71000	53.98000	35.87600
HRf^2*MRf	-25.12100	-22.28700	-41.96700	-27.86000
HRf*MRf^2	-215.68000	-187.93000	-337.40000	-219.68000
HRf^2*MRf^2	177.47000	154.40000	275.78000	179.17000
HRf*MRd	-0.08706	-0.07405	-0.11144	-0.07031
HRf*LRd	0.00212	0.00176	-0.00214	-0.00141
MRf*MRd	-0.07103	-0.06039	-0.07146	-0.04487
MRf*LRd	0.01184	0.00994	0.00488	0.00294
MRd*LRd	0.00041	0.00035	0.00045	0.00028
Analysis of Variance				
SS regresion	124.1321	40.5706	205.8484	30.8467
SS residual error	2.0109	1.444	2.776	1.0724
SS totale	126.1430	42.0146	208.6244	31.9191

DF regression	23	25	23	24
DF residual error	17576	17574	17576	17575
DF total	17599	17599	17599	17599
MS regression	5.3970	1.6228	8.9499	1.2853
MS residual error	0.0001	0.0001	0.0002	0.0001
F	47172.34	19570.72	56666.23	21062.82

For each regression some tests on residuals have been completed in order to validate the consistency of the model. In particular the Normal Probability Plot and the Histogram illustrate that residuals can be considered normally distributed; the Versus Fit graph indicates that there is no evidence of systematic error in the residuals and the Versus Order Graph does not show time series or periodicity. In appendix the graphs of residuals are shown.

V. IMPLICATIONS AND CONCLUSIONS

The proposed study aims at providing a methodology for the evaluation of travel times for AS/RS systems working in spaces with different areas of assignment. In particular the attention has been posed to class-based storage policy divided into three classes of rotation. The rate of rotation has been taken into account based on turnover of SKUs in terms of physical flows. The methodology has been inspired by Bozer and White [16] that provide a formula for the computation of travel times in an environment with equal probability of access. Our model integrates the previous studies related to both single and dual command cycles, through the introduction of new predictors associated with crucial variables of warehouse operation, and it is based on a simulation approach. The reliability of the simulator has been tested with the single command cycle, through the benchmark with the analytical computation of the travel time, so that it has been possible to extend the simulation to dual command cycles. The results of the simulations have been elaborated with a regression analysis, wherein the response variables taken into account were the travel time and the CRTT computed as the ratio between the travel time got through the simulator and the travel time provided by Bozer and White's formula. Thanks to the regression we have been able to identify the coefficients related to each crucial operational predictor. The ANOVA and the test of residuals prove the robustness of the regression, therefore the regression coefficient can be considered suitable for the computation of the travel times. A proper computation of travel times allows a better monitoring of the performance of the warehouse operations and it can supports practitioners in the choice of the configuration not only in terms of kind of cycle, but also from a policy assignment perspective. The model coaches on a lot of coefficient that make it complete, exhaustive and reliable from the error perspective. At the same time the high number of coefficients does not allow to propose a concise formula that is immediate to be adopted. For this reason future research will be addressed to the development of a univocal formula that groups more coefficients, able to keep the error within the range resulted by the current model, but that it can be easier to be applied.

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VI. APPENDINX

Figure 5. Single Command: graphs of residuals for T/Tmax

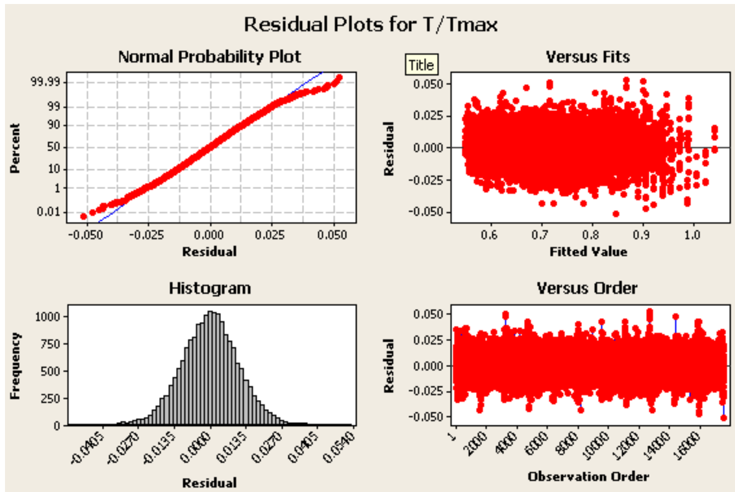

Figure 6. Single Command: graphs of residuals for CRTT

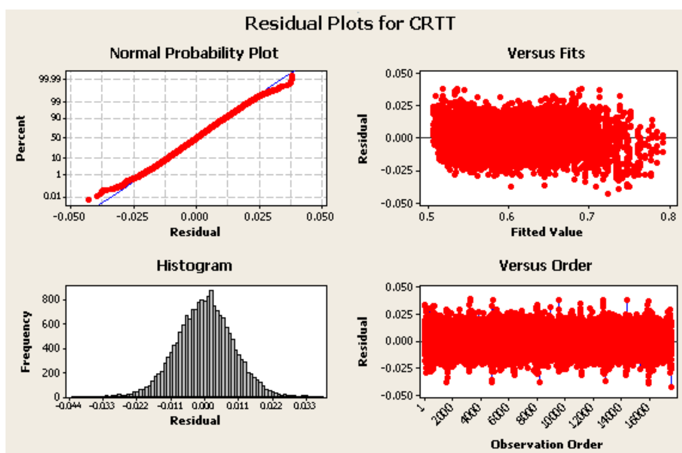

Figure 7. Dual Command: graphs of residuals for T/Tmax

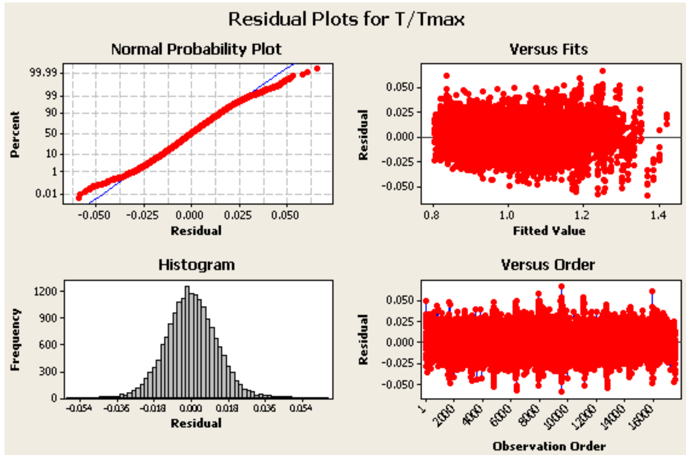

Figure 8. Dual Command: graphs of residuals for CRTT