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Warehousing 4.0 by using shuttle-based storage and retrieval systems

Warehousing 4.0 represents a new area of storing and retrieving goods by using shuttle-based storage and retrieval systems instead of fixed crane automated warehouses. Travel-time model that considers the real operating characteristics of the shuttle carrier and the elevator's lifting table, has been used. Assuming uniform distributed storage locations and the probability theory, expressions for the expected cycle time of the elevator's lifting table and the shuttle carrier have been presented. For the performance analysis of the shuttle-based storage and retrieval system, the method called design of experiments has been used, from which the performance of the shuttle-based storage and retrieval system can be evaluated.

Keywords: *industry 4.0, warehousing 4.0, shuttle-based systems, analytical modelling, performance analysis.*

1. INTRODUCTION

Industry 4.0 represents the Fourth Industrial Revolution, a new level of Organization und Control - concerning the whole value creation chain over the entire life cycle of products [14].

The initiative Industry 4.0 has been issued by the German government in 2010 and was first mentioned in 2011 on Hanover fair CeMat in Germany.

There are other initiatives like The Industrial Internet Consortium Smart Manufacturing Leadership Coalition, Made in China 2025, etc., which are manly driven by the companies [14].

There are many growth opportunities by imple–menting the Industry 4.0. in different industry fields like Automotive industry, Mechanical and Electrical indu–stry, etc. Alone in Germany it is expected the average growth of 1,7% per year, which will be created through: innovative products, new services and business models as well as more efficient operational processes [14].

There are many reasons why the initiative Industry 4.0 is needed [14]:

- Complexity of structure, since the globalization is still increasing and the degree of interconnection is growing exponentially.
- Complexity of data, since the information overload in production and logistics is growing dispropor–tionately high.
- Complexity of products with a request for indi–viduality with its opportunities "batch size one" is getting reality.
- Complexity through interaction, where participation in virtual life is increasing due to more open systems and interconnectedness of all systems.

Application fields of the Industry 4.0 can be manifested in many different fields such as Resource and energy efficiency, new business models, customer oriented engineering, interconnected production and Warehou–sing 4.0, which will be described in continuation.

2. WAREHOUSING 4.0

The modern development of warehousing process, known as Warehousing 4.0 requires the simultaneous treatment of production and warehouse infrastructure, transport-warehouse technology and warehouse mana–gement systems.

In order to meet this demand, there exist many opportunities for research work, such as the application of Shuttle-Based Storage and Retrieval Systems.

Shuttle-based storage and retrieval systems (Figure 1) consist of the elevator with a lifting table that is moving in the vertical direction and is feeding the Storage Rack (SR).

The elevator's lifting table has its own drive for vertical movement. The elevator's lifting table operates on single and double command sequence. The storage rack consists of columns in the horizontal direction and tiers in the vertical direction. At the beginning of each tier is a buffer position, where totes are delivered by the elevator's lifting table. Delivered totes wait for a shuttle carrier to be transferred in the storage rack. In each tier of the storage rack is a single tier-captive shuttle carrier that is traveling in the horizontal direction. The shuttle carrier is an autonomous vehicle with four wheels and has its own drive for horizontal movement. The shuttle carrier operates on single and double command sequence, as well ([5–7]).

The storage and retrieval sequencing take place based on the following transactions:

Storage Transaction

- The elevator's lifting table starts from the ground-floor, i.e., the first tier.
- The elevator's lifting table picks up the tote and moves to the designated tier.

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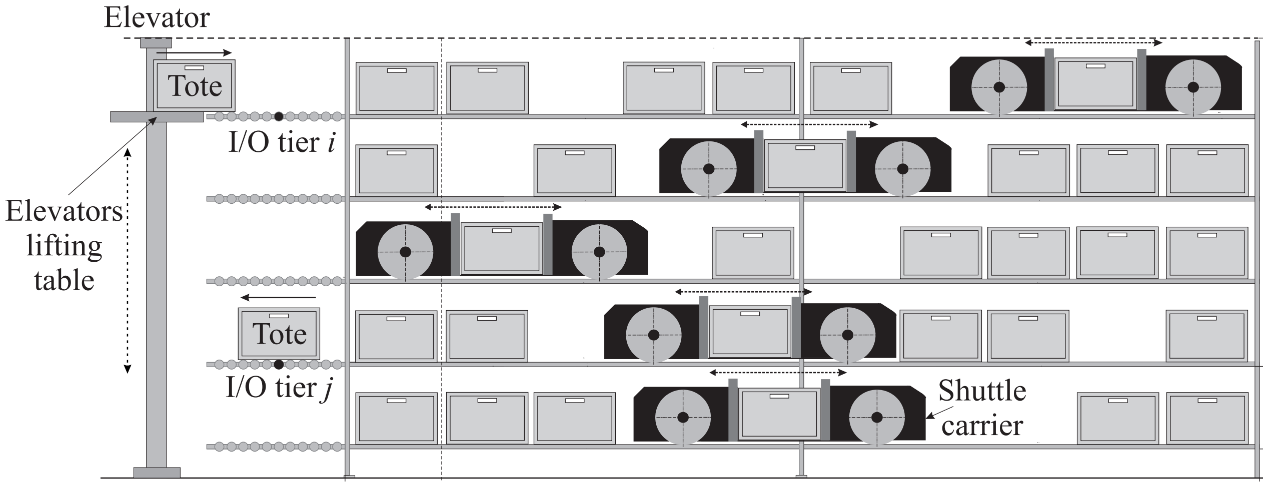

Figure 1. Side view of an SBS/RS [6]

- When the elevator's lifting table reaches its destination, it releases the tote in the buffer position.
- The shuttle carrier in the designated tier picks-up the tote from the buffer position.
- The shuttle carrier travels with the tote to the designated storage location and releases it in the storage location.

Retrieval Transaction

- The shuttle carrier in the designated tier moves to the retrieval location to pick-up the tote, and then travels to the buffer position.
- The shuttle carrier releases the tote in the buffer position.
- The elevator's lifting table moves to the designated tier and picks up the tote from the buffer position.
- The elevator's lifting table moves to the I/O point (first tier) with the tote and releases it.

The assumptions that were used in the SBS/RS modelling are summarized as follows ([5] – [7]):

- The SBS/RS is divided into storage racks on both sides (left and right), therefore totes can be stored at either side in i^{th} tier.
- The I/O location is located at the first tier of the SR.
- The dwell-point location of the tier-captive shuttle carrier in the i^{th} tier of the SR (when idle) is located at the I/O_i buffer position.
- The storage rack is divided by columns and tiers.
- At each tier of the storage rack, there are two buffer position (left and right) and a single tier-captive shuttle carrier.
- The elevator with the elevator's lifting table is feeding the SR with totes.
- The elevator and shuttle carriers work on a Single Command (SC) and on Double Command (DC) modes.
- The sequences of (*i*) Acceleration, constant velocity and deceleration and (*ii*) Acceleration and deceleration have been used.
- The tier-captive shuttle carrier travels simultaneously in the horizontal and vertical directions.
- The drive characteristics of the elevator's lifting table, as well as the height H_{SR} of the SR, are known in advance.
- The drive characteristics of the tier-captive shuttle carrier, as well as the length L_{SR} of the SR, are known in advance.
- The height H_{SR} of the SR is large enough for the elevator's lifting table to reach its maximum velocity v_{max} in the vertical direction.
- The length L_{SR} of the SR is large enough for the tier-captive shuttle carrier to reach its maximum velocity v_{max} in the horizontal direction.
- A randomized assignment policy is considered which means that any storage location is equally likely to be selected for storage or retrieval location to be processed.

3. PERFORMANCE OF SBS/RS

Throughput performance of the SBS/RS is inversely dependant from the cycle time of the elevator's lifting table and shuttle carriers. Cycle time of the SBS/RS is based on the analytical travel-time model, which is based on the assumption on a non-constant velocity time distribution and the probability theory.

3.1 Travel-time model of the elevator's lifting table

<u>**Single command cycle**</u>

The expected single command cycle time $E(\mathrm{SC})_{\mathrm{LIFT}}$ of the elevator's lifting table is calculated by (1):

$$E\left(\mathbf{SC}\right)_{LIFT} = 2 \cdot t_{\frac{P}{S}LIFT} + 2 \cdot \frac{v_y}{a_y} + \frac{H_{SR}}{v_y}\left(\mathbf{sec.}\right) \qquad (1)$$

By considering (1) the throughput performance $\lambda(\mathrm{SC})_{\mathrm{LIFT}}$ of the elevator's lifting table is calculated by (2):

$$\lambda\left(\mathbf{SC}\right)_{LIFT} = \frac{3600}{E\left(\mathbf{SC}\right)}\left(\frac{\mathbf{totes}}{\mathbf{hour}}\right) \qquad (2)$$

<u>**Double command cycle**</u>

The expected double command cycle time $E(\mathrm{DC})_{\mathrm{LIFT}}$ of the elevator's lifting table is calculated by (3):

$$E\left(\mathbf{DC}\right)_{LIFT} = 4 \cdot t_{\frac{P}{S}LIFT} + 3 \cdot \frac{v_y}{a_y} + \frac{4}{3} \cdot \frac{H_{SR}}{v_y}\left(\mathbf{sec.}\right) \qquad (3)$$

By considering (3) the throughput performance $\lambda(\text{DC})_{\text{LIFT}}$ of the elevator's lifting table is calculated by (4):

$$\lambda(\mathbf{DC})_{LIFT} = \frac{3600}{E(\mathbf{DC})} \cdot 2\left(\frac{\textbf{totes}}{\textbf{hour}}\right) \tag{4}$$

3.2 Travel-time model of the shuttle carrier

<u>**Single command cycle**</u>

The expected single command cycle time $E(\text{SC})_{\text{SCAR}}$ of the shuttle carrier is calculated by (5):

$$E(\mathbf{SC})_{CAR} = 2 \cdot t_{\frac{P}{S}SCAR} + 2 \cdot \frac{v_x}{a_x} + \frac{L_{SR}}{v_y}(\mathbf{sec.}) \tag{5}$$

By considering (5) the throughput performance $\lambda(\text{SC})_{\text{SCAR}}$ of the shuttle carrier is calculated by (6):

$$\lambda(\mathbf{SC})_{CAR} = \frac{3600}{E(SC)_{SCAR}}\left(\frac{\textbf{totes}}{\textbf{hour}}\right) \tag{6}$$

<u>**Double command cycle**</u>

The expected double command cycle time $E(\text{DC})_{\text{SCAR}}$ of the shuttle carrier is calculated by (7):

$$E(\mathbf{DC})_{SCAR} = 4 \cdot t_{\frac{P}{S}SCAR} + 3 \cdot \frac{v_x}{a_x} + \frac{4}{3} \cdot \frac{L_{SR}}{v_x}(\mathbf{sec.}) \tag{7}$$

By considering (7) the throughput performance $\lambda(\text{DC})_{\text{LIFT}}$ of the shuttle carrier is calculated by (8):

$$\lambda(\mathbf{DC})_{SCAR} = \frac{3600}{E(\mathbf{DC})_{SCAR}} \cdot 2\left(\frac{\textbf{totes}}{\textbf{hour}}\right) \tag{8}$$

3.3 Design of experiments

Design of Experiment (DOE) is a design tool that analyses the relation between constant, input and output variables in order to identify the significant factors affecting the output. For the constant variables, the following variables were used: velocity, acceleration / deceleration, pick-up and set-down time. For the input variables (factors), the following variables were used: length and height of the storage rack. For the output variables (performance measures), the follo–wing variables were used: cycle time and throughput capa–city of the elevator's lifting table and the shuttle carrier [9].

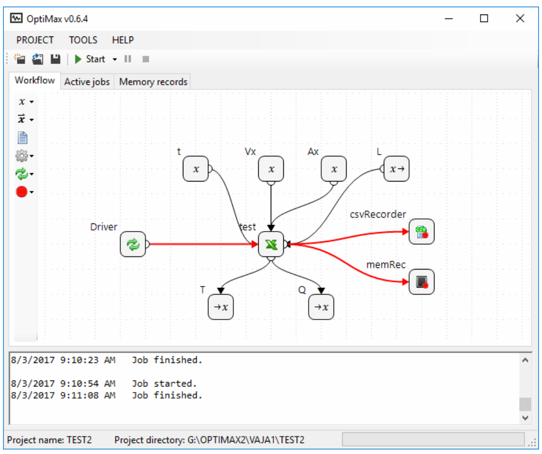

Figure 2: Design of Experiments with OptiMax [source: http://lace.fs.uni mb.si/wordpress/borovinsek]

For the DOE analysis, the OptiMax optimization package with graphical user interface for Windows platform has been used.

4. CASE STUDY

In the present section the case study by using the DOE analysis, will be presented and discussed.

Pick-up and set-down times of the elevator's lifting table and the shuttle carrier were set to $t_{\text{P/S SCAR}} = 3.0$ sec. and $t_{\text{P/S LIFT}} = 1.5$ sec., respectively.

The case study is based on a single command cycle.

Table 1. Levels of factors

Factors	Codes	Levels
Length	Low level	$L_{\text{SR}} = 50$ m
	High level	$L_{\text{SR}} = 100$ m
Height	Low level	$H_{\text{SR}} = 5$ m
	High level	$H_{\text{SR}} = 20$ m

Table 2. Velocity profile of the SBS/RS

SBS/RS velocity profile	Shuttle carrier		Elevator	
	v_x (m/s)	a_x (m/s^2)	v_y (m/s)	a_y (m/s^2)
vp	3	2	5	6

Table 3. Design scenarios and their results for the shuttle carrier

ID	$t_{\text{P/S}}$	v_x	a_x	L_{SR}	E(SC)	λ(SC)
1	3	3	2	50	25.67	140
2	3	3	2	51	26.00	138
3	3	3	2	52	26.33	137
4	3	3	2	53	26.67	135
5	3	3	2	54	27.00	133
6	3	3	2	55	27.33	132
7	3	3	2	56	27.67	130
8	3	3	2	57	28.00	129
…	…	…	…	…	…	…
43	3	3	2	93	40.00	90
44	3	3	2	94	40.33	89
45	3	3	2	95	40.67	89
46	3	3	2	96	41.00	88
47	3	3	2	97	41.33	87
48	3	3	2	98	41.67	86
49	3	3	2	99	42.00	86
50	3	3	2	100	42.33	85

Table 4. Design scenarios and their results for the elevator's lifting table

ID	$t_{\text{P/S}}$	v_y	a_y	H_{SR}	E(SC)	λ(SC)
1	1.5	5	6	5	5.67	635
2	1.5	5	6	6	5.87	614
3	1.5	5	6	7	6.07	593
4	1.5	5	6	8	6.27	574
…	…	…	…	…	…	…
12	1.5	5	6	17	8.07	446
13	1.5	5	6	18	8.27	435
14	1.5	5	6	19	8.47	425
15	1.5	5	6	20	8.67	415

According to Table 3 and Figure 3, the shuttle carrier performs well in the case of relatively short storage racks (<< L_{SR}). The highest throughput perfor–

mance of the shuttle carrier ($\lambda(SC)_{SCAR}$ = 140 totes/hour) lies within a small number of columns of the SR. Since the warehouse volume Q is constant we get a relatively high storage rack (>> H_{SR}), which is not the best solution from the elevator's performance pers–pective.

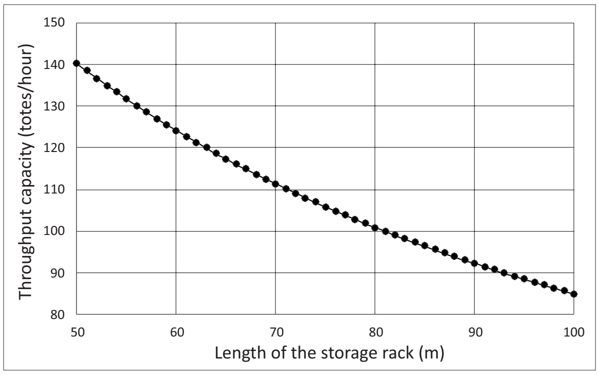

Figure 3: Throughput performance of the shuttle carrier

On the contrary, the elevator's lifting table (Table 4 and Figure 4) performs well in the case of relatively small storage racks (<< H_{SR}). The highest throughput performance ($\lambda(SC)_{LIFT}$ = 635 totes/hour) lies within a small number of tiers and large number of columns. In this case, we get a relatively small and long storage rack, which is not the best solution from the shuttle carrier's performance perspective.

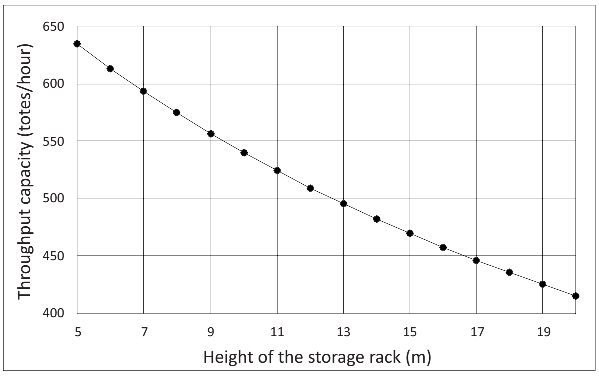

Figure 4: Throughput performance of the elevator's lifting table

The best throughput performance of the SBS/RS as a whole will be in the point where the elevator's lifting table and all shuttle carriers operate with the highest utilization (η_{LIFT} and η_{SCAR} ~ 1.0).

5. CONCLUSION

The aim of this study is to present design of experiments with the OptiMax optimization package that can estimate the throughput performance of the selected SBS/RS.

Various factors of SBS/RS were examined such as: velocity v, acceleration / deceleration a, length L_{SR} and height H_{SR} of the SR. The performance measures were considered as single command cycle times and throughput performance of the SBS/RS.

This study can be extended with (*i*) Different velocity and acceleration / deceleration scenarios for the elevator's lifting table and the shuttle carrier, (*ii*) Different configurations of SBS/RS, (*iii*) Application of the environment aspects like energy consumption and CO_2 emissions may also be considered in the analysis.

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NOMENCLATURE

SBS/RS	shuttle-based storage and retrieval systems
DC	dual command
I/O	input and output location
SC	single command
SR	storage rack
DOE	design of experiment
CO_2	carbon dioxide
a_x	acceleration / deceleration of the shuttle carrier
a_y	acceleration / deceleration elevator's lifting table
v_x	velocity of the shuttle carrier
v_y	velocity of the elevator's lifting table
L_{SR}	length of the storage rack
H_{SR}	height of the storage rack
$E(SC)_{LIFT}$	expected single command cycle time of the elevator's lifting table
$\lambda(SC)_{LIFT}$	throughput performance of the elevator's lifting table based on single command cycle
$E(DC)_{LIFT}$	expected dual command cycle time of the elevator's lifting table
$\lambda(DC)_{LIFT}$	throughput performance of the elevator's lifting table based on dual command cycle
$E(SC)_{SCAR}$	expected single command cycle time of the shuttle carrier
$\lambda(SC)_{SCAR}$	throughput performance of the shuttle carrier based on single command cycle
$E(DC)_{SCAR}$	expected dual command cycle time of the shuttle carrier
$\lambda(DC)_{SCAR}$	throughput performance of the shuttle carrier table based on dual command cycle
$t_{P/S\ SCAR}$	pick-up and set-down times of the shuttle carrier
$t_{P/S\ LIFT}$	pick-up and set-down times of the elevator's lifting table
η	efficiency

СКЛАДИШТЕЊЕ 4.0 ПРИМЕНОМ ШАТЛ ТЕХНОЛОГИЈЕ

Т. Лерхер

Складиштење 4.0 представља нов начин складиштења и проналажења ускладиштене робе применом система шатл технологије за разлику од аутоматских складишта са фиксираним дизалицама. Користи се модел за одређивање времена циклуса који узима у обзир реалне радне карактеристике шатл возила и подизне платформе лифта. Полазећи од претпоставке постојања равномерне дистри–буције локација за складиштење и теорије вероватноће, дати су изрази за очекивано време циклуса за платформу и шатл возило. Анализа учинка складиштења применом шатл система извршена је методом пројектовања експеримента, која омогућава да се изврши евалуација складиштења шатл технологијом.