Proceedings of the 2024 Winter Simulation Conference
H. Lam, E. Azar, D. Batur, S. Gao, W. Xie, S. R. Hunter, and M. D. Rossetti, eds.

MULTI-METHOD MODELING AND SIMULATION OF A VERTICAL LIFT MODULE WITH AN INTEGRATED BUFFER SYSTEM USING ANYLOGIC

Noe Tavira, Jr.[1], Abhimanyu Sharotry[1], Jesus A. Jimenez[1], Jakob Marolt[2], and Tone Lerher[2,3]

[1]Ingram School of Engineering, Texas State University, San Marcos, TX, USA
[2]Faculty of Logistics, University of Maribor, Mariborska, Celje, SLOVENIA
[3]Faculty of Mechanical Engineering, University of Maribor, Smetanova, Maribor, SLOVENIA

ABSTRACT

As industry trend continues to accelerate sellers to begin transitioning the sale of their products exclusively through e-commerce platforms, companies must remain vigilant and recognize the requirement for their products to be safely stored and quickly retrieved. This research presents a comprehensive model and simulation study of a Vertical Lift Module (VLM) with an integrated shuttle-based storage and retrieval system (SBS/RS) or buffer system. This work evaluates a proposed solution to the ever-increasing emergent storage and retrieval challenges faced by warehouses worldwide. The VLM system was modeled using AnyLogic software to evaluate system capacity, travel distance, velocity profiles, and other user-defined operational constraints. The VLM performance is modeled under various conditions and compared to the performance of a traditional stand-alone VLM in terms of throughput and cycle-time to identify potential VLM-Buffer system integration drawbacks or limitations.

1 INTRODUCTION

Order-picking (OP) retrieves items listed in customer orders from various warehouse locations. It determines a company's level of competitiveness. About 55% of warehouse costs are due to OP activities (Accorsi et al. 2012). OP can be either manual or automated, with the most conventional choice being to employ human operators (Grosse et al. 2016). The "picker-to-parts" system is the most common (De Koster et al. 2004), but it can be inefficient as up to 50% of the operator's time is spent traveling (Tompkins 2010). In contrast, the "part-to-system" system is a strategy where automated storage and retrieval systems (AS/RS) are employed. Multiple items are automatically transported from a storage location to a specific picker station, where a human picker collects the items needed to fulfill the order lists (De Koster et al. 2004).

With the large aisles of products, it is easy for workers to navigate to the wrong Stock Keeping Unit (SKU) for a given order. The same is true for the misplacement of items. U.S. retailers, on average, experience a 1.33% loss in sales due to inventory shrinkage, encompassing theft, shoplifting, errors, or fraud. This shrinkage equated to a staggering $46.8 billion loss for the U.S. retail economy in 2017 (Richter 2019). Furthermore, workers work under less-than-ideal ergonomic conditions. For hours at a time, workers' bodies are compromised by being put into prolonged postures of reaching, bending, and lifting maneuvers. According to the National Safety Council, the potential for worker injury is real, with $167 billion paid in worker-compensated medical bills annually for warehouse-related work injuries in 2021. This figure includes wage and productivity losses of $47.4 billion, medical expenses of $36.6 billion, and administrative expenses of $57.5 billion (NSC 2021). Worker falls, trips, and slips are the top causes of warehouse injury (OSHA 2019). The U.S. Department of Labor Statistics indicates that a worker died every 101 minutes from a work-related injury in 2021 in the United States (USDoL 2022).

Several automated solutions have been introduced to ease picking activities and reduce the impact of human labor (Calzavara et al. 2019). This paper focuses on two specific technologies, Vertical Lift Module (VLM) and shuttle-based-storage and retrieval systems (SBS/RS):

- VLM is an Automated Storage and Retrieval System (AS/RS) with a moderate capacity and throughput (Rosi et al. 2016). They automate the process of bringing trays of items to an operator at an ergonomically suitable height. Each tray can contain multiple totes. These trays are stored vertically, using previously poorly utilized vertical height in warehouses. A lift is in the center of the VLM, which performs both actions of retrieving and placing trays in different locations. The operator requests items coded in SKU. The lift retrieves and takes the tray to the picking station. Once the desired items are picked, the lift will return the tote to its previous shelf in the VLM (Lerher et al. 2017).
- SBS/RS are automated storage systems designed to efficiently store and retrieve items in a warehouse or distribution center. SBS/RS systems can offer fast and accurate storage and retrieval operations, reduce labor costs, and maximize storage capacity, making them ideal for warehouses and distribution centers with high inventory turnover rates and space constraints. In this paper, we will consider the application of an SBS/RS with multi-tier-captive shuttle carriers (Marolt et al. 2022). This special buffer design is not typical of an SBS/RS system. Traditional SBS/RS systems are typically designed to have only a single-tier-captive-shuttle carrier in each tier of the storage rack; but, in this research, we study a design with multiple shuttles.

Figure 1 shows a VLM and an SBS/RS system.

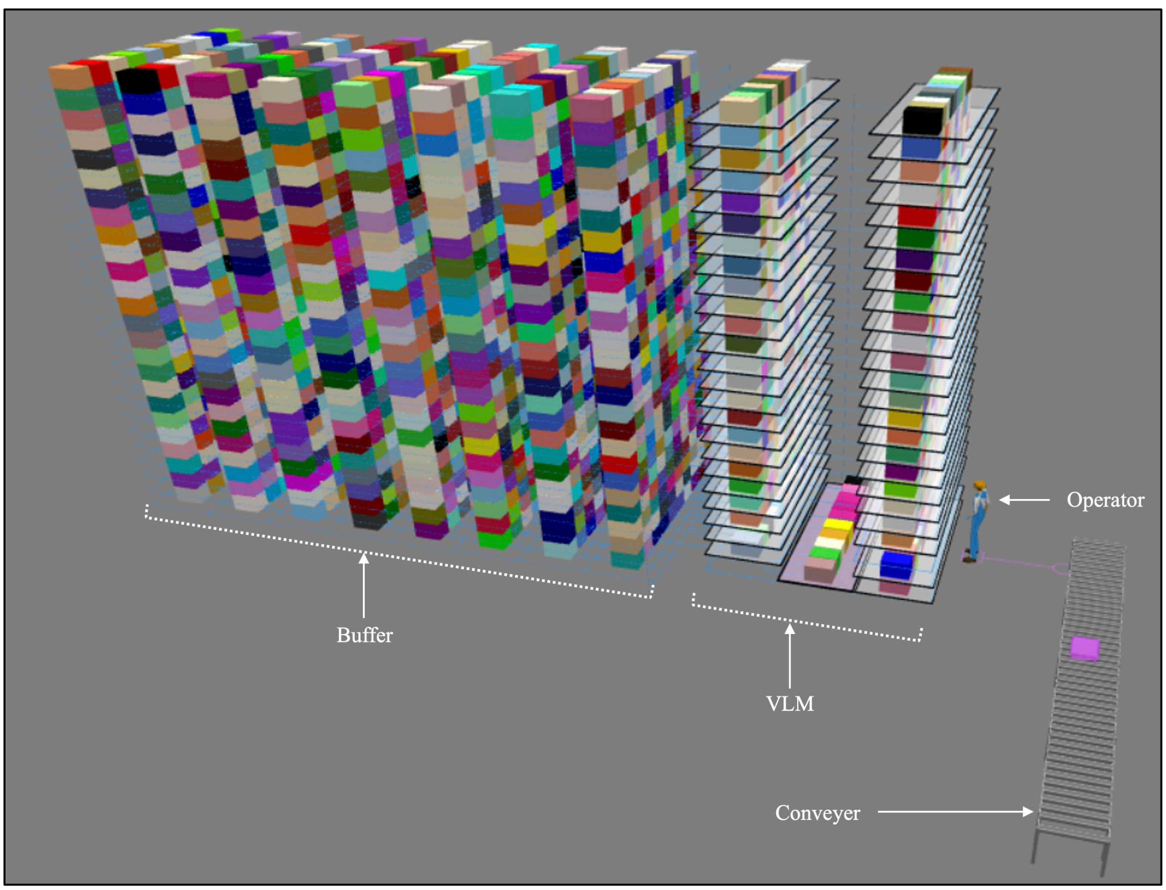


Figure 1: VLM and buffer (SBS/RS) systems.

One constraint associated with VLM systems is their storage capacity. Running out of space in the VLM can delay order fulfillment, increase picking times, alter customer delivery schedules, and cause downtime. To prevent or mitigate these potential issues, proactive measures such as regular inventory audits, optimizing storage configurations, implementing space-saving techniques, and evaluating storage needs based on demand forecasts can help maintain efficient operations within the VLM system (Lerher et al. 2017). Integrating a VLM with an SBS/RS system can offer several benefits to expand storage capacity. A key advantage is the efficient utilization of vertical space, allowing for higher storage density than traditional shelving rack and pallet systems (Marolt et al. 2022). This scalability could be crucial for handling growing inventories. Furthermore, integrating the two systems also enables better inventory management through AS/RS processes. Items can be tracked more accurately, reducing errors, and improving inventory visibility, leading to more efficient operations. VLMs integrated with buffer systems can also potentially expedite order fulfillment processes. Items can be retrieved quickly and accurately, reducing operator OP times and improving overall order processing speed. Lastly, VLMs and buffer systems could contribute to a safer and more ergonomic work environment by minimizing the need for forklift operations, manual lifting, and lowering. Operators can focus on tasks requiring skill and decision-making, improving workplace safety and productivity.

In the proposed integrated VLM-SBS/RS system, the SBS/RS component is intended to serve primarily as a buffer. It is not envisioned to operate as a high throughput component of the integrated system. The purpose of this paper is to simulate the integrated VLM and SBS/RS configuration. The simulation was developed in AnyLogic University v8.8.6 (AnyLogic 2024). The integrated system is based on the previous work by Marolt et al. (2022) and builds upon previous research in warehouse automation and storage systems integration. In this research, we aim to explore if discrete event simulation (DES) and agent-based model (ABM)simulation methodologies can be utilized to aid in optimizing the integration of a VLM with a SBS/RS in a warehouse environment.

By addressing this question, we aim to contribute valuable insights to the field of warehouse automation simulation and assist practitioners and modelers in making informed decisions regarding the implementation and optimization of such integrated storage and retrieval systems.

The remaining sections are organized as follows. In section 2, we present the literature review of VLM, SBS/RS, and hybrid systems. In section 3, we present the system design configuration and the experimental design, followed by the results in section 4. Finally, in section 5 we present the conclusions and future work.

2 LITERATURE REVIEW

We reviewed relevant literature in VLM research to find scientific work that had been done on the investigation or simulation of integrating these two types of systems: VLM and SBS/RS. The following section will discuss our findings from the current literature on VLM/SBS/RS systems.

After conducting a literature review, we found several scholarly articles that explore the uses and configurations of VLMs. Meller and Klote (2004) developed an analytical model for carousels and VLMs in a pod configuration. Under the author's framework, system throughput could be estimated for a single operator servicing one or multiple VLMs. Supported by the model developed by Meller and Klote (2004), Dukic et al. (2015) added to the work in this area by creating a deterministic model to attempt and predict a dual tray VLM's throughput under different configurations. A deterministic model allows the modeler to calculate a future event precisely without the involvement of randomness. If something is deterministic, the system analysts have all the data necessary to predict (determine) the outcome or response of the system with great certainty.

Battini et al. (2016) evaluated the effects class-based storage for trays, and order batching had on dual tray VLM throughput. Rosi et al. (2016) determined the parameters of a single tray VLM that generated the lowest cycle times. They noticed that shorter VLM heights with higher velocity profiles performed best. Lenoble et al. (2018) created a model to optimize the batching of orders for the fastest throughput in a single-tray VLM system. The orders to be processed by the VLM were given in advance, and their batching approach significantly increased throughput compared to random batching, with minimized tray visits needed. The model also accounted for an operator servicing multiple VLMs in a pod configuration. Calzavara et al. (2019) conducted an economic evaluation of single-tray VLM systems. The model compared the profitability of the VLM system with that of traditional warehouse storage systems. Sgarbossa et al. (2019) examined the effects of class-based storage and sequential retrievals in a dual-tray VLM system. They found that class-based storage and their algorithm for sequential retrievals increased throughput. Combined, however, they had a negligible effect on throughput. None of the articles evaluated the replenishment process of stocked-out goods, and none had done so using another AS/RS.

Vanhauweermeiren et al. (2020) found that companies that adopt VLM technologies consider them too slow for efficient order picking. Serafini and Ukovich (1989) provided a model for the sequence in which items should be retrieved within an AS/RS system. Potrc et al. (2004) created a simulation model of a multi-shuttle system. Eder (2019) sought to predict service times of a tier captive shuttle-based system analytically. Optimization was done through mathematical means, exploring what size of the aisle provided the lowest service time. Lerher et al. (2017) performed a parametric study of multiplier shuttle systems. Singh et al. (2019) proposed a hybrid model using DES and ABM, analyzing the throughput performance of horizontal and vertical storage systems. Marolt et al. (2022) proposed a binary integer programming model to minimize exchange of totes between a VLM and SBS/RS integrated system. Table 1 summarizes the discussed literature.

Table 1: Literature review matrix.

References	VLM	AS/RS or SBS/RS	Random Storage	DES	ABM
Meller and Klote (2004)	✓		✓		
Dukic et al. (2015)	✓		✓		
Battini et al. (2016)	✓				
Rosi et al. (2016)	✓		✓	✓	
Lenoble et al. (2018)	✓		✓	✓	
Calzavara et al. (2019)	✓		✓		
Sgarbossa et al. (2019)	✓		✓		
Serafini and Ukovich (1989)		✓			
Potrc et al. (2004)		✓	✓	✓	
Eder (2019)		✓	✓		
Lerher et al. (2017)		✓	✓		
Singh et al. (2019)	✓			✓	✓
Vanhauweermeiren et al. (2020)	✓				
Marolt et al. (2022)	✓	✓			
Proposed model	✓	✓	✓	✓	✓

As presented in Table 1, limited research has been conducted to study the VLM-SBS/RS configuration. Researchers have evaluated VLM and SBS/RS systems independently using probabilistic, DES, and other mathematical models. However, current research explores the possibility of utilizing the hybrid modeling approach to simulate the VLM-SBS/RS system.

3 SYSTEM CONFIGURATION

The integration of a VLM and a buffer system, such as SBS/RS, creates a hybrid storage and retrieval setup that combines the strengths of both systems. Below we provide a description of the proposed systems configuration.

VLM:
The VLM is a tall, vertical storage system consisting of multiple trays or shelves arranged in a vertical column (Figure 1). Each tray is divided into compartments or bins that can hold individual items or containers. A vertical lift mechanism moves up and down within the VLM, retrieving trays and presenting them to an access point for picking or storage. The VLM is positioned in front of the operator, with the buffer (SBS/RS) system behind it, and a conveyor to the left of the operator for transporting picked items. The VLM has different trays for various items, with one tray reserved for order-picking and another tray at the back for replenishing and rearranging totes.

Buffer System (SBS/RS):
The buffer system, represented here by an SBS/RS, can include multiple shuttle carriers that move horizontally and vertically within a storage rack structure. The shuttle carriers transport storage containers, such as bins or totes, to and from storage locations within the rack. In an SBS/RS, the shuttle that transports products or materials between different levels or locations within the storage system is a crucial component of AS/RS and is typically rectangular or cuboid-shaped with a motorized drive mechanism, wheels or rollers, and sensors. It moves along a fixed track or rail system, either horizontally or vertically. Its primary function is to transport products or materials to their intended storage or retrieval location. An AS/RS works with other components, such as conveyors, cranes, and lifts, to efficiently store and retrieve products. When a request for product retrieval is processed via an order list, the model sends a signal to the shuttle to retrieve the specified product. The shuttle(s) then moves to the designated storage location, picks up the product, and transports it to the designated retrieval location, where a human operator or other equipment picks it up. The use of multiple shuttles in AS/RS can significantly improve storage density, throughput, and efficiency, making it an ideal solution for high-volume storage and retrieval operations.

Integration Configuration:
In this integrated configuration, the VLM and the SBS/RS are connected, synchronized, and simulated to work together seamlessly. The VLM serves as the primary storage and retrieval mechanism for the system, housing a portion of the inventory in its trays. Each tray has ten totes, and each tote can store up to 100 products of the same item. The buffer system, represented by the SBS/RS, acts as an auxiliary storage and retrieval component that supplements the VLM's capacity by storing a significant portion of the inventory in its trays. When the VLM reaches its capacity limit or requires additional space for incoming items, the buffer system comes into play. Items or containers that cannot be accommodated in the VLM at a given time are temporarily stored in the buffer system until space becomes available in the VLM. The integration is managed by control software that ensures efficient retrieval and storage operations.

3.1 Simulation Model

The process of handling a given order by the VLM-Buffer and stand-alone VLM system is described in the model flowchart presented in Figure 2. A hybrid, DES-ABM was used to program the logic of the system using AnyLogic simulation software (AnyLogic 2024). The modeling decision of using a hybrid DES and ABM approach to program the logic of the integrated VLM-SBS/RS system using AnyLogic was made for several reasons.

First, DES is well-suited for modeling and analyzing the sequential processes and workflows of the VLM and SBS/RS. It excels in scenarios where events occur at discrete points in time, such as the movement of trays in the VLM or shuttles in the SBS/RS. Second, DES also effectively manages the allocation and utilization of resources, such as the shuttles, trays, and conveyors, ensuring optimal operational efficiency. Finally, DES helps us collect the precise performance metrics like throughput, utilization rates, and cycle times, which are crucial for evaluating the efficiency of the integrated system VLM-SBS.

On the other-hand, ABM allows for the modeling of individual components (agents) within the system, such as shuttles, operators, and control software, each with distinct behaviors and interactions. ABM captures the dynamic behaviors and interactions of agents, which is essential for understanding the emergent properties of the integrated system. For example, how shuttles in the SBS/RS interact with the VLM or how operators respond to varying workloads. Further, implementing ABM allows for model scalability. AnyLogic's ABM handles the complexity of interactions within the system, making it scalable for different operational scenarios and varying levels of system activity or configurations. The integration and combined strengths offered by the hybrid modeling approach leverages the strengths of both DES and ABM within AnyLogic, providing a more comprehensive modeling framework. DES handles the detailed process flows and resource management, while ABM captures the individual behaviors and interactions, leading to a more accurate and holistic simulation. Lastly, AnyLogic's ability to integrate DES and ABM seamlessly allows for the synchronized operation of the VLM and SBS/RS. This integration ensures that the control software can manage the interactions between the systems efficiently, optimizing storage and retrieval operations.

The flowchart describes the steps in our VLM simulation process:

1. A randomized order consisting of specific sequences of ID product numbers or SKUs with corresponding quantities is placed.
2. From a database containing SKU requests, a signal will request an SKU number from the VLM.
3. If the SKU is in the VLM, the lift will then vertically retrieve the tray where that SKU resides.
4. VLM lift will retrieve the tray with the given SKU.
5. Carrying the tray with SKU, the VLM will travel to the height of the picking station.
6. The lift will deposit the tray at the picking station's opening location.
7. The operator will pick up the requested items from the VLM tray.
8. After the picking, the automated VLM lift will return the tray containing SKU to its original shelf in the system.
9. The system will retrieve the next pending SKUs in the order list, restarting this process at Step 1.

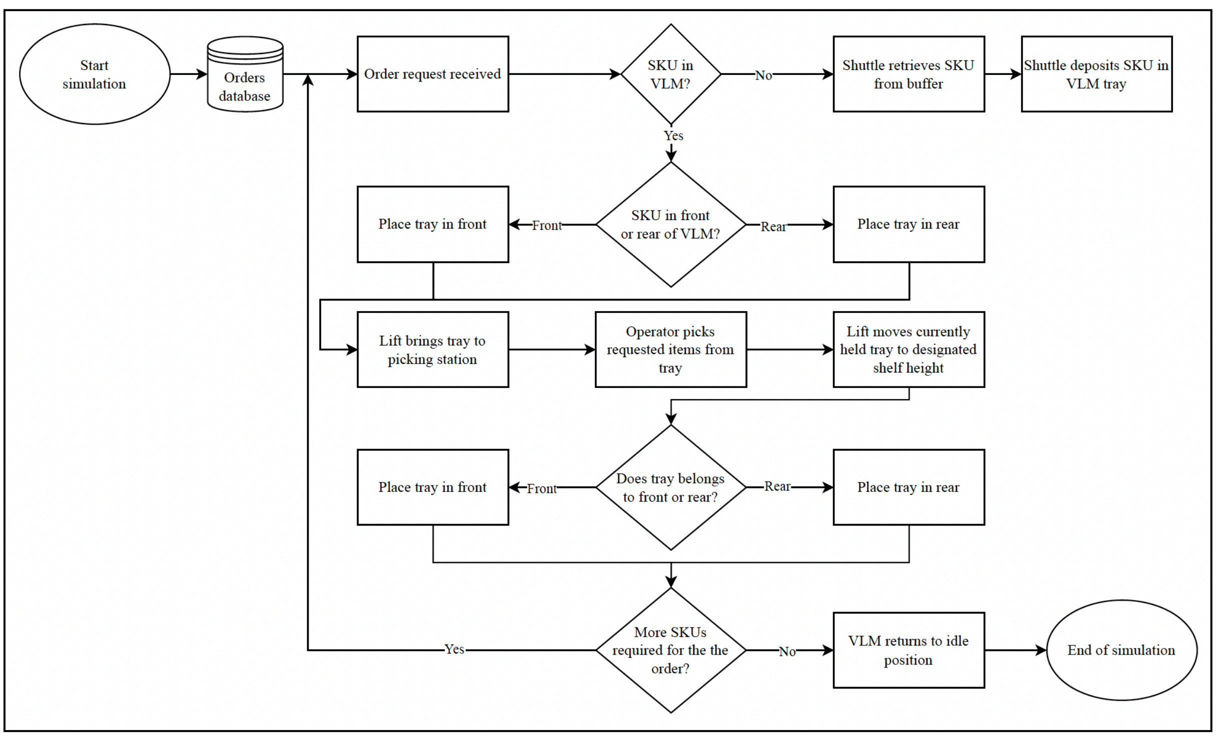


Figure 2: Simulation model flowchart.

Parameters of the simulation model are summarized in Table 2.

Table 2: Model parameters.

h_{VLM}	Height of VLM shelf	Meters, m
h_{buffer}	Height of buffer shelf	Meters, m
$c_{shuttle}$	SKU capacity of the shuttle	Positive integer
s_{VLM}	Number of shelves in VLM	Positive integer
c_{buffer}	SKU capacity of buffer	Positive integer
s_{buffer}	Number of shelves in buffer	Positive integer
$v_{h,shuttle}$	Max horizontal speed of shuttle	Meters per Second, m/s
$v_{v,shuttle}$	Max vertical speed of shuttle	Meters per Second, m/s
$a_{h,shuttle}$	Horizontal acceleration of shuttle	Meters per Second squared, m/s^2
$a_{v,shuttle}$	Vertical acceleration of shuttle	Meters per Second squared, m/s^2
a_{lift}	Acceleration of VLM lift	Meters per Second squared, m/s^2
v_{lift}	Max Velocity of VLM lift	Meters per Second, m/s
c_{tray}	SKU capacity of VLM tray	Positive integer
$t_{shuttles}$	Shuttle multi-tier capability	Binary value, ∈ {0, 1}
n_{buffer}	Number of shuttles in buffer	Positive integer
$p_{operator}$	Operator picking time per item	Seconds, s
$r_{shuttle}$	Deposit time of shuttles	Seconds, s
r_{lift}	Deposit time of VLM lift	Seconds, s
$d_{shuttle}$	Deposit time of shuttles	Seconds, s
D_{lift}	Deposit time of VLM lift	Seconds, s

Figure 3 shows the AnyLogic simulation model logic window.

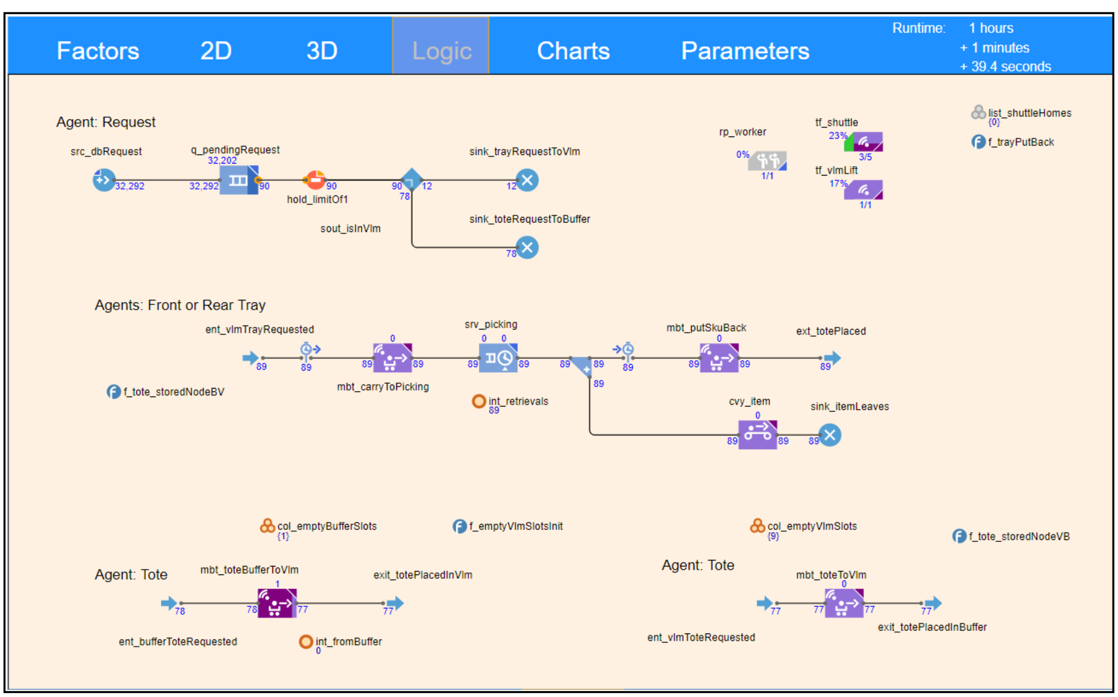


Figure 3: AnyLogic simulation model.

3.2 Design of Experiments

To compare the cycle-time and throughput of a VLM with an integrated buffer to that of a traditional stand-alone VLM, we performed experiments using the simulation model. First, we needed to model two identical VLMs, one with an integrated buffer and the other as a stand-alone VLM system. Then, a set of similar product SKUs where randomly selected, and the VLM and the VLM-Buffer systems are tasked with retrieving the items within a specified time frame. For this research, that time frame was one (1) hour. The cycle-time and throughput were measured for all our different VLM configurations (Table 3). We repeated this experiment multiple times to ensure the accuracy of the results obtained in our initial trials. To track experimental uncertainty, the experiment was replicated 12 times, twice for each VLM configuration.

Table 3: Model configurations.

Configurations	**Units**	**VLM_1**	**VLM_2**	**VLM_3**	**$(VLM+B)_1$**	**$(VLM+B)_2$**	**$(VLM+B)_3$**
Shuttle Speed, $v_{shuttle}$	m/s	2	3	4	2	3	4
Shuttle Acceleration, $a_{shuttle}$	m/s^2	1	1.5	2	1	1.5	1.5
VLM Speed, v_{lift}	m/s	2	3	4	2	3	4
VLM Acceleration, a_{lift}	m/s^2	3	5	7	3	5	7
Buffer Size, c_{buffer}	Positive integer	2000	2000	2000	2000	2000	2000
Shuttles, n_{buffer}	Positive integer	5	5	5	5	5	5
VLM Levels, s_{VLM}	Positive Integer	25	25	25	25	25	25
Buffer Levels, s_{buffer}	Positive integer	25	25	25	25	25	25

Finally, the collected throughput and cycle-time data were analyzed to determine system configuration with a better cycle-time and throughput value. Order requests were sent for SKUs contained only inside the VLM to isolate the VLM. We next engaged the SBS/RS by calling in orders for SKUs included only in the buffer. The design of experiments was tabulated, and data was collected from the model (Table 4). Total retrievals, throughput, and cycle times were tabulated.

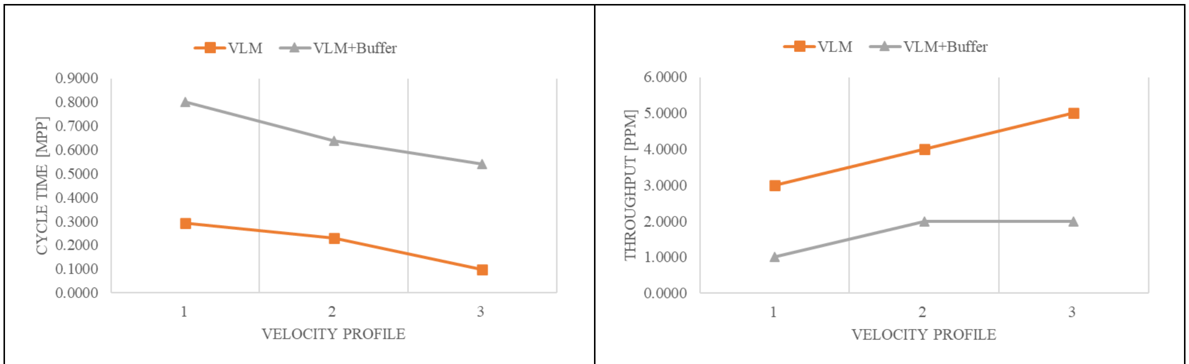
Throughput, request cycle-time, the volume of the system, shuttle service level, operator, and lift utilization are metrics of performance currently being studied in the system. The number of SKUs retrieved from the VLM in 1 hour were measured as throughput.

Table 4: Design of experiments table.

Trial	**Shuttle**		**Lift**		**Buffer**	**Response**		
	v_x	$a_x^{\pm}$	v_y	$a_y^{\pm}$	binary	Total Picks	Throughput	Cycle-time
	(m/s)	(m/s^2)	(m/s)	(m/s^2)	(0,1)	(qty.)	(Picks/min.)	(1 hr./picks)
1	2.0	1.0	2.0	3.0	0	206	3	0.0049
2	3.0	1.5	3.0	5.0	0	260	4	0.0038
3	4.0	2.0	4.0	7.0	0	303	5	0.0033
4	2.0	1.0	2.0	3.0	1	75	1	0.8000
5	3.0	1.5	3.0	5.0	1	94	2	0.6383
6	4.0	2.0	4.0	7.0	1	111	2	0.5405

4 RESULTS

Figure 3 below summarizes the cycle-time and throughput of the for three (3) different VLM and VLM+Buffer configurations. These were analyzed according to three (3) different velocity profiles of the lift and shuttle (Table 3).



CYCLE-TIME [units] = Minutes Per Pick [MPP]	THROUGHPUT [units] = Picks Per minute [PPM]

Figure 3: Throughput and cycle-time plots.

These metrics were calculated based on the number of picks per minute (PPM) that the VLM-SBS/RS could deliver to the picking area and the time it took to complete a certain number of picks within one hour (60 min) of operation, provided in picks per minute (PPM). The system configurations for the comparisons of the simulated systems made below are provided previously in Table 4.

A precise observation we can rapidly make is that throughput generally increases with increasing velocity profiles. Thus, the picking time per SKU decreases if the VLM and SBS/RS system has a higher velocity profile. Additional observations:

1. For all VLM velocity profiles (1-3), throughput capacity increases with system velocity, and as should be expected, a faster-moving system delivers faster.
2. Except for Velocity profile 3, all VLM and SBS/RS configurations perform better with increasing velocity and acceleration configurations.
3. The comparison shows that Velocity Profile 3, with randomly distributed order requests for the VLM system, performed better than the rest. The same cannot be said about the VLM and SBS/RS systems for the same Velocity Profile.
4. The cycle-time for the models confirms our general belief: If picking time is reduced, the throughput capacity of the VLM and SBS/RS system increases.
5. Picking times in our simulation model are between 17.5 and 32.4 seconds per SKU. In the case of a Shuttle speed of 2 m/s and a VLM lift acceleration of 3 m/s2, the throughput capacity of the VLM is 4 PPM. The VLM and SBS/RS system's capacity was 2 PPM under the same configuration.

The built-in flexibility of our AnyLogic DES and ABM model allows for additional VLM and SBS/RS system modeling configurations. Our current model considers a single lift in the VLM. Since throughput and cycle-time are paramount to this research, modeling our simulation with a second lift for the VLM could provide improved results. As noted by Vanhauwermeinren et al. (2020), adding a second lift could increase the throughput capacity by 50%, and optimizing the order sequencing could increase system capacity by 80%.

The VLM can process a larger volume of goods by optimizing throughput, reducing the cycles required, and increasing its overall productivity. This can lead to cost savings, increased customer satisfaction, and improved supply chain management. Optimizing throughput can also ensure the VLM operates at its maximum capacity, reducing downtime and maintenance needs.

Replenishment activities are crucial in all warehouse management environments. However, our simulation model did not consider replenishment strategies in the VLM-Buffer system and shall be the subject matter for future work. In our current working model, the inventory of each SKU tote will not be replenished. We are more concerned about the variety of available items the system can provide than the quantity per tote. In a warehouse environment, items can be subjected to changes of location from time to time due to item demand, item re-classification, or to make way for new and inventories. Since this cannot be easily foreseen, it was therefore not considered within our current simulation model's framework. Consequently, all items are therefore assumed to have fixed locations, insofar as all items currently contained in the VLM-SBS/RS systems, these are assumed to have been in their existing location and are to remain fixed in their locations for the entire duration of our simulations.

5 CONCLUSION AND FUTURE WORK

In conclusion, this research demonstrated a proof-of-concept hybrid simulation model of an integrated VLM and buffer system using AnyLogic. An ABM and DES model of the system was developed, and its performance was evaluated under various scenarios and conditions. The simulation can be used by warehouse managers and logistics professionals to evaluate the potential benefits of a VLM system for their operations and to optimize the design of the VLM system. Although it may be challenging to predict the future with certainty, this research illuminates that VLMs will likely continue to gain popularity and become much more widespread in the coming years. With the prevailing trend towards automation and increased efficiency in material handling and storage operations, the benefits offered by VLMs, such as increased storage density, improved inventory management, and faster picking operations, all suggest that VLMs will become increasingly prevalent in warehousing facilities. Although the pace of adoption of such systems will depend on various factors, integrated VLM-SBS/RS systems can play an essential role in the future of material handling and storage operations. These technologies, combined with simulation modeling applications, offer exciting and significant benefits that are difficult to achieve with existing traditional storage and retrieval methods.

Future work will address several limitations and areas for improvement identified in this research. Currently, the simulation model does not include replenishment strategies, which are essential for maintaining system efficiency over time. We will focus on incorporating these strategies in future studies. The model also considers only a single lift in the VLM, potentially underrepresenting the system's capabilities. Future research will explore configurations with multiple lifts to provide a more comprehensive analysis of their integration. Moreover, the assumption of static item locations in the current model does not reflect the dynamic nature of warehouse operations. Future models will account for this variability to enhance modeling accuracy. Additionally, a thorough revision of the experimental design will be provided in the future to include more variations and different configurations for our proposed system, which could yield more significant results and insights. The experiments conducted in this work mainly focus on comparing the integrated system with a stand-alone VLM. Future work will include more varied scenarios to provide a more comprehensive analysis. Practical challenges such as cost, and complexity of integration are acknowledged but not deeply explored in the current research. Future studies will delve deeper into these aspects to provide more practical insights.

ACKNOWLEDGMENTS

The authors would like to thank Jesse Contreras for his support during the study.

REFERENCES

Accorsi, R., R. Manzini, and M. Bortolini. 2012. "A Hierarchical Procedure for Storage Allocation and Assignment within an Order-Picking System. A Case Study". *International Journal of Logistics Research and Applications* 15(6): 351-364.

Grosse, E. H., C. H. Glock, and W.P. Neumann. 2017. "Human Factors in Order Picking: A Content Analysis of the Literature". *International Journal of Production Research* 55(5): 1260-1276.

De Koster, R., T. Le-Duc, and K. J. Roodbergen. 2007. "Design and Control of Warehouse Order Picking: A Literature Review". *European Journal of Operational Research* 182(2): 481-501.

Tompkins, J. A., J. A. White, Y.A. Bozer, and J. M. A. Tanchoco. 2010. *Facilities Planning*. John Wiley & Sons.

Richter, F. 2019. "Infographic: Retailers Lose Billions to Theft, Fraud and Human Error". Statista Daily Data. https://www.statista.com/chart/16609/sources-of-inventory-shrinkage-suffered-by-us-retailers/.

National Safety Council (NSC). 2021. Technical Appendix: https://injuryfacts.nsc.org/technical-appendix/costs/.

Occupational Safety and Health Administration (OSHA), 2019.

U.S. Bureau of Labor Statistics. 2023. National Census of Fatal Occupational Injuries in 2022. USDL-23-2615. U.S. Department of Labor, Washington, D.C. https://www.bls.gov/news.release/pdf/osh.pdf, accessed 19th December 2023.

Calzavara, M., F. Sgarbossa, and A. Persona. 2019. "Vertical Lift Modules for Small Items Order Picking: An Economic Evaluation". *International Journal of Production Economics* 210: 199-210.

Rosi, B., L. Grasic, and G. Dukic. 2016. Simulation-Based Performance Analysis of Automated Single-Tray Vertical Lift Module. *International Journal of Simulation Modelling* 15: 97-108.

Lerher, T., M. Borovinšek, M. Ficko, and I. Palcic. 2017. "Parametric Study of Throughput Performance in SBS/RS based on Simulation". *International Journal of Simulation Modelling* 16: 96-107.

AnyLogic 2019. "AnyLogic Simulation Software". www.anylogic.com.

Marolt, J., G. Đukić, F. Sgarbossa, and T. Lerher. 2022. "An Optimisation Model for Minimising Totes Exchange in VLM and SBS/RS Integrated System". *IFAC-PapersOnLine* 55(10): 514-519.

Meller, R. D., and J. F. Klote. 2004. A Throughput Model for Carousel/VLM Pods. *IIE Transactions* 36: 725 - 741.

Dukic, G., T. Opetuk, and T. Lerher. 2015. "A Throughput Model for a Dual-Tray Vertical Lift Module with a Human Order-Picker". *International Journal of Production Economics* 170: 874-881.

Battini, D., M. Calzavara, A. Persona, and F. Sgarbossa. 2016. "Dual-tray Vertical Lift Modules for Fast Order Picking". In *14th International Material Handling Research Colloquium – 2016.*

Lenoble, N., Y. Frein, and R. Hammami. 2018. "Optimization of Order Batching in a Picking System with a Vertical Lift Module". In *Information Systems, Logistics, and Supply Chain: 6th International Conference*, ILS 2016, Bordeaux, France, June 1–4, 2016.

Sgarbossa, F., M. Calzavara, and A. Persona. 2019. "Throughput Models for a Dual-Bay VLM Order Picking System under Different Configurations". *Industrial Management & Data Systems* 119(6): 1268-1288.

Singh, N.S., K. Herps, T. Martagan, and I. J. B. F. Adan. 2019. "Simulation-Based Performance Evaluation of A Manufacturing Facility with Vertical As/Rs". In *2019 Winter Simulation Conference (WSC)*, 2001-2012, https://doi.org/10.1109/WSC40007.2019.9004715.

Vanhauwermeiren, P., M. Versteyhe, and M. Juwet. 2020. "Throughput Models for a Stand-alone Vertical Lift Module". *International Journal of Industrial and Operations Research* 3: 005.

Serafini, P. and W. Ukovich. 1989. "A Mathematical Model for Periodic Scheduling Problems". *SIAM Journal on Discrete Mathematics* 2(4): 550-581.

Potrč, I., T. Lerher, J. Kramberger, and M. Šraml. 2004. "Simulation Model of Multi-Shuttle Automated Storage and Retrieval Systems". *Journal of Materials Processing Technology* 157: 236-244.

Eder, M. 2019. "An Analytical Approach for a Performance Calculation of Shuttle-Based Storage and Retrieval Systems". *Production & Manufacturing Research* 7(1): 255-270.

AUTHOR BIOGRAPHIES

NOÉ TAVIRA, JR. is an undergraduate at the Ingram School of Engineering with a diverse range of experience in both business and academia. His primary field of study is Industrial Engineering with additional studies in Applied Mathematics and Computer Science. In the summer of 2022, he was invited to join the research team at the University's Center for High-Performance Systems (CHiPS). His research interests include: Stochastic Modeling and Simulation, Simulation-based Optimization and Decision-Making, and Digital Twins Applications for Industry 4.0. His email address is ntavira@txstate.edu.

ABHIMANYU SHAROTRY is a Research Engineer at the Ingram School of Engineering. He received his B.Tech. degree in mechanical engineering from the SRM Institute of Science and Technology, India, in 2017, and the M.Sc. degree in industrial engineering from the Ingram School of Engineering, Texas State University in 2020. His research interests include: Human Digital Twins, Simulation of manufacturing systems, Digital Twins Applications for Industry 4.0, Worker ergonomics and safety on factory floor using integrated systems. His email address is absharotry@txstate.edu.

JESUS A. JIMENEZ is a Professor and Director of the Ingram School of Engineering at Texas State University. He received his B.S. and M.S. in Industrial Engineering from The University of Texas at El Paso, and his Ph.D. in Industrial Engineering from Arizona State University. His research interests are in modeling and analysis of manufacturing systems; data intensive analysis & simulation; and digital twins. His email address is jesus.jimenez@txstate.edu.

JAKOB MAROLT is a teaching assistant at Faculty of Logistics at the University of Maribor and a member of the Laboratory for Cognitive Systems in Logistics. Currently he is a PhD student under prof. Tone Lerher at the Faculty of Mechanical Engineering, UM. His research interests are numerical modelling, operation research and optimization in the field of material handling systems and warehousing. He is an author and co-author of original scientific papers in the International Journal of Production Research, International Journal of Advanced Manufacturing Technology and International Journal of Simulation Modelling. His email address is jakob.marolt@um.si.

TONE LERHER is Professor of Logistics Engineering and Structures of Material Handling Systems at the University of Maribor, Faculty of Logistics and Faculty of Mechanical Engineering (http://www.um.si/). In his career he has worked as a senior researcher in applied and basic research projects from the research area Material Handling Systems and warehousing. He is also a member of professional associations such as Society of Mechanical Engineers Maribor, Slovenian Institute of Standardization, Verein Netzwerk Logistik, etc. In 2018, he received the Best Paper Award 2018 from IJPR for the paper entitled "Travel time model for double-deep shuttle-based storage and retrieval systems". Last but not least, he is an author and co-author of original scientific papers in distinguished academic journals such as International Journal of Production Research, International Journal of Advanced Manufacturing Technology, International Journal of Production Economics and others. His email address is tone.lerher@um.si.