SIMULATION-BASED PERFORMANCE ANALYSIS OF AUTOMATED SINGLE-TRAY VERTICAL LIFT MODULE

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Abstract
In this paper a simulation analysis of an automated single-tray Vertical Lift Module (VLM) system is presented. Compared to other well-known warehouse systems, a VLM system can provide moderate throughput capacity and lower investment cost. The objective of the study is to investigate benefits of a single-tray VLM system design in terms of reducing transactions' mean cycle time, which results in increased throughput of the system. Performance of the single-tray VLM is evaluated regarding alternative design configurations and the velocity profiles. The results show that single-tray VLM systems are effective and may serve as guideline for warehouse designers in designing a new or improving an existing automated warehouse system.

Key words: logistics, automated warehouse, warehousing, vertical lift module, discrete event simulation, performance analysis.

1. INTRODUCTION

Warehouses are logistics systems. Based on a traditional saying, a system is a complex or very complex feature made of a set of elements and a set of these elements' relations. Due to relations and hence interactions, a system is more than a sum; the whole system has properties, which single elements do not have: it has *synergies* [1]. Systems science is required by the complexity of modern technology's »systems«, which is also the case for logistics system in modern warehouses [2].

There are many reasons why warehouses are required, like facilitation of the coordination between the supply and demand using buffers of products, accumulation and consolidation of products from several producers for combined shipments, enabling same-day delivery service for customers, supporting product customization activities like packaging or assembly, etc. [3], [4].

Typically, a warehouse system consists of several sub-systems (areas), which are related with each other. At the receiving area, incoming shipments with products are unloaded from trucks or railway, and inspected whether quantity and quality of the products are as ordered. Products could be transported directly to the shipping area, which is also known as a "cross-docking" process, or could be transported and placed to the "reserve and forward" area and later on the shipping area. At the shipping area, outgoing shipments with products are checked for the quality and quantity, issued to the internal costumer or loaded to trucks or trains for distribution to the external customers [3], [4], [5].

Automated systems play significant role in warehouses, studied by a lot of researchers over the past few decades. Intensive developments of automated systems have begun with the development of computer science and information technology, being an important and almost inevitable part of today's modern warehouses. Main advantages of automated warehousing are savings in labour costs and used floor space, increased accuracy (reduced error rates) and high reliability. The most frequently used automated systems are systems to store and retrieve unit-load and mini-load items without interference of an operator, named Automated Storage and Retrieval Systems (AS/RS). AS/RS have quite long history of the application in warehouses, since first installations appeared in 1960s.

Due to a large product variety accompanied with the customer's requirements for fast deliveries (sometimes at the same day) and more frequent deliveries (many smaller orders), material handling system producers are constantly developing new solutions of automated storage systems. To meet throughput demand of small parts and layout related constraints, automated Vertical Lift Modules (VLM), have been developed (Fig. 1).

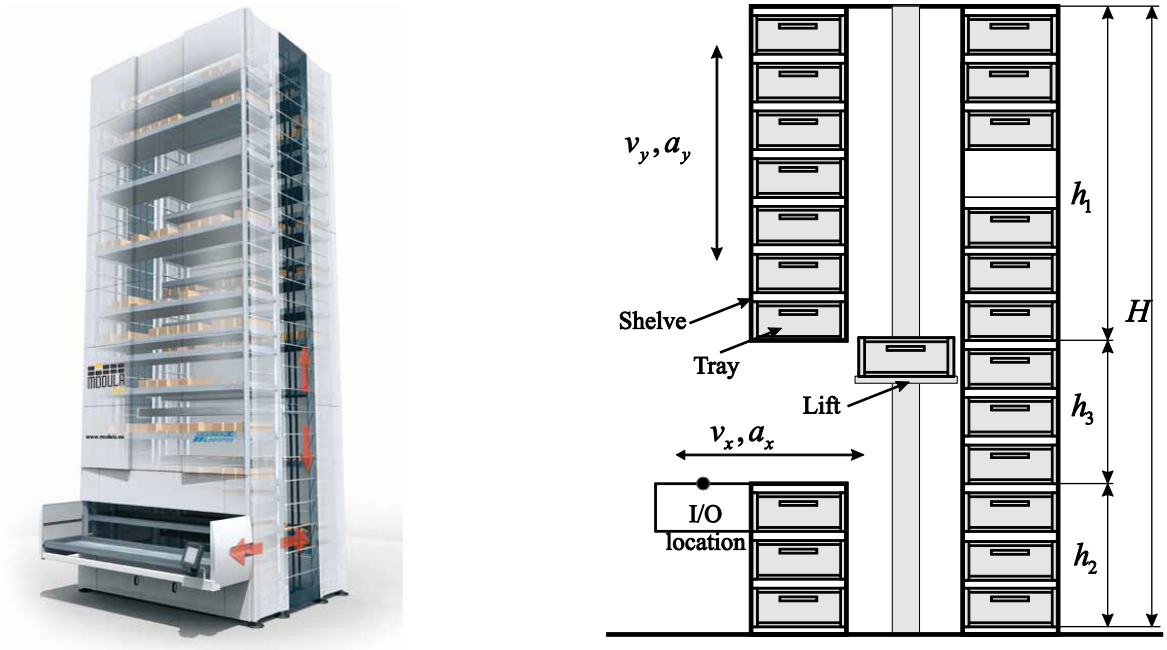

Fig. 1: Vertical lift module of the material handling provider MODULA (http://www.modula.eu/)

This new automated system, VLM, has been developed as an alternative to picker-to part order picking system with shelving. In this technology, the insertion/extraction device called as a lift is capable of vertical movement of trays with products (Fig. 1), thus delivering parts to the picker.

The goal of this paper is an evaluation of VLM's throughput performance by using discrete event simulation technique. The VLM performance is evaluated based on system's throughput which depends on the expected system's cycle time. The rest of the paper is structured as follows. Literature review is given in Section 2. Section 3 presents simulation model of the VLM system after the brief description of VLM device, while section 4 presents analysed VLM design scenarios. Simulation results with relevant discussion are presented in Section 5. Main conclusions from this study are given in final section 6.

2. LITERATURE REVIEW

AS/RS are studied well in the literature. There are primarily two types of AS/RS: unit-load AS/RS and the mini-load AS/RS. AS/RS usually consist of conveyors, storage racks and automated Storage/Retrieval (S/R) machines travelling in narrow aisles between the storage racks to store and retrieve loads. The S/R machine can manipulate either pallets (unit-load system) or totes (mini-load system). Many studies of AS/RS have been performed in the material handling research community in the past few decades, from which only some are mentioned bellow.

Hausman et al. [6] and Graves et al. [7] were among the first presenting travel time models for AS/RS, also analyzing different storage strategies, e.g. randomized, turnover-based and class-based storage assignment rules, however only for so called square-in-time racks (SIT rack). Gudehus [8] presented principles for calculation of the cycle time for the Single Command (SC) cycle and Dual Command (DC) cycle. In case of the SC cycle, the S/R machine can perform storage or retrieval request per cycle. More advanced is the DC cycle where both storage and the retrieval request are done in one cycle. With regard to other cycle time models, he also considered the influence of the acceleration and deceleration on calculated cycle time. Bozer and White [9] presented analytical travel time models of SC and DC cycles for non-SIT racks. Models are based on randomized storage and retrieval request, assuming that the S/R machine travels all the time with constant velocity. Hwang and Lee [10] presented travel time models considering the real operating characteristics of the S/R machine in non-SIT racks. Sari et al. [11] presented closed-form travel-time expressions for flow-rack AS/RS. Lerher et al. [12] developed analytical travel time models for multi-aisle AS/RS considering the operating characteristics of the S/R machine. With the proposed analytical travel time models, average travel time can be evaluated. Gu et al. [13] presented a comprehensive review of research on warehouse operation. Roodbergen and Vis [14] presented an extensive overview of the literature on AS/RS. Lerher et al. [15] presented simulation analysis of mini-load multi-shuttle AS/RS while Lerher et al. [16] presented simulation analysis of Shuttle Based Storage and Retrieval Systems (SBS/RS).

Smew et al. [17] presented a simulation study about production and inventory control at the supply chain level, examining the Hybrid Kanban-CONWIP production control strategy. Bekker [18] proposed the extended buffer allocation problem (BAP) to the multi objective method and proposed a method to optimise two conflicting objectives of the BAP, namely throughput performance and allocation buffer capacity. Berlec et al. [19] proposed the methodology for the calculation of the optimal batch quantity by using the basic and the extended model, which consider the tied-up capital in a production along to the cost of changing the batch and storage cost.

Systems like carousels (horizontal and vertical) and VLM received much less attention in literature than the others. The most important paper that presented throughput models for carousels and VLM was the paper from Meller and Klote [20]. The VLM assumed in this paper was with single picking place (so called single-tray or single-level delivery VLM). With the appearance of VLM with two pick places on opening (so called dual-tray or dual-level delivery), a throughput model for such systems was proposed in the paper of Dukic et al. [21]. Other papers regarding VLM are more like technical papers focusing on application areas and benefits of using VLM compared to a shelving system, plenty of them being published by producers.

Unlike the (mentioned) existing studies, in this paper we approach the single-tray VLM design from a velocity profile design of lift by using discrete event simulation modelling technique.

3. SIMULATION MODEL OF VLM

VLM are used in warehouses and industrial applications since the early 1970's. A VLM can be viewed as enclosed, six-sided box that works using three columns. The front and the rear columns are functioning like shelves to store trays and totes. The centre column is used for lift, which operates within front and rear columns in vertical motion to store or retrieve trays by order [21].

First versions were much slower and with limited capability in storage and retrieval orders. Today's VLM provide increased operational velocity, higher weight capacities, automated control systems and easy-to-use user interface. The operator (order picker) requests a tray or SKU number via keypad or touch-screen display. The lift is directed to the exact position to extract a tray from storage location and to deliver it at the pick window. Operator picks products and presses button to confirm completion. The tray is then returned to its storage location. The process can be repeated depending on the size of the order or a batch of orders [21].

In simulation model of VLM the following assumptions and notations were used.

Main assumptions

- VLM is divided into front and the rear columns, equipped with brackets to support trays with products (Fig. 1).
- The centre column is used for the lift, which operates within front and rear columns in vertical motion to store or retrieve trays by order (Fig. 1).
- When a tray is requested by an operator, it is extracted and delivered to the work station window, where the I/O location is set.
- The lift moves trays up and down to and from the I/O location. The horizontal movement of trays is illustrated with picking up and depositing times.
- The lift moves one tray at a time. There is one pick place for delivered trays.
- The lift complete retrieval commands only.
- Drive characteristics (v_y, a_y) of the lift as well as the heights h_1, h_2, h_3 and H of the VLM are known in advance.
- Randomized assignment policy has been considered.

Notations

AS/RS	Automated storage and retrieval systems.
DC	Dual command.
I/O	Input and output.
I/E	Insertion/extraction device
SC	Single command.
S/R	Storage and retrieval.
SIT	Square in time.
vp	Velocity profile.
VLM	Vertical lift module.
a_y	Acceleration/deceleration of the lift in the vertical direction.
d	Distance.
H	Height of the VLM.
h	Height of the tray.
h^*	Height of the storage location (position) of the VLM.
h_1	Height of the section 1 of the VLM.
h_2	Height of the section 2 of the VLM.

h_3	Height of the section 3 of the VLM.
W	Length of the tray.
v_y	Maximum velocity of the lift in the vertical direction.
v_{max}	Maximum velocity.
$t_{\text{I/O, } i^{\text{th}}\text{tier}}$	Mean travel (retrieval) time of the lift for moving from the I/O location to randomly selected i^{th} shelve of the VLM.
$t_{i^{\text{th}}\text{tier, } j^{\text{th}}\text{tier}}$	Mean travel (retrieval) time of the lift for moving from the randomly selected i^{th} shelve of the VLM to randomly selected j^{th} shelve of the VLM.
$t_{j^{\text{th}}\text{tier, I/O}}$	Mean travel (retrieval) time of the lift for moving from the randomly selected j^{th} shelve of the VLM to the I/O location of the VLM.
$\overline{T(R)}$	Mean travel (retrieval) time of the VLM.
n	Number of trays.
t_{PICK}	Picking time.
$t_{\text{P/S}}$	Pick-up and set-down times of the tray.
$\lambda(R)$	Throughput performance of trays per hour.
T	Time.
$T(d)$	Time in dependence of distance.
V_t	Tray volume.
V	VLM (total) volume.
D	Width (depth) of the tray.

Discrete event simulation was used to evaluate the performance of the VLM system. Movement of the lift is based on the real velocity-time dependence, of which two types can be distinguished. If the obtained peak velocity $v(t_p)$ is less than $v_{\max}$ we named it type I, while if the obtained peak velocity $v(t_p)$ is equal to $v_{\max}$ we named it type II.

Lift movement for type I. ($d < v^2 / 2$)

Time in dependence of distance $T(d)$ is calculated by (1)

$$T(d) = 2\sqrt{\frac{d}{a}} \tag{1}$$

Lift movement for type II. ($d >= v^2 / 2$)

Time in dependence of distance $T(d)$ is calculated by (2)

$$T(d) = \frac{d}{v} + \frac{v}{a} \tag{2}$$

In our paper retrieval requests for the parts picking have been analysed only (therefore refilling storage containers was not considered). In the case of a VLM, retrieval operations correspond with dual command cycles. This means that after the order picker (operator) picks all the products from the tray at the I/O location, the lift moves back the tray to the i^{th} shelve of the VLM. Next, the lift takes another tray from the j^{th} shelve of the VLM and moves back to the I/O location. Selection of trays in the i^{th} and the j^{th} shelve of the VLM is based on randomly selected location, which corresponds with the random storage strategy.

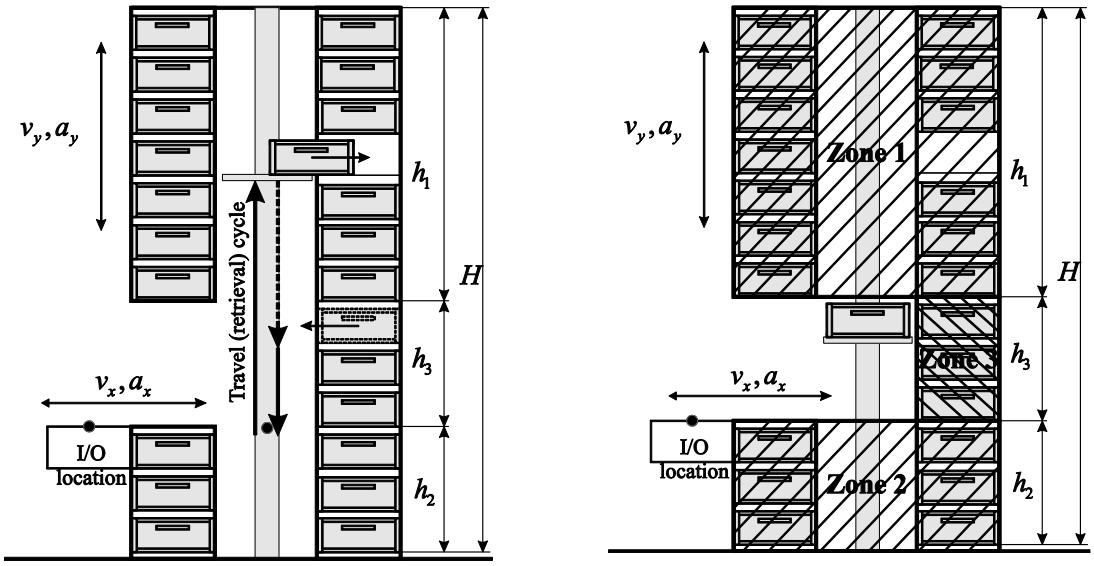

Fig. 2: Definition of the travel (retrieval) cycle and zoning of the VLM

According to the retrieval request selection rule in VLM, mean travel (retrieval) time $\overline{T(R)}$ of lift equals collection of (Fig. 2):

- mean travel (retrieval) time from the I/O location of the VLM to randomly selected i^{th} shelve of the VLM;
- mean travel (retrieval) time from randomly selected i^{th} shelve of the VLM to randomly selected j^{th} shelve of the VLM;
- mean travel (retrieval) time from randomly selected j^{th} shelve of the VLM to the I/O location of the VLM.

Since the VLM is divided into three areas or zones (Fig. 2), probabilities p_i for accessing zones different zones is calculated by (3) [21]:

$$p_1 = \frac{2h_1}{(2H - h_3)}; p_2 = \frac{2h_2}{(2H - h_3)}; p_3 = \frac{h_3}{(2H - h_3)} \tag{2}$$

Mean cycle (retrieval) time $\overline{T(R)}$ consists of mean lift's travel times, additional times for pick-up and set-down and picking time (including identification and confirmation)

$$\overline{T(R)} = t_{\text{PICK}} + 4 \cdot t_{\text{P/S}} + t_{\text{I/O, } i^{\text{th}}\text{tier}} + t_{i^{\text{th}}\text{tier, } j^{\text{th}}\text{tier}} + t_{j^{\text{th}}\text{tier, I/O}} \tag{4}$$

By considering (4) the throughput performance known as number of trays per hour is calculated by (5):

$$\lambda(R) = \frac{3600}{\overline{T(R)}} \tag{5}$$

4. VLM CASE STUDY

This section presents and discusses main input data for the analysis. Total volume - V - of all spare parts is set to 10 m^3. Trays filled with items (storage containers) have the following dimensions: length of the tray W = 1.9 m, 2.5 m, 3.1 m and 4.1 m, width (depth) of the tray D = 0.857 m and height of the tray h = 0.12 m. Height of the section 1 - h_1 - of the VLM is a variable value, which has an influence on the tray capacity n_1 of the section 1 (Fig. 2). Height of the section 2 - h_2 - of the VLM was set to 0.6 m with tray capacity n_2 = 6 trays (Fig. 2). Height of the section 3 - h_3 - of the VLM was set to 0.6 m with tray capacity n_3 = 3 trays (Fig. 2). Note that the height of the storage location is higher than the tray and is marked with h^* = 0.2 m.

Dimensions of the VLM (W, D and H) depends on the selected tray dimensions and number of trays. Velocity scenarios of the lift are as follows: (vp_1) stands for v_y = 1.0 m/s, $a_y^+ = a_y^-$ = 0.5 m/s^2; (vp_2) stands for v_y = 1.0 m/s, $a_y^+ = a_y^-$ = 1.5 m/s^2; (vp_3) stands for v_y = 1.5 m/s, $a_y^+ = a_y^-$ = 1.5 m/s^2; (vp_4) stands for v_y = 2.0 m/s, $a_y^+ = a_y^-$ = 1.5 m/s^2 and (vp_5) stands for v_y = 2.0 m/s, $a_y^+ = a_y^-$ = 2.0 m/s^2. Pick-up and delivery time $t_{P/D}$ is set to 4.0 seconds. Velocity scenarios from vp_1 to vp_5 were chosen based on the material handling equipment producers' references and authors' practical experiences.

As seen in Table I, four VLM_i configurations are analysed. Geometrical data (W, D, h and h^*) were used from the material handling provider Modula (http://www.modula.eu/).

Table I: VLM configurations

VLM configurations	VLM_1	VLM_2	VLM_3	VLM_4
W (m)	1.9	2.5	3.1	4.1
D (m)	0.857	0.857	0.857	0.857
h (m)	0.12	0.12	0.12	0.12
h^* (m)	0.20	0.20	0.20	0.20
V_t (m^3)	0.20	0.25	0.32	0.42
h_1 (m)	4.2	3.2	2.4	1.6
n_1 (/)	42	32	24	16
h_2 (m)	0.6	0.6	0.6	0.6
n_2 (/)	6	6	6	6
h_3 (m)	0.6	0.6	0.6	0.6
n_3 (/)	3	3	3	3
H (m)	5.4	4.4	3.6	2.8
n (/)	51	41	33	25
p_1 (/)	82	78	73	64
p_2 (/)	12	15	18	24
p_3 (/)	6	7	9	12

Volume of the single tray is calculated by (6):

$$V_t = W \cdot D \cdot h \tag{6}$$

Number of trays according to the total volume V is calculated by (7):

$$n = \frac{V}{V_t} \tag{7}$$

Heights of the VLM sections are calculated by (8):

$$h_1 = n - 9 \text{ trays} \tag{8}$$

Height of the rack (VLM) is calculated by (9):

$$H = h_1 + h_2 + h_3 \tag{9}$$

5. ANALYSIS OF RESULTS AND DISCUSSION

Table II summarizes mean cycle (retrieval) time of the lift $T(R)$ for four (4) different VLM configurations, which were analysed according to five (5) different velocity profiles of the lift (see Chapter 4).

Table II: Mean cycle (retrieval) time $T(R)$ of the VLM

Velocity profile	$T(R)$			
	VLM_1	VLM_2	VLM_3	VLM_4
vp_1	27.7	26.1	24.9	23.6
vp_2	25.1	23.7	22.6	21.5
vp_3	23.0	22.0	21.2	20.4
vp_4	22.6	21.8	21.1	20.4
vp_5	21.9	21.1	20.5	19.8

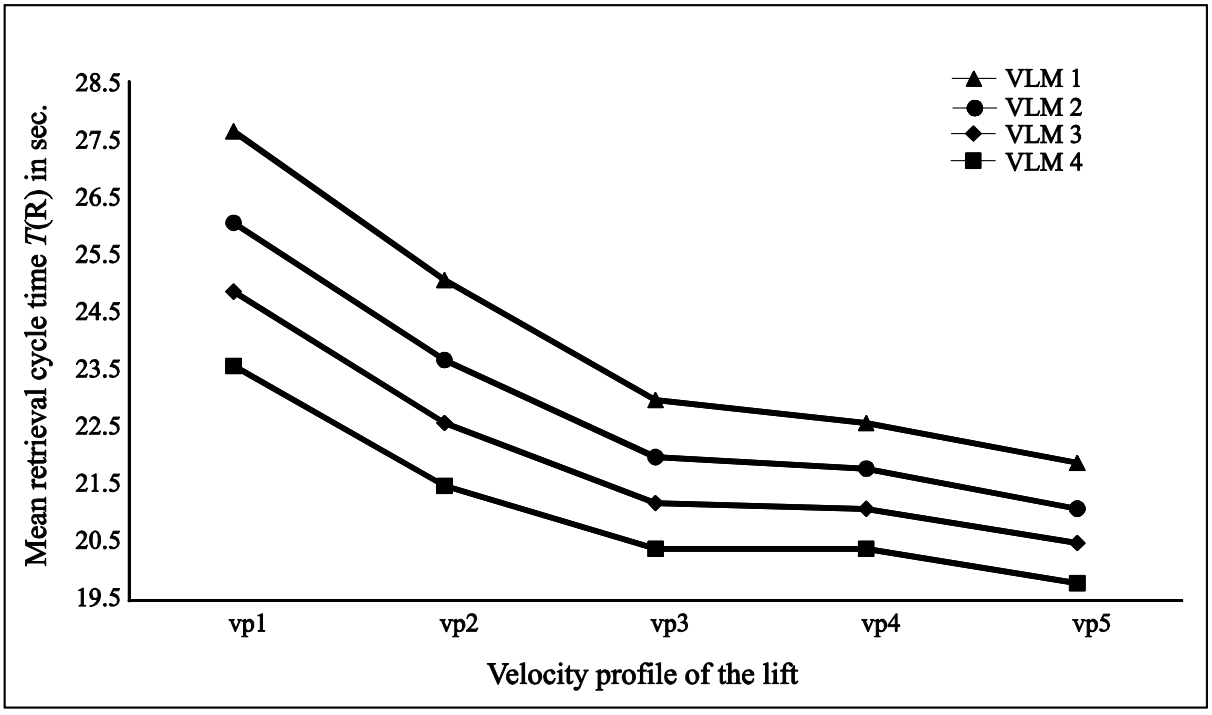

Fig. 3: VLM cycle (retrieval) time analysis

Mean cycle (retrieval) time $T(R)$ of the lift depends on the height H of the VLM and the velocity profile vp_i (v_y and a_y) of the lift. The fastest transactions of the lift belongs to VLM with relatively small height H (VLM_4). The above-mentioned condition stands for all velocity profiles vp_i of the lift (Fig. 3). On the contrary, the slowest transactions of the lift belongs to VLM with relatively large height H (VLM_1).

Regarding to the distribution of the mean cycle (retrieval) time $T(R)$, an expressive dependency has been noticed (Fig. 3) between the velocity profile vp_i and the mean cycle (retrieval) time $T(R)$. In general, the best results are achieved by the lift with fast drives in the vertical travelling direction (Fig. 3).

Table III summarizes VLM performance measured in number of trays per hour for different VLM configurations (see Chapter 4).

Table III: Number of trays per hour of the VLM_i

Velocity profile	$\lambda(R)$											
	VLM_1			VLM_2			VLM_3			VLM_4		
	Picking time			Picking time			Picking time			Picking time		
	5	15	30	5	15	30	5	15	30	5	15	30
vp_1	110	84	62	116	88	64	120	90	66	126	93	67
vp_2	120	90	65	125	93	67	130	96	68	136	99	70
vp_3	129	95	68	133	97	69	137	99	70	142	102	71
vp_4	130	96	68	134	98	70	138	100	70	142	102	71
vp_5	134	98	69	138	100	70	141	101	71	145	103	72

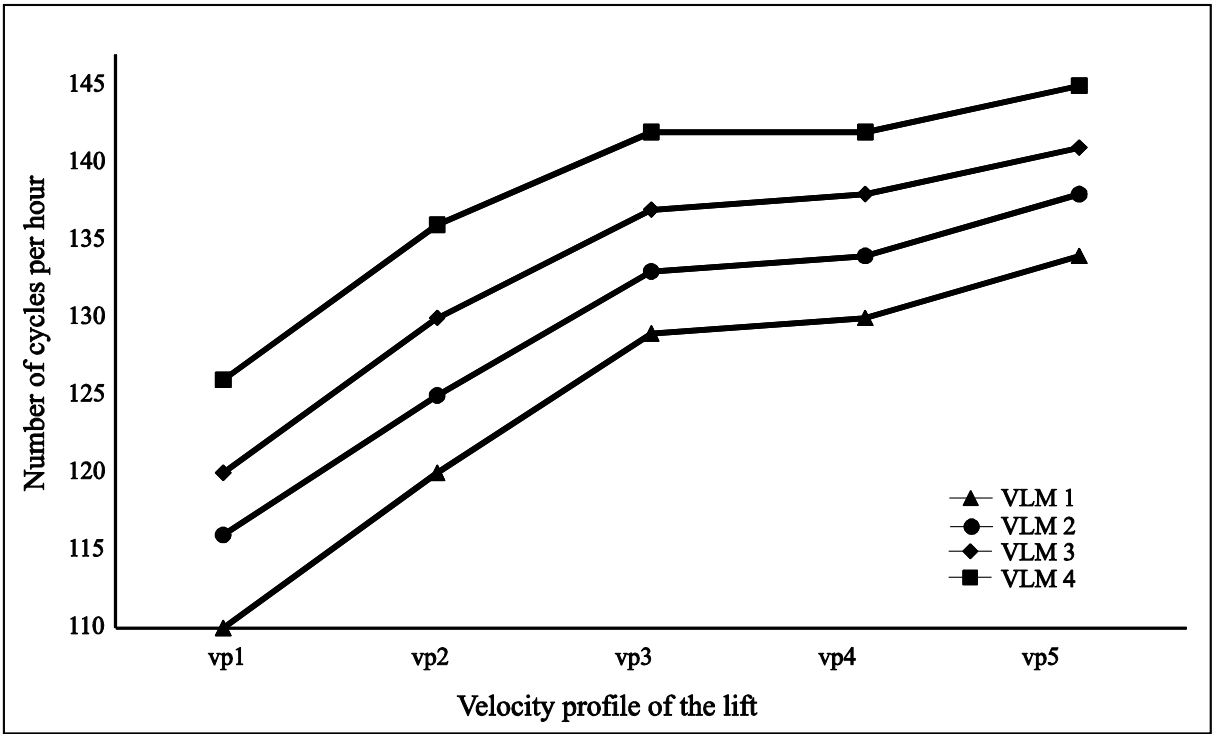

Fig. 4: VLM performance in number of trays per hour when t_{pick} = 5 sec.

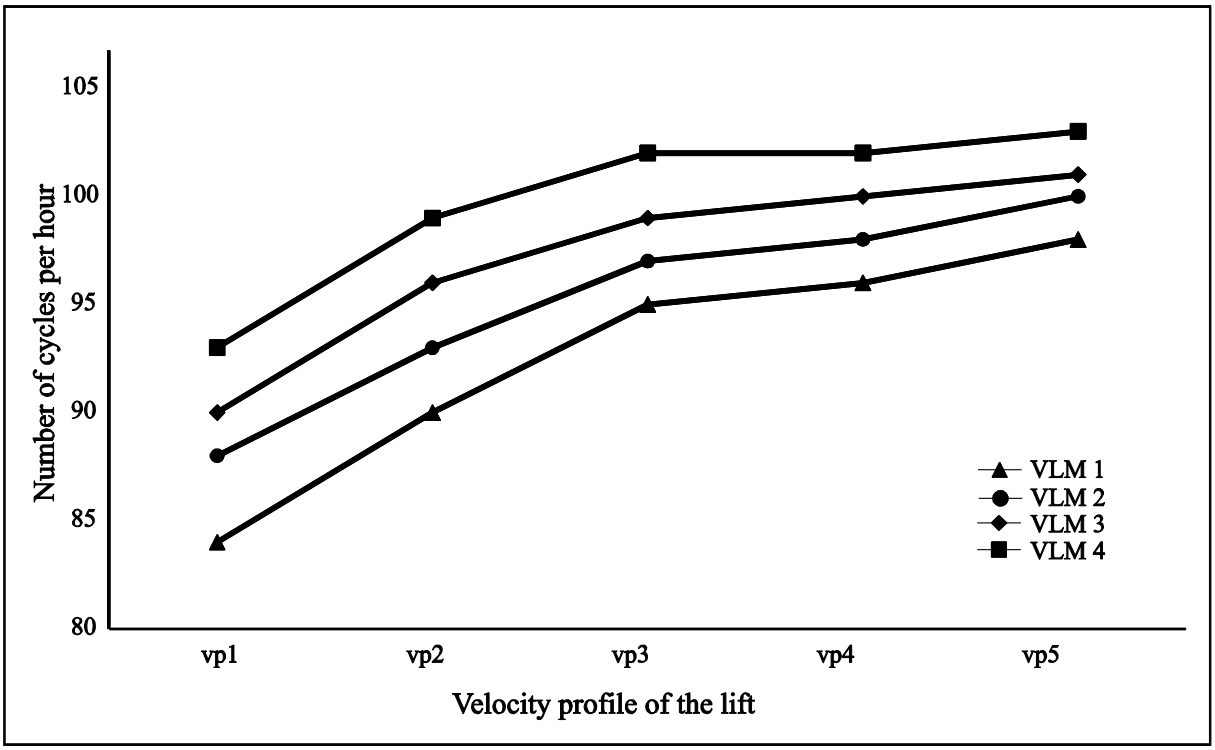

Fig. 5: VLM performance in number of trays per hour when t_{pick} = 15 sec.

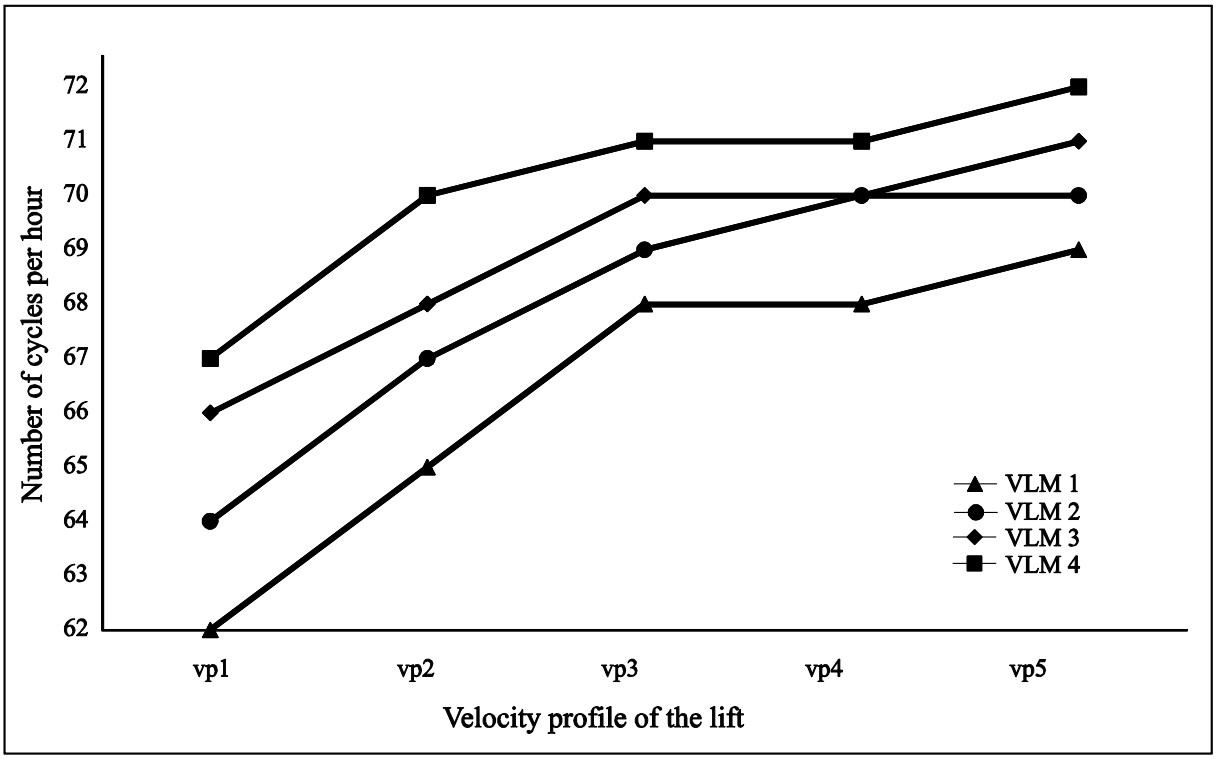

Fig. 6: VLM performance in number of trays per hour when t_{pick} = 30 sec.

For the reason that the throughput performance $\lambda(R)$ is inversly dependent on the mean cycle (retrieval) time $T(R)$, the highest throughput performance $\lambda(R)$ belongs to the VLM with small heights H of the VLM (VLM_4) and better velocity profile vp_i of the lift (vp_5). Opposite,

the lowest throughput performance $\lambda(R)$ belongs to the VLM with relatively large heights H of the VLM (VLM_1) and moderate velocity profile vp_i of the lift (vp_1).

According to picking times (5, 15 and 30 seconds) of the order picker (operator) at the I/O location, the next relationships can be noticed. It is expected that lower VLM with faster lift will achieve higher throughputs. However, the difference in throughput between alternatives also depends on picking time. For small values of picking times (in this case 5 seconds), the height H of the VLM and the velocity profile vp_i of the lift show a significant influence on the throughput performance $\lambda(R)$ between different VLM configurations (Fig. 4, 5, 6). The lowest VLM_4 reaches higher throughput performances of 11-16 trays per hour (8-15% increased throughput) compared to the highest VLM_1, depending on the velocity profile. On the contrary, for higher values of picking times (in this case 30 seconds), the height H of the VLM and the velocity profile vp_i of the lift show smaller influence on the throughput performance $\lambda(R)$ between different VLM configurations (Fig. 4, 5, 6). In this case, the lowest VLM_4 reaches higher throughput performances of only 3-5 trays per hour (4-8% increased throughput) compared to the highest VLM_1, depending on the velocity profile. If one is to choose between all alternatives (heights and velocity profiles), the lowest and fastest VLM_4 with vp_5 will achieve 32% better throughput compared to the highest and slowest VLM_1 with vp_1 in case of the picking time of 5 seconds, while just 16% in case of the picking time of 30 seconds.

6. CONCLUSION

This paper presents VLM's performance analysis using simulation. The simulation model of the VLM is based on the real velocity-time dependence for the lift in the vertical direction, assuming randomized storage assignment.

Various VLMs have been examined alternating VLM design (height and width) and the velocity of the lift in order to investigate the throughput performance of the VLM. Main result of this study is observation that the throughput performance $\lambda(R)$ of the VLM significantly depends on the small heights H of the VLM (VLM_4) and better velocity profile vp_i of the lift (vp_5). Hence, if we decrease the height H of the VLM and use even better velocity profile vp_i of the lift, we can obtain better throughput capacity (however smaller VLMs for required storage capacity comes with the increased floor space of theVLM).

Generally, when deciding on a VLM design, picking time, height H of the VLM and the velocity profile vp_i of the lift have significant influance on system's performance. For small values of picking times, the height H of the VLM and the velocity profile vp_i of the lift show an expressive influence on the throughput performance $\lambda(R)$ between different VLM configurations. On the contrary, for high values of picking times, the height H of the VLM and the velocity profile vp_i of the lift show relatively small influence on the throughput performance $\lambda(R)$ between different VLM configurations.

According to the proposed simulation model for the design of VLM, we can conclude, that presented results are useful for engineering practice. Based on the results shown on Figures 4, 5 and 6 and in Table III, one can relatively quickly select the most efficient type of VLM.

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