VIII. AN ANALYSIS OF SINGLE-COMMAND OPERATIONS IN A MOBILE RACK (AS/RS) SERVED BY A SINGLE ORDER PICKER

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Abstract

A Mobile rack Automated Storage and Retrieval Systems (M-AS/RS) are picker-to-stock retrieval model which are a variation of the multi aisles AS/RS. This mobile storage system is composed of racks moving laterally on rails so that one can open an aisle between any two adjacent racks, the input/output system, the storage and retrieval (S/R) machine and the computer management system or the control system.

Evaluating an AS/RS could be done using several performance indicators, the two most important ones are: The utilization rate of the S/R machine and the average time necessary to serve storage or retrieval requests (the travel time).

The S/R machine could operate either in single command or in dual command. In a single command, the S/R machine executes either a storage or retrieval operation by cycle. The time necessary to execute a single command is said single cycle time. While in a dual command, the S/R machine executes a storage operation followed by a retrieval operation in the same cycle. The time needed to execute a dual command is said dual cycle time.

In this paper our interest is concerned with the mathematical modeling of single-command operations in a Mobile rack (AS/RS) system. We developed a closed form analytical expression allowing an approximate calculation of the travel time of Mobile Racks-AS/RS.

This expression was compared with an exact discrete expression developed earlier by one of the authors. The models developed in this work are used by Kouloughli et al to determine optimal dimensions of the mobile rack AS/RS that minimize expected travel times.

1 Introduction

Automated storage /retrieval systems (AS/RS) are common in numerous manufacturing and distribution centers since their introduction in 1950s. An AS/RS usually consists of racks served by cranes running through aisles between the racks. AS/RS are actually attracting much attention in modern manufacturing thanks to their numerous advantages, namely low labor cost, low storage cost, best space exploitation and high output .The apparent disadvantages of materials handling are centered around high investments costs, which varies usually between $250 000 to $ 400 000 per aisle **(Bhaba R, 1995).**Hence, economic justification of these systems is usually limited to applications with extremely high inventory volumes. These costs include machinery, constructing software and hardware and employee training expenses.

There exist a variety of AS/RS systems in industry; the basic shape of an AS/RS is composed of one aisle including a rack on each side. Racks are themselves composed of bins. The aisles are served by an AS/RS machine. The function of this machine is to store or retrieve products in the bins. We can classify AS/RS as follows [13]:

1. Unit load AS/RS: it is composed of one aisle including a rack on each side. Racks are themselves composed of bins. The aisle is served by a S/R machine. It is the basic and the most studied form.

2. Miniload AS/RS: Used to store/retrieve small parts and tools that can be stored in a storage bin or drawer.

3. Man-On-Board AS/RS: Used for in-aisle picking; operator picks from shelves, bins, or drawers within the storage structure

4. flow-rack systems : A flow-rack AS/RS includes a rack which consists of sloping bins, where items loaded by a storage machine at one end of the rack on the store face travel along sloping wheels or rollers to the other end of the rack on the pick face, to be retrieved by a retrieval machine. [15]

5. Multi aisles AS/RS : This type of AS/RS comprises several aisles, all served by only one S/R machine. This allows the storage of a big number of products.

6. Carousel systems: in this kind of systems the racks rotate on a circular track, and the picking machine carries out storage and retrieval activities at a fixed position.

7. Mobil racks AS/RS: a M- AS/RS is a picker-to-stock retrieval model which is a variation of the multi aisles AS/RS. This mobile storage system is composed of racks moving laterally on rails so that one can open an aisle between any two adjacent racks.

After separating two adjacent rows of equipment, an aisle is formed. The picker (S/R-m) then enters the aisle to pick and place the item on a storage rack. The aisle at any two adjacent rows of equipment is ‘mobilized’. Because only one aisle is required to be left for the whole of the system, aisle space can be significantly minimized, and the efficiency of storage space can be increased. [3]

Evaluating an AS/RS could be done using several performances indicators, the two most important ones are: The utilization rate of the S/R machine and the average time necessary to serve storage or retrieval requests.

Generally, the cycle time of an AS/RS is the subject of many researchers over the past few years. **Hausman, Graves, and Schwarz (1976)** [9] presented travel time models for single aisle; they pointed out that there is an important reduction in travel time by using dedicated storage policy. **Graves et al (1977)** [7] extended the work done by **Hausman et al (1976)** [9] to compare the operating performance of several storage assignment policies by using both continuous and discrete evaluation models. Each rule is compared on the basis of expected travel time of S/R machine. **Bozer and white (1984)** [2] calculated the average operation time of S/R machine with random storage when the rack is rectangular or square as assumed by **Hausman et al (1976)** [9]. Therefore, they introduced a shape factor to calculate the average operation time of S/R machine with rectangular racks. **Tompkins and white (1984)** [19] introduced a static analysis to estimate the utilization of S/R machine with the known number of requests.

Wen et al (2001) [20] proposed a travel time model for class-based assignment which considered various travel speeds with known acceleration and deceleration ration rates. In (2004) [18], Tone Lerher and al considered acceleration and deceleration of the S/R machine and they proposed an analytical model of the cycle time for multi aisle AS/RS. **Ghomri and al (2008)** [4] used a continuous approximation of the rack of storage in order to develop a mathematical expression that allows the time calculation in both single and dual command of multi aisle AS/RS. After that, **Ghomri and Sari (2009)** [6] presented new models for single and dual cycle time of multi-aisle AS/RS. These models were compared with an exact model for validation**. Kouloughli et al. (2008)** [11] and **Kouloughli et al. (2010)** [12] determined optimal dimensions of multi aisle AS/RS that minimize single and dual cycle time.

Ashayeri et al (2002) [1] presented a geometry- based analytical model to compute the cycle time with single command, dual command, or both. The rack can be either square in time (SIT) or not square in time (NSIT) and no fixed layout shape are assumed in this model. This approach can make the AS/RS more appealing for use in integrated supply chain system. **Sari et al (2007)** [14] presented travel time expressions for flow-rack AS/RS based on continuous approach and compared them with simulation to demonstrate that this analytical model can estimate performance measures by requiring less computing time than simulation. **Duc and De Koster(2007)** developed an optimization method to determine the average throughput time for an order batching problem in a two blocks rectangular warehouse by applying the well-known S-shape heuristic method. **Hwang and Ko (1988)** [10], Their study is based on travel time models considering average uniform velocity.

In this paper, we consider the cycle time of the Mobile rack AS/RS. We presented a mathematical expressions estimating the simple cycle time in the case when the sliding time of the racks is higher than time necessary to travelling the principle aisle. In section 2 of this paper we will present the configuration system and some basic assumptions of the studied model and the notations which will be adopted later on. Section 3 will present an exact discrete mathematical expression model for calculating the single cycle time of the S/R machine as defined in works of sari (1998) [15]. Then we propose a continuous analytical expression estimating the single cycle time of the M-AS/RS. We will validate our proposed model with de exact discrete mathematical expression in section 4. Finally, conclusions are given in Section 5.

2 Configuration systems and basic assumptions

The mobile rack system (M-AS/RS) is a storage system of high-density (see figure.1). There is only one aisle needed to handle goods, so the space is utilized great fully. Movement is achieved by the motor-driven bearing trolley, on which the racks are installed. After separating two adjacent rows of equipment, an aisle is formed. The picker (S/R-m) then enters the aisle to pick and place the item on a storage rack. Movement velocity is commanded by a very precise control system, so the movement is very steady.

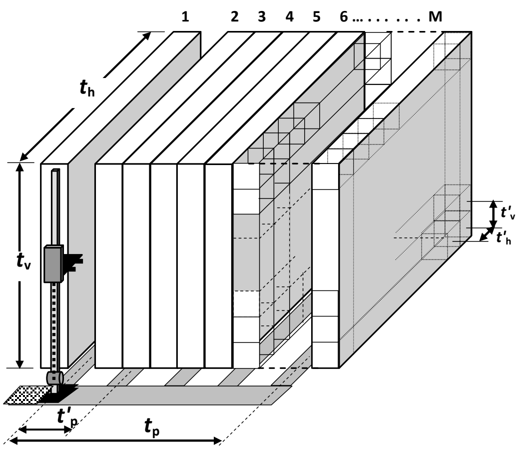


Figure 1: The Mobile Automated Storage and Retrieval Systems (M-AS/RS)

Assumptions and notation

The following assumptions are made throughout this paper:

1. The I/O point is positioned at the lower left corner of the system.

2. The S/R machine is able to simultaneously moving both vertically and horizontally at constant speeds. Therefore, the travel time needed to reach any location in the system is approximated by the Tchebyshev travel.
3. The S/R machine has a single shuttle and can operate only in single or dual-command modes.

The following notations are used for the mathematical modelling of this system:

TABLE 1. Definitions of symbols used in M-AS/RS operation model

M	: The number of racks in a M- AS/RS;
N_L	: The number of bins per line
N_H	: The number of bins per column;
N	: The entire number of bins;
t'_h	: The horizontal travelling time from a bin to the next one;
t'_v	: The vertical travelling time from a bin to the next one;
t'_p	: The travelling time from an aisle to the nearest one;
t_h	: Time necessary to traverse the length of a rack
t_v	: Time necessary to traverse the height of a rack;
t_P	: Time necessary to traverse the principle aisle of the M- AS/RS;
t_r	: Time necessary for the opening of an aisle; (slipping of racks)
$\overline{E(SC)}$	: Mean simple cycle time;

3 Travel-time models for the M-AS/RS

In this section of work, we will analyze the travel time using continuous models that significantly reduce the difficulty of the subsequent analysis. Then, we validate the proposed model by comparing it with the results predicted by a discrete model.

3.1 Discrete model

The single cycle time of the S/R machine (see figure 2) is the time needed to go from the input/output point to the storage (retrieval) cell, plus the time needed to return from this cell to the input/output point.

In 1998, Sari has developed a discrete model for the single cycle time [15] as stated below:

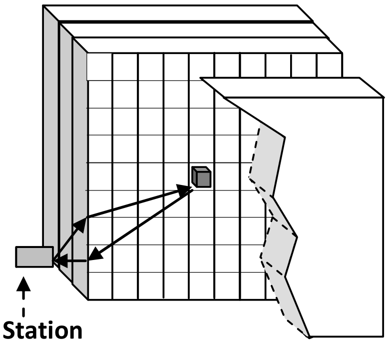


Figure 2: Single cycle in a (M-AS/RS)

The horizontal displacement required to reach the rack with the coordinates (i,j) which is in the k^{th} aisle is given by:

$$t'_h.i + \max(t_r \,;\, t'_p.(k-1)) \quad (1)$$

The vertical displacement needed to reach this same cell is:

$$t'_v.(j-1) \quad (2)$$

Since to technology used in the storage retrieval machines provide a Tchebychev travel, so, the total time that S/R machine to reach this rack is the maximum between horizontal and vertical displacement.

$$\mathrm{Max}[t'_h.i + \max(t_r \,;\, t'_p.(k-1)) \,;\, t'_v.(j-1)] \quad (3)$$

Total time that the S/R machine needs to return to the input/output point does not depend on "t_r" is given by:

$$\mathrm{Max}[t'_h.i + t'_p.(k-1) \,;\, t'_v.(j-1)] \quad (4)$$

So, the average cycle time for all the cells is given by the following expression:

$$\overline{E(SC)} = \frac{2}{N}\sum_{k=1}^{M/2}\sum_{i=1}^{N_L}\sum_{j=1}^{N_H}(\max[t'_h.i + \max(tr\,,\, t'_p.(k-1))\,,\, t'v.(j-1)] + \max[t'_h.i + t'_p.(k-1)\,,\, t'_v.(j-1)]) \quad (5)$$

3.2 Continuous model

The formulation of the continuous model for the travel time of the storage/Retrieval machines is based on works of Bozer (1984) [2]and Ghomri and al (2008) [4]. Our idea here is to split the cycle time into a set of uniformly distributed travelling times. From these distributions we calculate the distribution of the total cycle time. The expected value of this distribution is the average cycle time.

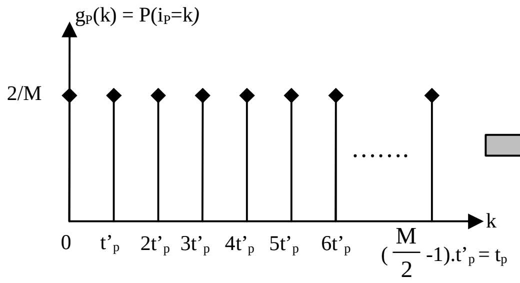


Figure 3: Exact discrete distribution of variable i_P

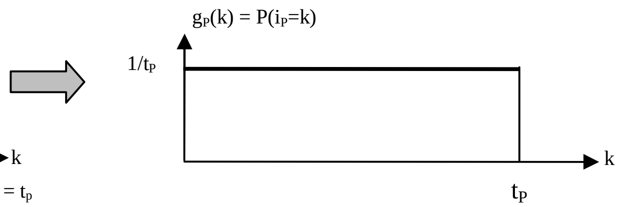


Figure 4: Approximate continuous distributions of the random variables i_P

In the present study, we rely on this idea; an analytical expression for a single command cycle has been developed. This continuous model has several features which can be used during the process of AS/R systems planning and design.

First, we calculate the average time needed to go from the I/O point to a storage (retrieval) cell as presented in (Figure 5):

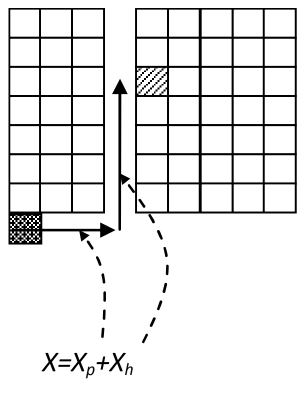


Figure 5: Horizontal travel time of the S/R machine (forward)

In this case, $X=X_p+X_h$ is a random variables representing time of horizontal displacement towards the storage system. X is the sum of two random variables X_p and X_h having functions of distributions g_p (K) and g_h (K):

Let us note that:

G(k) = P(X≤ k) is the cumulative density functions of X, Consequently its function of distribution g(k), which models the horizontal travel of the S/R machine in the forward, is the convolution product $g_P(k) * g_h(k)$.

According to the value of t_p, t_h, t_v and the variation of t_r. Many cases appear in this study.

$$
\begin{cases}
case1 & t_r \le t_p < t_h < t_h + t_r \\
case2 & t_p < t_r \le t_h < t_h + t_r \\
case3 & t_p < t_h \le t_r \\
case4 & t_r \le t_h < t_r + t_h < t_p < t_p + t_h \\
case5 & t_h < t_r \le t_r + t_h < t_p < t_p + t_h \\
case6 & t_h < t_r \le t_p < t_r + t_h < t_p + t_h \\
case7 & t_h < t_p \le t_r
\end{cases}
$$

In the figure 6 we present all possible cases of the random distribution of the variable X which models the horizontal travel of the S/R machine in the forward:

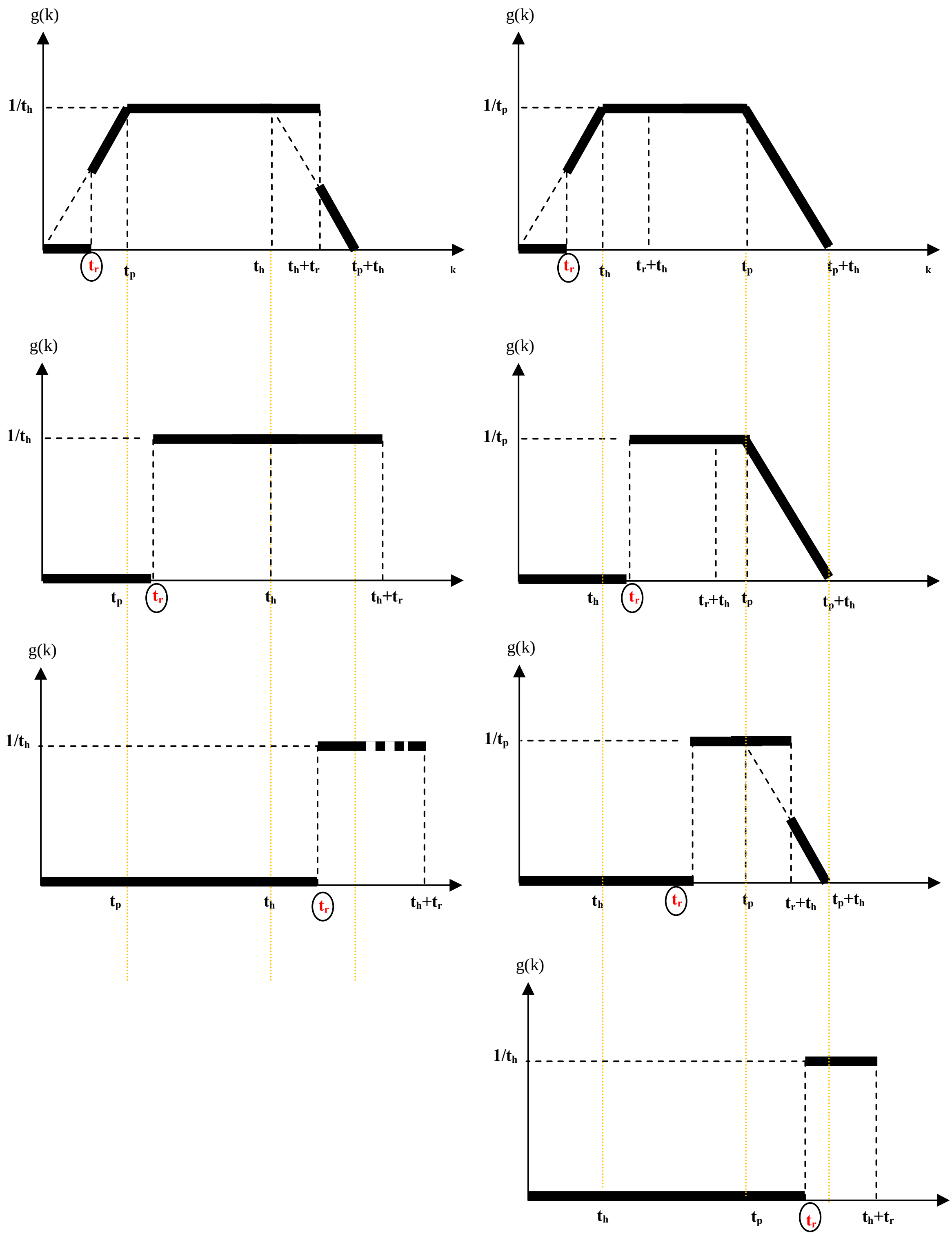


Figure 6 : Random distribution of the variable X which models the horizontal travel of the S/R machine in the forward (all possible cases)

Taking for example the case where the sliding time of racks is less than time necessary to travelling the principle aisle: ($t_p < t_r <= t_h$).

In this case the random variable $X=X_p+X_h$ is the sum of two random variables X_p and X_h having functions of distributions g_p (K) and g_h (K):

$$g_p(k) = \begin{cases} 1 & if \quad k = t_r \\ 0 & elsewhere \end{cases} \tag{6}$$

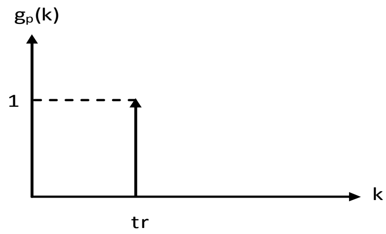


Figure 7: Approximate continuous distributions of the random variables X_h

Since $X = X_p + X_h$.

Consequently its function of distribution g(k) is the convolution product $g_P(k) * g_h(k)$ Then:

$$g(k) = g_p * g_h(k) = \int_{-\infty}^{+\infty} g_p(u) g_h(k-u) du = \int_0^k g_p(u) g_h(k-u) du \qquad g(k) = \begin{cases} 0 & if \quad k \le t_r \\ \frac{1}{t_h} & if \quad t_r < k \le t_h + t_r \\ 0 & elsewhere \end{cases} \Rightarrow$$

$$G(k) = \begin{cases} 0 & if \quad k \le t_r \\ \frac{k-t_r}{t_h} & if \quad t_r < k \le t_h + t_r \\ 0 & elsewhere \end{cases} \tag{7}$$

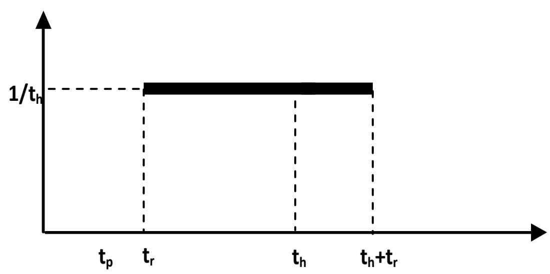


Figure 8: Random distribution of variable X, which models the horizontal travel of the S/R machine in the forward.

Let us consider now Y as a random variables representing time of vertical displacement towards the storage system.

h(k) is the probability density functions of Y and H(k) is its cumulative density functions. Let us note that:

$H(k) = P(Y \leq k)$, $h(k) = H'(k)$

So, the vertical displacement of the S/R machine can be modeled by the following distribution:

$$h(k) = \begin{cases} \frac{1}{t_v} & if \quad 0 < k < t_v \\ 0 & elsewhere \end{cases} \quad \text{THUS:} \quad H(K) = \int_{-\infty}^{k} h(k)dk = \begin{cases} 0 & if \quad k \leq 0 \\ \frac{k}{tv} & if \quad 0 < k < tv \\ 1 & k \geq tv \end{cases} \quad (8)$$

The total travel time toward a cell is Max(X, Y), the cumulative density function for Max(X, Y) noted by F is given by : F(k)= G(k).H(k)

Then three cases arise during the calculation of this distribution, which models the S/R machine travel during the forward.

- 1st case : $t_v < = t_r$
- 2nd case : $t_r < t_v <= t_h + t_r$
- 3rd case : $t_v > t_h + tr$

The expected value of Max(X, Y) noted by E(Max(X,Y)=E(SC) is obtained as follows:

$$E(SC) = E(\max(X, Y)) = \int_{-\infty}^{-\infty} kf(k)dk \quad (9)$$

Since in our problem the function F is cancelled out of the interval [0, m], then we can calculate the expected value with this function by using the integration by parts, we obtain:

$$\int_{-\infty}^{-\infty} kf(k)dk = \int_0^m kf(k)dk = \left[kF(k)\right]_{k=0}^{k=m.} - \int_0^m F(k)dk$$

So we have:

$$E(SC) = m - \int_0^m F(k)dk \quad (10)$$

Using equation (10) and after calculation of the cumulative density function F(k) , the average cycle time (E(SC1)) of the S/R machine that’s needed to go from the I/O point to a storage (retrieval) cell is given by:

$$E(SC_1)=\begin{cases}\frac{1}{2}t_h+t_r & if \quad t_v\le t_r\\ \frac{1}{2}t_h+t_r+\frac{(t_v-t_r)^3}{6t_ht_v} & if \quad t_r<t_v\le t_h+t_r\\ \frac{1}{2}t_h+t_r+\frac{(t_v-t_r)^3}{6t_ht_v}+\frac{(t_h+t_r-t_v)^3}{6t_ht_v} & if \quad t_v>t_h+t_r\end{cases} \qquad (11)$$

Finally and after simplification, these 3 formulas can be expressed as follows:

$$E(SC_1)=\frac{1}{2}t_h+t_r+\frac{\max(0,t_v-t_r)^3}{6t_ht_v}+\frac{\min(0,t_h+t_r-t_v)^3}{6t_ht_v} \qquad (12)$$

Now we calculate E(SC_2): (the average time needed to return to the I/O point)

Total time that S/R machine needs to return to the input/output point does not depend on the sliding racks time (t_r) as shown in figure.9; it is calculated in the same preceding way:

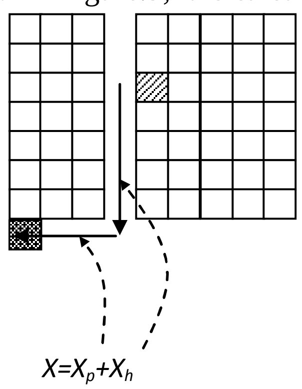
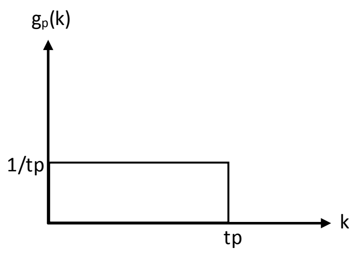
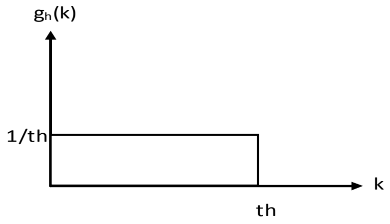


Figure 9. Horizontal travel time of the S/R machine (the return).



$$g_p(k)=\begin{cases}\frac{1}{t_p} & if \quad 0<k<t_p\\ 0 & elsexhere\end{cases} \qquad (13)$$

Figure 10. Approximate continuous distributions of the random variables X_P



$$g_h(k) = \begin{cases} \frac{1}{t_h} & if \quad 0 < k < th \\ 0 & elsewhere \end{cases} \qquad (14)$$

Figure 11. Approximate continuous distributions of the random variables X_h

The distribution of the total horizontal displacement of the S/R machine is the convolution of the two distributions gp(k)and gh(k). After calculation of this convolution product, one finds the following expression (see figure 12):

$$g(k) = \begin{cases} \frac{k}{t_p t_h} & if \quad 0 < k \le t_p \\ \frac{1}{t_h} & if \quad t_p < k \le t_h \\ \frac{t_p + t_h - k}{t_p t_h} & if \quad t_h < k \le t_p + t_h \\ 0 & elsewhere \end{cases} \qquad (15)$$

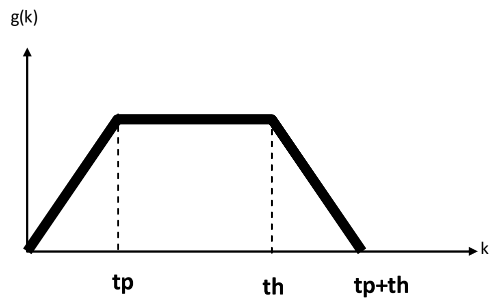


Figure 12. Random distribution of the variable X, which models the horizontal travel of the S/R machine in the return.

Concerning vertical displacement of the S/R machine , one can model it by the following distribution:

$$h(k) = \begin{cases} \frac{1}{t_v} & if \quad 0 < k < t_v \\ 0 & elsewhere \end{cases} \quad \text{then:} \quad H(k) = \int_{-\infty}^{k} h(k)dk = \begin{cases} 0 & if \quad k \le 0 \\ \frac{k}{tv} & if \quad 0 < k < tv \\ 1 & if \quad k \ge tv \end{cases} \qquad (16)$$

Similarly to previous calculation steps, we find:

$$E(SC_2) = \begin{cases} \frac{1}{2}tp + \frac{1}{2}th + \frac{tv^3}{24\,tp\,th} & \textbf{\textit{if}}\ t_v < t_p \\ \frac{1}{2}tp + \frac{1}{2}th + \frac{tv^3}{24\,tp\,th} - \frac{(tv-tp)^4}{24\,tp\,th\,tv} & \textbf{\textit{if}}\ tp < t_v < t_h \\ \frac{1}{2}tp + \frac{1}{2}th + \frac{tv^3}{24\,tp\,th} - \frac{(tv-tp)^4 + (tv-th)^4}{24\,tp\,th\,tv} & \textbf{\textit{if}}\ t_h > t_p + t_h \\ \frac{1}{2}tp + \frac{1}{2}th + \frac{tv^3}{24tpth} + \frac{(tv-tp-th)^4 - (tv-tp)^4 - (tv-th)^4}{24tpthtv} & \textbf{\textit{if}}\ t_v > t_p + t_h \end{cases}$$

Finally we obtain the following expression after some mathematical operation and simplifications:

$$E(SC_2) = \frac{1}{2}t_p + \frac{1}{2}t_h + \frac{t_v^3}{24t_pt_h} + \frac{(t_v - t_p - t_h)^3 \max(0, t_v - t_p - t_h) - (t_v - t_p)^3 \max(0, t_v - t_p) - (t_v - t_h)^3 \max(0, t_v - t_h)}{(17)24t_pt_ht_v} \qquad (17)$$

Since the average cycle time (E(SC)) of the S/R machine that's needed to go from the I/O point to a storage (retrieval) cell then return to the I/O station $E(SC) = E(SC_1) + E(SC_2)$ and After some mathematical operation and simplifications we obtain

$$E(SC) = t_h + t_r + \frac{1}{2}t_p + \frac{\max(0, t_v - t_r)^3}{6t_ht_v} + \frac{\min(0, t_h + t_r - t_v)^3}{6t_ht_v} + \frac{t_v^3}{24t_pt_h} + \frac{(t_v - t_p - t_h)^3 \max(0, t_v - t_p - t_h) - (t_v - t_p)^3 \max(0, t_v - t_p) - (t_v - t_h)^3 \max(0, t_v - t_h)}{24t_pt_ht_v} \qquad (18)$$

4 Validation

To validate the mathematical expression proposed for single command for its accuracy, we carried out a comparison between the results given by the continuous expression with those given by the discrete one, under a variety of configurations of Mobil racks AS/RS. The results are illustrated in Table. 2. and Figure 13. In this figure we can notice that the results of both equations are very close to each other.

These results show that the continuous model gives a good approximation of the discrete one, knowing that the discrete model gives exact results.

Table 2 : Comparison between results given by the continuous and discrete expression.

Configuration. Nbr	1	2	3	4	5	6	7	8
N	400	720	1000	1000	3000	10800	40000	60000
M	10	6	4	4	15	24	20	6
N_L	10	10	10	10	20	30	40	100
N_H	4	12	25	25	10	15	50	100
t_v	3	11	24	24	9	14	49	99
t_h	10	10	10	10	20	30	40	100
t_p	8	4	2	2	13	22	18	4
t_r	9	8	4	10	15	28	30	10
E(SC) Discrete	24,02	22,13	27,32	30,44	39,43	70,19	86,22	139,97
E(SC) Continuous	23,01	21,19	26,79	29,79	41,61	69,17	85,29	139,23

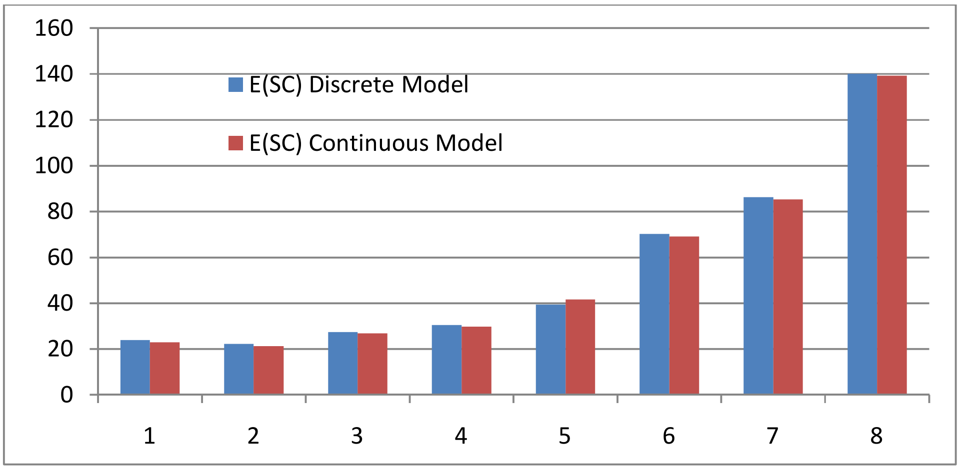


Figure 13. Comparison between results given by the continuous and discrete expression

5 Conclusion

The travel time of the storage/Retrieval machines (S/R-m) is one of the most important criteria of the AS/RS performances. To calculate this time, an analytical expression for a single command cycle has been developed in the present study. The expressions are developed using a continuous approach and are compared with an exact discrete approach.

These mathematical expressions have many advantages. First, easily calculable, then purely continuous, therefore, the continuous travel-time expressions developed can be used to design new configurations, dimension optimization, evaluate throughput performance for the system, compare different storage techniques for improved system performance and a good management of this kind of installation.

To improve the proposed models. The following issues deserve further research: Consider all possible case of sliding time variation, storage and retrieval speed, error rate, the cost of storage ...

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