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Original scientific paper

Single-Tray VLM vs Dual-Tray VLM: Quantitative Throughput Comparison

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Abstract: In this paper quantitative comparison of resulting throughputs for single-tray and dual-tray VLM devices is presented. Comparison is based on mathematical models for throughput approximating dual command times of VLM's crane, for selected parameters of VLM device (height and crane's velocity) and selected picking times per delivered tray. Analysis showed that throughput increase achieved by using dual-tray VLM's depends mostly on the average picking time relative to the expected dual command time of the VLM's crane. Highest improvements are possible for picking time equal to expected dual command time and amounts over 80%, however for extremely low or high picking times improvements are significantly reduced.

Keywords: dual-tray VLM; order-picking; single-tray VLM; throughput model; vertical lift module systems

1 INTRODUCTION

Automated storage and retrieval systems (AS/RSs) are often implemented in logistics and manufacturing systems. We distinguish between several AS/RSs that enable storing and retrieving logistics units (loads) differing in dimensions and masses. Compared to non-automated systems, the use of AS / RS has a number of advantages, like reduction of labour costs, reduction of required space, increased reliability, accuracy, safety and security. There are also disadvantages higher investments costs and less flexibility [1]. Several different types of automated storage/retrieval systems have found their application in order-picking process, mainly due to the principle of bringing parts to human picker (making them so called parts-to-picker systems).

Process of order-picking is known as usually very laborious, with up to 55% of warehouse operating costs [2] or about 65% of logistics centre operating costs [3]. Therefore, it is understandable why many companies seek to improve order-picking with implementations of more efficient systems. The improvements are the most commonly built on reducing the time required to walk between the storage locations of ordered items, which often represents half of the time required to prepare a customer order [2]. Among all the types, part-to-picker AS/RSs allow the greatest reduction in travel time. Their main advantage is that the picker does not move along the storage racks. Instead of walking, the system delivers required items to the operator, to the area of his/her standing. Besides the name part-to picker, those systems are also found with names stock-to-operator, goods-to-man or end-of-aisle system.

An example of part-to-picker AS/RS is Vertical Lift Module (VLM). In VLM, the insertion/extraction (I/E) device is moving vertically and on its way extracts trays or totes from the shelves and delivers them to the operator) [4, 5]. Trays or totes are deposited on the pick shelf (or pick window) in front of the operator, colored red in Fig. 1. Usual VLM systems have only one picking place, one extractor and one lift (and are named single-tray VLM or single bay VLM). Producers of VLMs provide also various extended solutions, like dual-tray VLM, double extractor VLM, buffer VLM and double lift VLM. All those extensions are aimed to increase throughput (a.k.a. increased picking productivity) by reducing the system's cycle time. However, how much improvement would be expected using some advanced device instead of basic single-tray VLM configuration is not so simple to answer. It would be wrong and naive to simply assume that dual-tray or dual-lift might achieve doubled throughput compared with single-tray single-lift VLM. This paper focuses on dual-tray VLM and its throughput. Additionally, throughputs of dual-tray and single-tray VLMs are compared. The main idea is to search for picking productivity differences based on various parameters. The aim is to investigate the degree of efficiency increase of a dual-tray VLM in relation to a single-tray VLM, based on a developed analytical models of the analysed devices and corresponding processes. Overall, such analysis contributes to the logistics engineering field, both from the scientific and the managerial aspect.

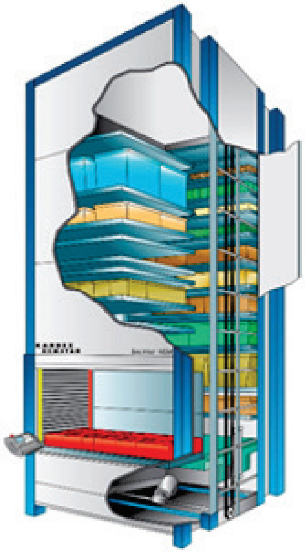

Figure 1 Vertical Lift Module (VLM)

The paper is several main chapters. Chapter 2 presents a brief review of research papers regarding VLM throughput models (developing and usage). Chapter 3 reviews with more details two used throughput models, namely single-tray VLM throughput model from Meller & Klote, 2004 [6] and dual-tray VLM throughput model from Dukic et al., 2015 [7]. Chapter 4 presents details of the conducted analysis and results. Paper ends with the conclusions and further research directions.

2 BACKGROUND AND LITERATURE REVIEW

Up to the last several years, literature about VLMs was relatively scarce, although those systems have been in use for almost 50 years [4]. Apart from some papers discussing applications, main parts and benefits of using VLMs [4, 5], the first paper that presented throughput model of single-tray VLM was by Meller & Klote, 2004 [6]. Model from this paper is used for analysis in this paper, so details are explained in sub-chapter 3.1. As single-tray VLM was supplemented by dual-tray VLM (also named dual bay VLM, dual delivery configuration VLM, or VLM with double access handling option), a demand for a throughput model arose to aid the warehouse designers and managers to determine expected throughput. Considering mini-load AS/RS models [8-10] and single-tray VLM model [6] previously presented in literature, dual-tray VLM throughput model was developed and presented by Dukic et al., 2015 [7]. Accuracy of analytical model was determined by comparing results to the results obtained by simulation. The proposed model confirmed satisfactory accuracy for estimating throughput of system with single dual-tray VLM and human order-picker. The model assumed random storage policy without using batching or retrieval sequencing.

Several more papers dealing with both single- and dual-tray VLMs were published afterwards. Battini et al. [11] performed case study, considering different storage assignment policies and batch retrievals. Rosi et al. [12] analysed VLMs using simulation model, considering various velocity profiles of lifts. Lenoble et al., [13] analysed order batching optimization in single-tray VLMs, confirming that batching increases throughput. Dukic et al. [14] used single-tray VLM model for cycle-time and ergonomic assessment. Sgarbossa et al. [15] analysed class-based storage and sequencing retrievals to increase throughput of dual-tray VLMs with short picking times. Same authors were dealing with economic evaluation of VLM's application in [16], developing cost model for dual-tray VLM. Dukic et al. [17] analysed influence of pick-time distribution on expected throughput of dual-tray VLMs. Lastly, Vanhauwermeiren et al. [18] presented throughput models for double extractor VLM, buffer VLM and double lift VLM, providing some insights into throughput differences of additional various types of VLM devices.

In this paper, authors also compared resulted throughput of all VLM types, varying only height of the units and picking time. The authors presented results in form of graphs, however lacking details and exact quantitative differences.

3 SINGLE-TRAY AND DUAL-TRAY VLM THROUGHPUT MODELS

In this chapter single-tray VLM and dual-tray VLM throughput models are presented. Although published with explanations in original papers, the presentation is repeated in some parts to show the models more clearly and adjusted for comparison analysis.

3.1 Single-Tray VLM Throughput Model

Single-tray VLM model was presented in [7]. Model assumed system of one VLM device and one human picker. VLM is with one pick location, from which picker is picking items from delivered trays (or could be totes). Those trays are delivered by I/E device (called crane in the text below).

Model originally calculated total throughput time to complete a set of orders with n items, which is actually the sum of the expected retrieval time (crane) and picking time (human), considering that storages and retrievals are always performed in a combination as dual command cycle, except the first and the last operations which are performed as single command cycles. Also model calculated expected number of trays to be delivered based on number of picking items and number of trays device. In this paper we assumed work of VLM with only dual commands, in order to calculate throughput of the single-tray VLM and human picker expressed in number of delivered trays per hour. Therefore, picking time is expressed by average pick time per tray, not per picked item, avoiding calculation of expected items per delivered tray. In other words, no batching or picking sequencing is assumed. Expected dual command cycles is calculated based of expected travel between picking position and sections within VLM (h_1, h_2, h_3) and velocity of the crane v, as illustrated in Fig. 2.

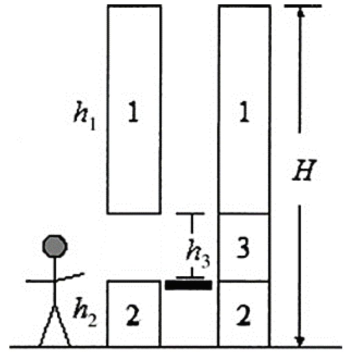

Figure 2 Side view of VLM with typical sections [7]

Assuming random storage, model first calculates expected travel times from/to picking place and sections (t_{0i}) and expected travel times between sections (t_{ij}). Expected dual-command VLM crane travel time *E(DC)* is then calculated based on probabilities of a storage/retrieval of a tray in corresponding sector (p_1, p_2, p_3) as a basis to calculate probabilities that dual command cycle stores a tray in section i and retrieves a tray in section $j(p_{ij})$. According to the 4 pickups and deposits and three delay times due to acceleration and deceleration, there is an additional constant time per cycle (C). As said, expected system cycle time $E(CT)$ is then simply a sum of expected dual command cycle time and picking time.

Model is given below. For more detailed explanation readers are referred to [7] and [11].

$$\begin{aligned} t_{01} &= \left(h_3 + h_1/2\right)/v \\ t_{02} &= \left(h_2/2\right)/v \\ t_{03} &= \left(h_3/2\right)/v \end{aligned} \tag{1}$$

$$\begin{aligned} t_{11} &= \left(h_1/3\right)/v \\ t_{12} = t_{21} &= \left(h_1/2 + h_3 + h_2/2\right)/v \\ t_{13} = t_{31} &= \left(h_1/2 + h_2/2\right)/v \\ t_{22} &= \left(h_2/3\right)/v \\ t_{23} = t_{32} &= \left(h_2/2 + h_3/2\right)/v \\ t_{33} &= \left(h_3/3\right)/v \end{aligned} \tag{2}$$

$$\begin{aligned} p_1 &= 2h_1/\left(2H - h_3\right) \\ p_2 &= 2h_2/\left(2H - h_3\right) \\ p_3 &= h_3/\left(2H - h_3\right) \end{aligned} \tag{3}$$

$$E(DC) = \sum_{i=1}^{3}\sum_{j=1}^{3}(t_{0i} + t_{ij} + t_{0j})\cdot p_i p_j \tag{4}$$

$$C = 3\cdot t_{\mathrm{a/d}} + 4\cdot t_{\mathrm{p/d}} \tag{5}$$

$$E(CT) = E(DC) + C + p_{\mathrm{T}} \tag{6}$$

3.2 Dual-Tray VLM Throughput Model

Dual-tray VLM model presented in [11] assumed system of single VLM with two picking locations (two locations for delivered trays). With 2 picking position, VLM crane is able to store previous tray and retrieve next tray from the rack location while human picker is picking item(s) from another place. Storage and retrieval of trays are still done with dual commands, however now alternatively form those 2 mentioned locations, positions A and B, which is illustrated together with sections of VLM device in Fig. 3. The throughput model in this case is based on system's cycle similar to mini-load AS/RS model developed by Bozer and White [8-10], but using idea of calculation crane's expected dual-command of VLM presented in section 3.1. Since crane is doing alternatively dual commands from two positions, first average $E(DC)$ is calculated from those 2 expected dual-commands and time to move between them (which again were calculated based on travel times between picking places and sections ($t_{\mathrm{A}j}$, $t_{\mathrm{B}j}$). Travel time between sections and probabilities are the same as for single-tray VLM model. Standard deviation of dual command travel time was approximated as $S(DC) \approx 0.383\cdot E(DC)$, based on calculation for various configurations, leading to the limits of uniform distribution of approximated dual command travel time (k_1 and k_2) and limits of uniform distribution of dual command cycle time (t_1 and t_2). Please note that in this case constant time per cycle C consists of four times to pickup/deposit a tray and four acc./dec. delay times.

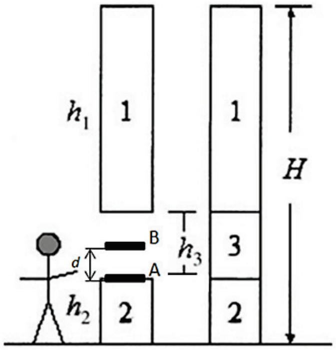

Figure 3 side view of dual-tray VLM with typical sections [7]

Then, based on assumption that pick time is deterministic or exponentially distributed, expected system cycle time $E(CT)$ could be calculated in two variations.

This model is given below, while for more detailed explanation readers are also referred to paper [11].

$$E(DC) = \frac{E(DC)_{\mathrm{A}} + E(DC)_{\mathrm{B}}}{2} + \frac{d}{v} \tag{7}$$

$$\begin{aligned} E(DC)_{\mathrm{A}} &= \sum_{i=1}^{3}\sum_{j=1}^{3}(t_{\mathrm{A}i} + t_{ij} + t_{\mathrm{A}j})\cdot p_i p_j \\ E(DC)_{\mathrm{B}} &= \sum_{i=1}^{3}\sum_{j=1}^{3}(t_{\mathrm{B}i} + t_{ij} + t_{\mathrm{B}j})\cdot p_i p_j \end{aligned} \tag{8}$$

$$\begin{aligned} t_{\mathrm{B}1} &= \left(h_3 - d + h_1/2\right)/v \\ t_{\mathrm{B}2} &= \left(d + h_2/2\right)/v \\ t_{\mathrm{B}3} &= \left[\left((h_3 - d)/2\right)\cdot\left((h_3 - d)/h_3\right) + \left(d/2\right)\cdot\left(d/h_3\right)\right]/v = \\ &= \left[\left((h_3 - d)^2 + d^2\right)/2h_3\right]/v \end{aligned} \tag{9}$$

$$\begin{aligned} k_1 &= E(DC) - 1.7321\cdot S(DC) \\ k_2 &= E(DC) + 1.7321\cdot S(DC) \end{aligned} \tag{10}$$

$$\begin{aligned} t_1 &= k_1 + C \\ t_2 &= k_2 + C \end{aligned} \tag{11}$$

$$E(CT) = \begin{cases} E(DC) + C & \text{for } 0 < p_{\mathrm{T}} \le t_1 \\ \dfrac{p_{\mathrm{T}}^2 - 2p_{\mathrm{T}}t_1 + t_2^2}{2(t_2 - t_1)} & \text{for } t_1 < p_{\mathrm{T}} \le t_2 \\ p_{\mathrm{T}} & \text{for } t_2 < p_{\mathrm{T}} \end{cases} \tag{12}$$

$$\begin{aligned} E(CT) &= E(DC) + C + \\ &+ \frac{p_{\mathrm{T}}^2}{t_2 - t_1}\left[exp\left(-\frac{t_1}{p_{\mathrm{T}}}\right) - exp\left(-\frac{t_2}{p_{\mathrm{T}}}\right)\right] \end{aligned} \tag{13}$$

4 RESULTS OF THROUGHPUT COMPARISON

With presented models for single-tray VLM and dual-tray VLM, one can for same input parameters (VLM's height, dimensions of sections, crane velocity, acceleration/deceleration delay time, pickup/deposit delay time, pick time per delivered tray) compare resulting system's cycle time and therefore throughput in delivered trays per hour RT as

$$q = 3600 / E(CT) \tag{14}$$

Comparison was done for plenty combinations of systems. For four various VLM heights and three different speeds of lift, there were total 12 different VLM configurations used in research (dimensions of section h_2 = 900 mm, h_3 = 750 mm and d = 300 mm were constant in all analysed configurations). For each configuration throughputs were calculated for five different values of average pick times per delivered tray. In first step, three pick time values were specifically selected to be approximately equal to the lower value of approximated uniform distribution of dual-command cycle time of VLM's crane mean (average) dual-command cycle time and upper value of approximated uniform distribution of dual-command cycle time of VLM's crane, respectively, named p_{T1}, p_{T2} and p_{T3}. In next step of the research two other picking times were selected to be relatively small and high, named p_{T0} and p_{T4}, defined as

$$\begin{aligned} p_{\mathrm{T0}} &= p_{\mathrm{T1}} / 2 \\ p_{\mathrm{T4}} &= 2 \cdot p_{\mathrm{T3}} \end{aligned} \tag{15}$$

Tab. 1 presents values of first three selected picking times for analysed 12 configurations

Table 1 Picking times per tray, in seconds

H (mm)	*v* (cm/s)								
	50			100			150		
	p_{T1}	p_{T2}	p_{T3}	p_{T1}	p_{T2}	p_{T3}	p_{T1}	p_{T2}	p_{T3}
4500	27	34	41	25	29	33	25	27,5	30
6000	28	37,5	47	26	31	36	25	28,5	32
7500	29	41,5	54	26	32,5	39	25	29,5	34
9000	31	45,5	60	27	34,5	42	26	31	36

Based on models presented above, resulting throughputs are given in Tab. 2 and Tab. 3.

Comparison of achieved throughputs, expressed in percentage of increased throughput by using dual-tray VLM, is given in Tab. 4.

Table 2 Single-tray VLM's throughput (delivered trays per hour)

H (mm)	*v* (cm/s)								
	50			100			150		
	q_1	q_2	q_3	q_1	q_2	q_3	q_1	q_2	q_3
4500	61,43	54,88	49,59	69,50	64,52	60,20	71,71	68,31	65,22
6000	56,76	49,36	43,67	65,79	60,28	55,62	69,93	65,48	61,56
7500	52,69	44,54	38,57	63,53	56,99	51,67	68,21	62,85	58,27
9000	48,48	40,56	34,86	60,37	53,63	48,24	65,35	59,91	55,31

Table 3 Dual-tray VLM's throughput (delivered trays per hour)

H (mm)	*v* (cm/s)								
	50			100			150		
	q_1	q_2	q_3	q_1	q_2	q_3	q_1	q_2	q_3
4500	106,26	101,12	87,80	124,40	120,81	109,09	131,92	128,80	116,13
6000	95,64	90,36	76,60	116,81	112,32	100,00	126,09	122,95	112,50
7500	86,75	81,08	80,00	109,92	105,63	92,31	120,68	117,49	105,88
9000	79,30	73,65	60,00	103,75	99,12	85,71	115,64	111,77	100,00

Table 4 Increased throughput of dual-tray VLMs compared with single-tray VLMs

H (mm)	*v* (cm/s)								
	50			100			150		
	p_{T1}	p_{T2}	p_{T3}	p_{T1}	p_{T2}	p_{T3}	p_{T1}	p_{T2}	p_{T3}
4500	72,96%	84,27%	77,07%	78,99%	87,25%	81,21%	83,95%	88,55%	84,00%
6000	68,52%	83,06%	75,38%	77,55%	86,33%	79,78%	80,32%	87,77%	82,75%
7500	64,65%	82,05%	72,83%	73,04%	85,36%	78,64%	76,94%	86,95%	81,71%
9000	63,57%	81,59%	72,10%	71,84%	84,83%	77,69%	76,97%	86,56%	80,81%

Visualizing results of throughput of one selected configuration (in this case H = 6000 mm, v = 100 cm/s) with Fig. 4 clearly shows that resulting throughput is higher for smaller picking times, but also that difference is variable (in our cases between 63,57% and 88,55%).

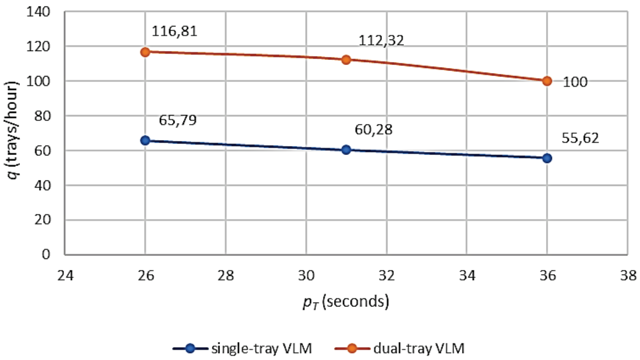

Figure 4 Throughput's of single-tray and dual-tray VLMs depending on picking time per delivered tray (three analysed picking times)

From the Tab. 4 one can conclude that largest increase of throughput by using dual-tray instead of single-tray VLM is possible in cases where picking time per tray equals mean (average) dual-command cycle time of VLM's crane. However, question arises whether curves will continue on both sides for lower and higher throughputs with the same tendencies, which the reason for analysis of throughputs for p_{T0} and p_{T4} is picking times.

Table 5 Increased throughput of dual-tray VLMs compared with single-tray VLMs including 2 additional extreme picking times

H (mm)	*v* (cm/s)														
	50					100					150				
	P_{T0}	P_{T1}	P_{T2}	P_{T3}	P_{T4}	P_{T0}	P_{T1}	P_{T2}	P_{T3}	P_{T4}	P_{T0}	P_{T1}	P_{T2}	P_{T3}	P_{T4}
4500	33	73	84	77	39	36	79	87	81	41	38	84	89	84	42
6000	31	69	83	75	38	35	78	86	80	40	37	80	88	83	41
7500	30	65	82	73	36	33	73	85	79	39	35	77	87	82	41
9000	29	64	82	72	36	33	72	85	78	39	35	77	87	81	40

Tab. 5 is now showing extended Tab. 4, with percentages of increased throughput including those two extreme picking times. In this case it is very interesting to see how the potential of using dual-tray VLM compared to single-tray

VLM is heavily reduced in cases of picking times significantly lower or higher than lower and upper value of approximated uniform distribution, respectively, as shown in Fig. 5 for one selected configuration.

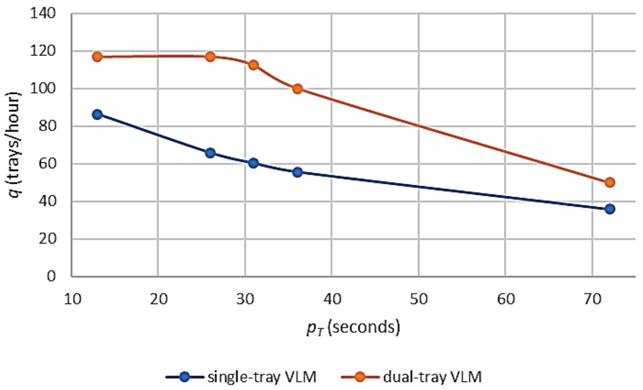

Figure 5 Throughput's of single-tray and dual-tray VLMs depending on picking time per delivered tray (all analysed picking times)

5 CONCLUSIONS

VLM systems are evolving intensively, which raises their importance among AS/RSs. Development is taking place in the direction of new possibilities of process use, capacity improvement, improved productivity and rational use of space. Importance is also given to the health of workers in terms of ergonomics. The system's throughput calculation is used to achieve the desired performance indicators through the selection of the optimal type of VLM system. Research has shown advantages of the dual-tray VLM system in comparison to the single-tray VLM system. The dual-tray VLM system does not wait for the order-picker to complete picking items from the delivered tote but already delivers the next tote in the meantime. Comparison of throughputs of mentioned systems revealed that installing a dual-tray VLM system could benefit in up to 90% higher throughput than the single-tray VLM systems. However, the performance of dual-tray VLM system relative to the performance of dingle-tray decreases for average picking times lower and higher than the mean dual command cycle time of lift. Calculations done for two arbitrary chosen picking times extraordinary different that (2 times less and 2 times higher than lower and upper values of uniformly distributed dual command cycle time) showed that in those cases performances of dual-tray VLMs were just 30 to 40% better compared to the single-tray VLMs. The calculation revealed that actual time spent for picking from delivered tray influences absolute throughput and relative difference of throughputs achieved by VLM systems as well. The calculated result can be beneficially used by warehouse designers and managers when deciding on the VLM system type.

In the future it would be interesting to check how much efficiency increase is possible to achieve by storage and/or batching methods implemented with dual-tray VLMs. It would be also interesting to investigate differences between dual-tray, double extractor and double lift VLMs, not only in expected throughputs but also in investment and operating costs.

Another direction of further research is related with the ergonomics. As already mentioned, paper [14] analysed single-tray VLM from the ergonomic aspect as well. Such analysis could be done for dual-tray VLM, revealing how much increased productivity increases energy expenditure of the picker, therefore affecting more fatigue.

Notice

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