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Advanced Technologies in Logistics Engineering: Automated Storage Systems with Shuttles integrated with Hoisted Carriage

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Abstract: This paper presents automated storage systems with shuttles integrated with hoisted carriage for successful application in intralogistics. The first part of the paper presents classic and advanced AVS/RS along with specific intralogistics automation systems known as AutoStore from Swisslog and Skypod from Exotec. The second part of the paper focuses on an advanced system with shuttle vehicles capable of serving multiple tiers of the storage rack. An analytical model for the shuttle vehicles capable of serving multiple tiers of the storage rack is presented, which is based on (*i*) the sequences of acceleration, constant velocity and deceleration, and (*ii*) randomised assignment policy. Based on the presented model, the expected Single Command (SC) and Dual Command (DC) travel (cycle) time as well as the throughput performance of the shuttle vehicles capable of serving several tiers of warehouse, could be calculated. A programme code in MATLAB has been presented for the computation of throughput performances of automated storage systems with shuttles integrated with hoisted carriage capable of serving several tiers of the storage rack.

Keywords: analytical and numerical model; automated vehicle-storage and retrieval systems AVS/RS; automated warehouses; cycle time and throughput performance; shuttles integrated with hoisted carriage

1 INTRODUCTION

The processes in Logistics are crucial for the existence of modern society, as they provide the right services at the right time. The Council of Supply Chain Management Professionals [1] defines the Logistics as an integral part of Supply Chain in the way, that it plans, implements, controls the efficient flow and storage of goods, services and related information between point of origin and consumption. Of course, Logistics services must be organised in the way that they meet the ever-increasing customer requirements.

One of the most important parts of Logistics is Intralogistics (or Internal Logistics), which ranked second in 2018 global Logistics market share [2]. Intralogistics describes the organisation, realisation and optimization of internal material flow between different logistics hubs – material flow in production, in goods distribution centres and in airports and seaports along with the related information [3]. To ensure reliable and predictable flow of physical goods in the nodes of a supply network, processes of the intralogistics domain must be as efficient as possible. Therefore, many investments in intralogistics are related to warehouses and internal transport.

The strive for more efficient processes to reduce the Carbon Greenhouse Emissions (CGH), achieve lower energy consumption and fill the gap of worker deficiency, new technologies and concepts have been proposed, such as Industry 4.0 [6] and based on its paradigms, Logistics 4.0 [7]. Automation and robotization (along with the application of collaborative robots) [8] is therefore practically a necessity to overcome all of the above challenges.

To keep up with the increasing demands of e-commerce, such as minimum order sizes, high product range, short delivery and variable order quantities [9], new types of warehouses have emerged. Conventional warehouses hardly meet those requirements, since one of the most labour-intensive and demanding processes in warehouses (both automated and non-automated) is the order-picking process [10]. Due to the order-picking process demands for high precision work and the costs associated with its automation, the process is usually at the most partially automated. Order-pickers often suffer from musculoskeletal disorders due to the poor ergonomics along with psychical stress that stems from the demand for high precision work [11]. Furthermore, the work usually takes place in multiple work shifts, which makes the work further unattractive. However, simply employing automation and robotization without highly skilled logistics employees, which are sparse, the efficiency of logistics processes does not increase. Along with the digitization [13] this is one of the major challenges in logistics [14]. Owing to the above, automation and robotization of warehousing processes are certainly key factors in warehouses of the future [12], where we see a great potential for progress.

This paper is structured as follows. Chapter 2 presents classical and advanced AVS/RS as well as specific intralogistic automation systems such as AutoStore by Swisslog and Skypod by Exotec. In chapter 3, travel-time models for automated storage systems with shuttles integrated with hoisted carriage will be presented. Finally, chapter 4 presents main conclusions.

2 AUTOMATED-VEHICLE BASED STORAGE AND RETRIEVAL SYSTEMS

The development of Automated and (autonomous) Vehicle-Based Storage and Retrieval Systems (AVS/RS) contributed significantly to warehouse automation. AVS/RS consist of storage rack with an elevator capable of executing vertical movements of stock keeping units and shuttle vehicles which are performing horizontal movements. AVS/RS are superior compared to classical crane-based AS/RS in terms of higher throughput capacity, higher flexibility and scalability, lower energy consumption, etc. AVS/RS are therefore preferentially chosen over crane-based AS/RS in practice.

A study by the European Materials Handling Federation (FEM) shows that the use of AVS/RS in practise has increased significantly since 2015 compared to other automated storage systems [15]. This confirms the fact that the application of AVS/RS in practice is effective.

The concept of using a combined lift and automatic vehicles dates back to the 1970s in the form of technical sketches and patent applications. Although the concept of a combined system for the use of elevators and automatic vehicles was relatively advanced, the technology was not sufficiently developed for practical use at that time.

In 2015, the Association of German Engineers (Verein Deutscher Ingenieure; VDI) published the technical guideline "VDI 2692 Blatt 1 - Automated vehicle storage and retrieval systems for small unit loads" [16]. Also in 2017, the European Materials Handling Federation (FEM) published the technical guideline "FEM 9.860 - Cycle time calculation for automated vehicle storage and retrieval systems" [17]. The two technical guidelines "VDI 2692 Blatt 1" and "FEM 9.860" describe in detail the individual AVS/RS components and models for calculating throughput capacity under various AVS/RS operating conditions.

2.1 Classical Automated Vehicle-Based Storage and Retrieval Systems

Classical AVS/RS are special type of automated warehouses that are used for handling totes and is comprised of the elevator with a lifting table that is moving in the vertical direction and is feeding the storage rack (Fig. 1).

The elevator's lifting table has its own drive and operates according to the non-constant ($v \neq$ constant) velocity-time relationship. The velocity of the elevator's lifting table is capable of reaching up to v_y = 6 m/s, meanwhile the acceleration/ deceleration can reach up to a_y = 5 m/s^2. The elevator's lifting table operates on single and dual command sequence.

The Storage Rack (SR) consists of columns in the horizontal direction and tiers in the vertical direction. The maximum length of the SR could reach up to L_{SR} = 100 m, while the maximum height of the SR could reach up to H_{SR} = 15 m. A buffer location is situated at the beginning of each tier, where totes are delivered by the elevator's lifting table. Delivered totes wait for a shuttle vehicle to be transferred in the SR.

In each tier of the SR is a single tier-captive shuttle vehicle that is traveling in the horizontal direction (Fig. 2).

The shuttle vehicle is an automatic vehicle with four wheels, capable of carrying loads of up to 50 kg. It has its own drive and operates according to the non-constant ($v \neq$ constant) velocity-time relationship. The velocity of the shuttle vehicle can reach up to v_x = 3 m/s, meanwhile the acceleration/ deceleration can reach up to a_x = 2 m/s^2. The shuttle vehicle operates on single and dual command sequence.

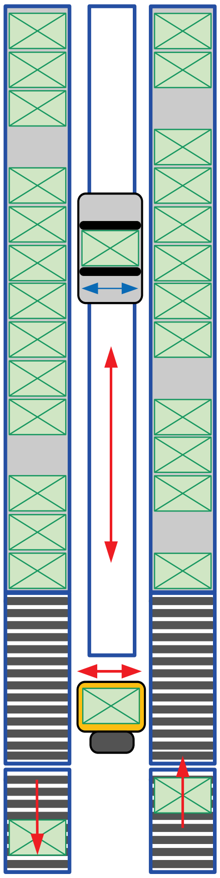

Figure 1 Layout of the Classical AVS/RS

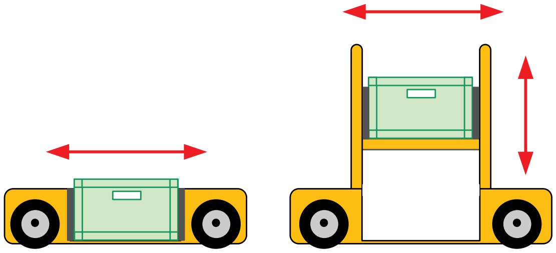

Figure 2 Shuttle vehicle

2.2 Advanced Vehicle-Based Storage and Retrieval Systems

Throughput performance of the elevator's lifting table and shuttle carriers depends on the number of transactions for the single and dual cycles. According to a sequential processing policy, a throughput performance of the elevator's lifting table and shuttle carriers is calculated individually for both material handling devices. Usually, it happens that the elevator's lifting table is not capable of keeping up with the shuttle carriers and, therefore, it works with max. utilization ($>> \eta_{LIFT}$). On the other hand, shuttle carriers work with relatively low utilization ($<< \eta_{SCAR}$) especially with short types of storage rack as they wait in idle mode for tasks to be performed. The most efficient design of the AVS/RS will be achieved when the elevator's lifting table and shuttle carriers utilization will be maximum ($\eta_{LIFT} = \eta_{SCAR} \approx 1.0$). This problem can be solved by using other designs of AVS/RS as follows (Figs. 3, 4, 5).

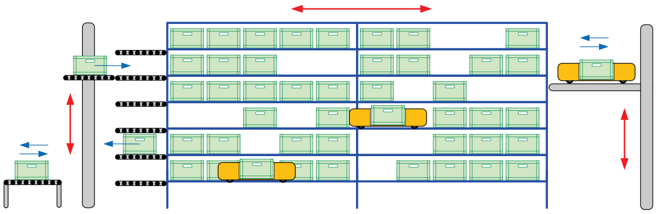

Figure 3 Tier-to-tier AVS/RS

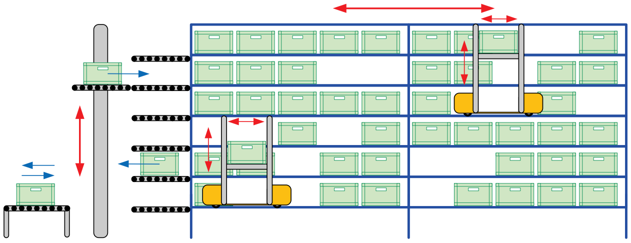

Figure 4 AVS/RS with shuttles integrated with hoisted carriage

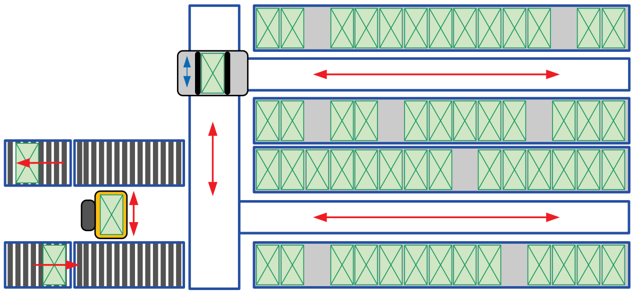

Figure 5 3D-level-captive shuttle carriers in AVS/RS

2.3 Specific Automated Vehicles-Based Storage and Retrieval Systems

AutoStore is a unique solution that uses robots and bins to quickly process small parts orders. AutoStore provides better use of available space than any other automated system thanks to its unique design that enables direct stacking of bins on top of each other and storage of multiple SKUs in a single bin (Fig. 6) [18].

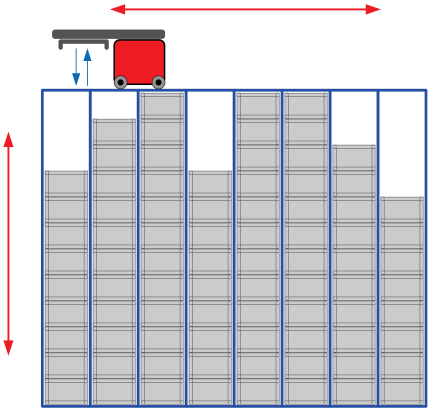

Figure 6 Autostore Swisslog

Skypod (Fig. 7) is a retail order picking solution, which offers the best performance on the market while remaining flexible and adaptable to the customer's needs. The system sizing considers storage requirements and flows independently. This allows extreme adaptability to customer's specifications and allows subsequent phasing as needs evolve [19].

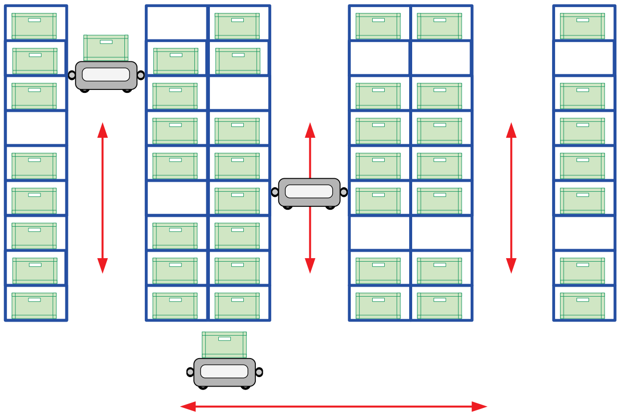

Figure 7 Skypod Exotec

3 MODEL FOR THE THROUGHPUT PERFORMANCE OF AUTOMATED STORAGE SYSTEMS WITH SHUTTLES INTEGRATED WITH HOISTED CARRIAGE

Throughput capacity of automated storage systems with shuttles integrated with hoisted carriage is inversely dependant from the travel (cycle) times of the shuttle vehicles.

Note: In this research paper, the elevator will not be included, although is very important part in a system throughput performance of AVS/RS.

Cycle time of automated storage systems with shuttles integrated with hoisted carriage, which are capable of serving numerous tiers of the storage rack is founded on the analytical travel-time model with the assumption on a non-constant velocity time distribution (the sequence of acceleration, constant velocity, and deceleration) and the probability theory.

The proposed model is based on the following assumptions:

- The AVS/RS is divided into SR on both sides (left and right). Totes can be therefore stored at either side in i^{th} tier of the AVS/RS.
- The I/O location is located at the first tier of the SR.
- The dwell-point location of the shuttle vehicle in the i^{th} tier of the SR (when idle) is located at the I/O$_i$ buffer location.
- The SR is divided by columns and tiers.
- At each level of the SR, there are two buffer locations (left and right) and a single shuttle vehicle capable of serving numerous tiers of SR. One level is combined by individual number of tiers.
- The shuttle vehicle works on a Single Command (SC) and on Dual Command (DC) cycles.
- The sequence of (i) Acceleration, constant velocity and deceleration have been used.
- The shuttle vehicle travels simultaneously in the horizontal (x) and vertical (y) directions.
- The shuttle vehicle's drive characteristics, as well as the length L_{SR} of the SR, are known in advance.

- The shuttle vehicle can reach its maximum velocity $v_{\max}$ in the horizontal (x) direction, as the length L_{SR} of the SR is large enough.
- A randomized assignment policy is chosen meaning any storage location is equally likely to be selected for storage or retrieval location to be processed by the shuttle vehicle capable of serving numerous tiers of SR.

Abbreviation

AS/RS	Automated storage and retrieval systems.
AVS/RS	Automated Vehicles-Based Storage and Retrieval Systems.
DC	Dual command.
LIFT	Elevator (elevator's lifting table).
I/O	Input/output location.
MTC	Multi-tier-captive.
SCAR	Shuttle vehicle capable of serving numerous tiers of SR.
SC	Single command.
SR	Storage rack.

Notations

L_{SR}	–	length of the storage rack.
H_{SR}	–	height of the storage rack.
H_{LEVEL}	–	height of one level of the storage rack.
H_{TIER}	–	height of one tier of the storage rack.
v	–	velocity.
a	–	acceleration/deceleration.
b	–	shape factor.
A	–	surface of the storage rack.
$E(\mathrm{SC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}}$	–	the expected single command cycle time ($b \leq 1$).
$E(\mathrm{SC}_2)_{\mathrm{SCAR}}^{\mathrm{MTC}}$	–	the expected single command cycle time ($b > 1$).
$\lambda(\mathrm{SC})_{\mathrm{SCAR}}^{\mathrm{MTC}}$	–	throughput capacity of the single command cycle time.
$E(\mathrm{DC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}}$	–	the expected dual command cycle time ($b \leq 1$).
$E(\mathrm{DC}_2)_{\mathrm{SCAR}}^{\mathrm{MTC}}$	–	the expected dual command cycle time ($b > 1$).
$\lambda(\mathrm{DC})_{\mathrm{SCAR}}^{\mathrm{MTC}}$	–	throughput capacity of the dual command cycle time.
$t_{\mathrm{P/S\,SCAR}}^{\mathrm{MTC}}$	–	time to pick up and set down the load.

Based on work of Gudehus [20], the expressions for SC and DC cycles along with throughput performance have been developed.

In continuation the expressions $E(\mathrm{SC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}}$, $E(\mathrm{SC}_2)_{\mathrm{SCAR}}^{\mathrm{MTC}}$ and $\lambda(\mathrm{SC})_{\mathrm{SCAR}}^{\mathrm{MTC}}$ for single command cycle along with the expressions $E(\mathrm{DC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}}$, $E(\mathrm{DC}_2)_{\mathrm{SCAR}}^{\mathrm{MTC}}$ in $\lambda(\mathrm{DC})_{\mathrm{SCAR}}^{\mathrm{MTC}}$ for dual command cycles will be presented.

Shape factor (b) of one level of the AVS/RS equals Eq. (1):

$$b = \frac{H_{\mathrm{LEVEL}}}{L_{\mathrm{SR}}} \cdot \frac{v_x}{v_y} \tag{1}$$

Note: According to Fig. 8, one level of the storage rack represents 3 consecutive tiers.

Surface of one level of SR (A) equals Eq. (2):

$$A = H_{\mathrm{LEVEL}} \cdot L_{\mathrm{SR}} = \mathrm{const.} \tag{2}$$

Single command cycle of automated storage systems with shuttles integrated with hoisted carriage

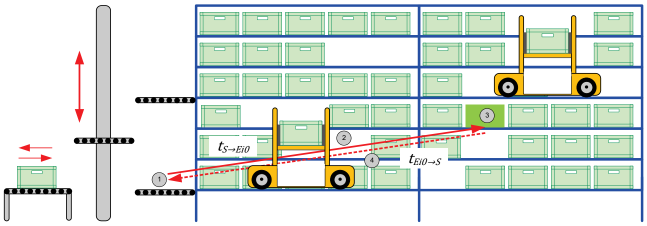

Figure 8 Single command cycle of automated storage systems with shuttles integrated with hoisted carriage

Note: (1) – I/O location, (2) – travelling of the shuttle vehicle to destination storage location (3), (4) – travelling of the shuttle vehicle to (1); Fig. 8.

The expected single command cycle time $E(\mathrm{SC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}}$, when ($b \leq 1$) equals Eq. (3):

$$E(\mathrm{SC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}} = 2 \cdot t_{\mathrm{P/S\,SCAR}}^{\mathrm{MTC}} + \frac{L_{\mathrm{SR}}}{v_x} + \frac{2v_x}{a_x} + \frac{A \cdot v_x}{L_{\mathrm{SR}}^2 \cdot a_y} + \frac{A^2 \cdot v_x}{3L_{\mathrm{SR}}^3 \cdot v_y^2} - \frac{A \cdot v_x^2}{L_{\mathrm{SR}}^2 \cdot a_x \cdot v_y} \tag{3}$$

The expected single command cycle time $E(\mathrm{SC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}}$, when ($b > 1$) equals Eq. (4):

$$E(\mathrm{SC}_2)_{\mathrm{SCAR}}^{\mathrm{MTC}} = 2 \cdot t_{\mathrm{P/S\,SCAR}}^{\mathrm{MTC}} + \frac{A}{L_{\mathrm{SR}} \cdot v_y} + \frac{2v_y}{a_y} + \frac{L_{\mathrm{SR}}^2 \cdot v_y}{A \cdot a_x} + \frac{L_{\mathrm{SR}}^3 \cdot v_y}{3A \cdot v_x^2} - \frac{L_{\mathrm{SR}}^2 \cdot v_y^2}{A \cdot a_y \cdot v_x} \tag{4}$$

Throughput capacity of the single command cycle time $\lambda(\mathrm{SC})_{\mathrm{SCAR}}^{\mathrm{MTC}}$ equals Eq. (5):

$$\lambda(\mathrm{SC})_{\mathrm{SCAR}}^{\mathrm{MTC}} = \frac{3600}{E(\mathrm{SC}_i)_{\mathrm{SCAR}}^{\mathrm{MTC}}} \cdot 1 \tag{5}$$

Dual command cycle of automated storage systems with shuttles integrated with hoisted carriage

The expected dual command cycle time $E(\mathrm{DC}_1)_{\mathrm{SCAR}}^{\mathrm{MTC}}$, when ($b \leq 1$) equals Eq. (6):

$$E(\mathrm{DC}_1)^{\mathrm{MTC}}_{\mathrm{SCAR}} = 4 \cdot t^{\mathrm{MTC}}_{\mathrm{P/S\,SCAR}} + \frac{4L_{\mathrm{SR}}}{3v_x} + \frac{3v_x}{a_x} + \frac{3A \cdot v_x}{2L^2_{\mathrm{SR}} \cdot a_y} - \frac{A^3 \cdot v_x^2}{30L^5_{\mathrm{SR}} \cdot v_y^3} + \frac{A^2 \cdot v_x}{2L^3_{\mathrm{SR}} \cdot v_y^2} - \frac{3A \cdot v_x^2}{2L^2_{\mathrm{SR}} \cdot a_x \cdot v_y} \tag{6}$$

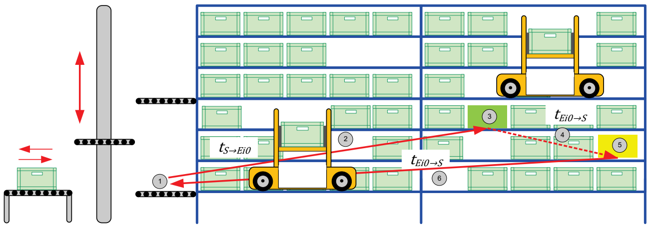

Figure 9 Dual command cycle of automated storage systems with shuttles integrated with hoisted carriage

Note: (1) – I/O location, (2) – travelling of the shuttle vehicle to destination storage location (3), (4) – travelling of the shuttle vehicle to retrieval location (5), (6) – travelling of the shuttle vehicle to (1); Fig. 9.

The expected dual command cycle time $E(\mathrm{DC}_2)^{\mathrm{MTC}}_{\mathrm{SCAR}}$, when ($b > 1$) equals Eq. (7):

$$E(\mathrm{DC}_2)^{\mathrm{MTC}}_{\mathrm{SCAR}} = 4 \cdot t^{\mathrm{MTC}}_{\mathrm{P/S\,SCAR}} + \frac{4A}{3L_{SR}v_y} + \frac{3v_y}{a_y} + \frac{2L^2_{\mathrm{SR}} \cdot v_y}{2A \cdot a_x} - \frac{L^5_{\mathrm{SR}} \cdot v_y^2}{30A^2 \cdot v_x^3} + \frac{L^3_{\mathrm{SR}} \cdot v_y}{2A \cdot v_x^2} - \frac{3L^2_{\mathrm{SR}} \cdot v_y^2}{2A \cdot a_y \cdot v_x} \tag{7}$$

Throughput capacity of the dual command cycle time $\lambda(\mathrm{DC})^{\mathrm{MTC}}_{\mathrm{SCAR}}$ equals Eq. (8):

$$\lambda(\mathrm{DC})^{\mathrm{MTC}}_{\mathrm{SCAR}} = \frac{3600}{E(\mathrm{DC}_i)^{\mathrm{MTC}}_{\mathrm{SCAR}}} \cdot 2 \tag{8}$$

Note: for more complex AVS/RS analytical model that is based on travelling of the shuttle vehicles capable of serving numerous tiers of SR with (*i*) acceleration and deceleration and (*ii*) acceleration, constant velocity and deceleration, see paper from Lerher et al. [21].

For the performance calculation of automated storage systems with shuttles integrated with hoisted carriage, a programme in MATLAB has been developed.

A calculation of SC and DC cycle times along with the throughput performances is presented by using the following parameters: $L_{\mathrm{SR}} = 30$ m, $H_{\mathrm{LEVEL}} = 2{,}1$ m, $v_x = 2{,}5$ m/s, $v_y = 2$ m/s, $a_x = 1{,}5$ m/s^2, $a_y = 1{,}5$ m/s^2, $t^{\mathrm{MTC}}_{\mathrm{P/S\,SCAR}} = 3{,}4$ s.

Note: $H_{\mathrm{LEVEL}} = 2{,}1$ m which means that one level has 6 consecutive tiers; hight of the tier equals $H_{\mathrm{TIER}} = 0{,}35$ m.

```
 %Input data

H_SR = 2.1 %m
L_SR = 30 %m
vel_x = 2.5 %m/s
vel_y = 2 %m/s
acc_x = 1.5 %m/s^2
acc_y = 1.5 %m/s^2
T_PS = 3.4 %s

%Single command cycle

%Shape factor

b=(H_SR/L_SR)*(vel_x/vel_y)

%Surface of the storage rack

A=H_SR*L_SR

if b<=1

    E_SC_1 =
2*T_PS+(L_SR/vel_x)+((2*vel_x)/acc_x)+((A*ve
l_x)/(L_SR^2*acc_y))+((A^2*vel_x)/(3*power(L
_SR,3)*vel_y^2))-
(A*vel_x^2)/(L_SR^2*acc_x*vel_y)
    L_SC_1 = 3600/E_SC_1

elseif b>1

    E_SC_2 = 2*T_PS +
(A/(L_SR*vel_y))+((2*vel_y)/acc_y)+((L_SR^2*
vel_y)/(A*acc_x))+((power(L_SR,3)*vel_y)/(3*
A*vel_x^2))-
((L_SR^2*vel_y^2)/(A*acc_y*vel_x))
    L_SC_2 = 3600/E_SC_2

end

%Double command cycle

if b<=1

E_DC_1 =
4*T_PS+((4*L_SR)/(3*vel_x))+((3*vel_x)/(acc_
x))+((3*A*vel_x)/(2*L_SR^2*acc_y))-
((power(A,3)*vel_x^2)/(30*power(L_SR,5)*powe
r(vel_y,3)))+((A^2*vel_x)/(2*power(L_SR,3)*v
el_y^2))-
((3*A*vel_x^2)/(2*L_SR^2*acc_x*vel_y))
    L_DC1 = (3600/E_DC_1)*2

elseif b>1

E_DC_2 =
4*T_PS+((4*A)/(3*L_SR*vel_y))+((3*vel_y)/acc
_y)+((2*L_SR^2*vel_y)/(2*A*acc_x))-
((power(L_SR,5)*vel_y^2)/(30*A^2*vel_x^3))+(
(power(L_SR,3)*vel_y)/(2*A*vel_x^2))-
((3*L_SR^2*vel_y^2)/(2*A*acc_y*vel_x))
    L_DC2 = (3600/E_DC_2)*2

end
```

```
%Results

b = 0.0875 %/

A = 63 %m^2

E_SC_1 = 22.1348 %s

L_SC_1 = 162.6399 %totes/hour

E_DC_1 = 34.6019 %s

L_DC1 = 208.0809 %totes/hour
```

4 CONCLUSIONS

The aim of this paper is to present a specific design for an automated storage systems with shuttles integrated with hoisted carriage, which can move synchronously parallel, and vertically.

An analytical model for calculating the throughput performance of an AVS/RS with shuttle vehicles capable of serving numerous tiers of SR was presented. The proposed model assumes the condition of a non-constant velocity (sequence of acceleration, constant velocity and deceleration) of the shuttle vehicle and a randomised allocation policy for the storage and retrieval requests. A programme in MATLAB has been developed for the performance calculation.

The advantages of the proposed analytical and numerical model are that it is relatively simple and quick to evaluate the performance of automated storage systems with shuttles integrated with hoisted carriage. This is very important for warehouse integrators and warehouse managers, as they can very quickly compare a relatively large number of different AVS/RS designs before deciding on the most optimal one.

This study can be extended by applying environmental aspects such as energy consumption and CO_2 emissions, which can be considered in further analysis.

Acknowlegements

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Notice

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5 REFERENCES

[1] CSCMP. CSCMP Supply Chain Management Definitions and Glossary. https://cscmp.org/CSCMP/Educate/SCM_Definitions_and_Glossary_of_Terms.aspx (Accessed 22.04.2022)

[2] Statista. Size of the global logistics market in 2018, by segment (in billion euros). https://www.statista.com/statistics/1069853/total-global-logistics-market-size-segment (Accessed 21.12.2021)

[3] WGTL. Intralogistics Definition. https://www.logistics-journal.de/about/intralogistics (Accessed 22.04.2022)

[4] Nagel, L., Roidl, M., & G. Follert (2008). The Internet of Things: On standardisation in the domain of intralogistics. *First International Conference on the Internet of Things. Adjunct Proceedings*, 16-21.

[5] Günthner, W. & Hompel, M. (Eds.) (2010). *Internet der Dinge in der Intralogistik (VDI-Buch)*. Berlin Heidelberg: Springer-Verlag. (in German)

[6] Lasi, H., Fettke, P., Kemper, H. G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business and Information Systems Engineering, 6*(4), 239-242. https://doi.org/10.1007/s12599-014-0334-4

[7] Winkelhaus, S. & Grosse, E. H. (2019). Logistics 4.0: a systematic review towards a new logistics system. *International Journal of Production Research, 58*(1), 18-43. https://doi.org/10.1080/00207543.2019.1612964

[8] Cohen, Y., Shoval, S., Faccio, M., & Minto, R. (2021). Deploying cobots in collaborative systems: major considerations and productivity analysis. *International Journal of Production Research*, 1-17. https://doi.org/10.1080/00207543.2020.1870758

[9] Boysen, N., de Koster, R., & Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. European *Journal of Operational Research, 277*(2), 396-411. https://doi.org/10.1016/j.ejor.2018.08.023

[10] Park, B. C. (2012). Order Picking: Issues, Systems and Models. Manzini, R. (Ed.). *Warehousing in the Global Supply Chain: Advanced Models, Tools and Applications for Storage Systems*, London: Springer London, Chapter 1, 1-30.

[11] Gajšek, B., Đukić, G., Butlewski, M., Opetuk, T., Cajner, H., & Kač, S. M. (2020). The impact of the applied technology on health and productivity in manual "picker-to-part" systems. *Work*, 65, 525-536. https://doi.org/10.3233/WOR-203107

[12] Azadeh, K., de Koster, R., & Roy, D. (2018). Robotized and Automated Warehouse Systems: Review and Recent Developments. *Transportation Science, 53*(4), 917-945. https://doi.org/10.1287/trsc.2018.0873

[13] Winkler, H. & Zinsmeister, L. (2019). Trends in digitalization of intralogistics and the critical success factors of its implementation. *Brazilian Journal of Operations & Production Management, 16*, 537-549. https://doi.org/10.14488/BJOPM.2019.v16.n3.a15

[14] Bonkeburg, T. (2016). *Robotics in Logistics: A DPDHL Perspective on Implications and Use Cases for the Logistics Industry*. DHL Trend Research.

[15] FEM. World production of materials handling equipment. https://www.fem-eur.com/wp-content/uploads/2021/02/WMHS-Stats-2019.pdf (Accessed: 22.04.2022)

[16] VDI 2692 Blatt 1 - Automated vehicle storage and retrieval systems for small unit loads, VDI, 2015.

[17] FEM. (2017). FEM 9.860. Cycle time calculation for automated vehicle storage and retrieval systems.

[18] Swisslog. Intralogistics, Warehouse Automation & Material Handling. https://www.swisslog.com/en-us (Accessed 22.04.2022)

[19] Exotec. Exotec - Home Page. https://www.exotec.com/en/home/ (Accessed 22.04.2022)

[20] Gudehus, T. (1973). *Principles of order picking: Operations in Distribution and Warehousing Systems*. Essen, Germany.

[21] Lerher, T., Ficko, M., & Palčič, I. (2021). Throughput performance analysis of Automated Vehicle Storage and Retrieval Systems with multiple-tier shuttle vehicles. *Applied Mathematical Modelling, 91*, 1004-1022. https://doi.org/10.1016/j.apm.2020.10.032

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