SIMULATION BASED EVALUATION OF CONCEPTS AND STRATEGIES FOR AUTOMATED STORAGE AND RETRIEVAL SYSTEMS WITH MULTIPLE I/O POINTS

Lantschner Daniel[a], Atz Thomas[b], Prof. Dr. Günthner Willibald A.[c]

[a] [b] [c] fml - Institute of Materials Handling, Material Flow, Logistics
Technische Universität München

[a]lantschner@fml.mw.tum.de, [b]atz@fml.mw.tum.de, [c]kontakt@fml.mw.tum.de

ABSTRACT
In recent years, there has been an increasing demand for high speed automated storage and retrieval systems (AS/RS). A possibility to increase the throughput of AS/RS rarely considered so far is the use of more than one I/O point in order to reduce the mean travel distance between I/O and storage locations. In this paper concepts for the alignment of multiple I/O points and strategies for their optimal use are presented. Since no suitable calculation methods for most of those concepts and strategies are available, a simulation model has been developed for their evaluation in terms of cycle times. The simulation results are compared with those of AS/RS with a single I/O point in order to show the benefit of the new concepts.

Keywords: AS/RS, storage, retrieval, travel time, multiple I/O, discrete-event simulation

1. INTRODUCTION

Automated storage and retrieval systems are computer controlled systems for depositing and retrieving loads from defined storage locations (MHI 2013). Warehouses, distribution centres and manufacturing facilities are the most common application areas of AS/RS. The major components of an AS/RS are: the storage rack, the input/output system (I/O system), the storage and retrieval machine (S/R machine) and the warehouse management system.

The performance of an AS/RS can be estimated by the mean cycle time. According to Gudehus (2007) the cycle time depends primarily on the travel time for the partial movement in the three directions in space. To improve the performance, manufacturers of AS/RS continuously develop S/R machines capable of higher speeds and accelerations. The main development directions are weight savings and mostly the use of more powerful drives with a higher power requirement. A solution to increase the throughput without increasing or even reducing the power requirement would be a reduction of the S/R machine's mean travel distance. This can be achieved, for example, by shifting the I/O location from a corner of the rack in a horizontal and/or vertical direction towards the storage rack's centre of area. Such concepts have been analyzed sufficiently in the past (see Gudehus 1972a, Knepper 1980, Eggert et al. 2010, among others) and several calculation models have been developed (see Gudehus 1972b, Bozer and White 1984, among others). In this paper, an approach for a further reduction of the mean travel distance by using more than one I/O location will be examined. Arantes and Kompella (1993) developed analytical expressions for the calculation of the expected cycle time for a specific case of an AS/RS with multiple I/O points which aren't suitable for most of the concepts and strategies proposed by the authors. Therefore, a purpose-built simulation model will be presented.

2. STATE OF THE ART

Simulation is a well-established tool for the analysis of AS/RS. Besides cycle time calculation, simulation is used to optimize the design, analyze different storage assignment and dwell point strategies, to evaluate scheduling rules as well as for several other analyses. Roodbergen and Vis (2009) give a detailed overview of simulation and analytical models and an explanation of the current state of the art in AS/RS design.

3. STORAGE AND RETRIEVAL SYSTEMS WITH MULTIPLE I/O POINTS

With multiple I/O points placed at different locations, the I/O point leading to the shortest travel distance and thus the shortest travel time can be used for each storage or retrieval cycle. Assuming a symmetrical distribution of the I/O points for the racks on either side of an aisle, single racks are shown to illustrate the alignment of the I/O points (see Figure 1).

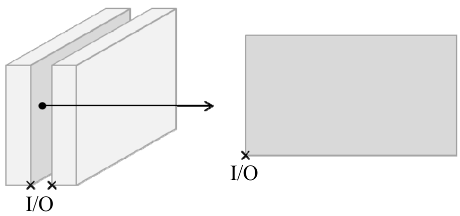

Figure 1: AS/RS aisle and single rack

The shown I/O configuration represents the most frequent I/O alignment in practical applications. A selection of reference concepts with a single I/O point as well as new concepts for the alignment of multiple I/O points in an AS/RS aisle are presented in the following. After that, possible strategies for the selection of an I/O point for storage and retrieval cycles in AS/RS with multiple I/O points will be introduced.

3.1.1. Reference Concepts

As reference for the evaluation of the new concepts, the following alignments of a single I/O point will be selected:

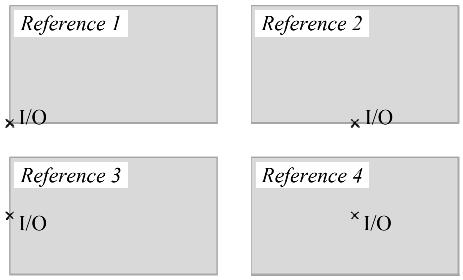

Figure 2. Reference I/O alignments

Reference 1 is the most commonly used alignment. The other alternatives are of less practical importance but will be useful to show the potential of different single I/O locations in comparison to the new concepts with multiple I/O points.

3.1.2. Concepts with multiple I/O points

Multiple I/O points can be aligned in various ways in an aisle. Since each I/O point has to be connected via a conveyor to the pre-storage area on the front side of the rack for the supply and removal of storage goods, only horizontally and vertically aligned I/O points will be considered to allow the use of standardized conveyors or lifters. These I/O points can be places either on the border of the rack face or centred for a further reduction of the mean distance between the storage shelves of the rack and the I/O points. Figure 3 shows those alignments as an example with three I/O points. In the first row concepts with horizontally aligned I/O points are illustrated (*Concept 1* and *Concept 2*), whereas in the second row two concepts with vertically aligned I/O points are shown (*Concept 3* and *Concept 4*):

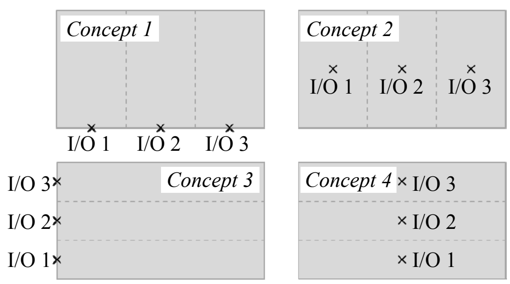

Figure 3: Examples for different I/O configurations

Two or more I/O points are aligned by dividing the rack area into equal subareas and placing the points at mid-length or mid-height of each subarea. It will be assumed that all I/O points of an aisle are equivalent and always available for either picking up or depositing storage goods.

3.2. Strategies

While a conventional AS/RS usually comes with a single I/O point, the presented concepts contain a variety of I/O points. For efficient use of the additional I/O points new strategies are required. Since all of these points are equivalent, each point can be chosen to pick up or put down a storage unit. The strategies define which point will be selected in order to minimize the travel time of the S/R machine. The authors propose three different strategies:

1. Random selection of an I/O point
2. Selection of the nearest I/O point
3. Selection of an I/O point by minimizing the sum of the travel times from a starting shelf to I/O and from I/O to the next target shelf

The difference between the latter two strategies is illustrated in Figure 4. While the second strategy defines a selection of the I/O point for the travel from a storage shelf P1 to I/O independent of the next destination of the S/R machine (P2), the third strategy considers the location of the next target selecting the optimal I/O point.

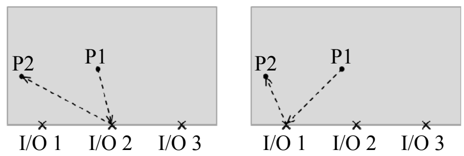

Figure 4: Selection of the nearest I/O point (left) and by minimizing the sum of the two travel times (right)

4. THE SIMULATION MODEL

To calculate the estimated travel times for the new concepts and strategies, a simulation model has been implemented. The model is used to determine the mean cycle time. For the travel time calculation using the simulation model, the following assumptions are made:

- randomized storage, i.e. every shelf of the rack is equally likely to be selected for storage or retrieval
- no empty trips between different I/O points
- constant acceleration and deceleration of the S/R machine
- equal absolute value of acceleration and deceleration

In addition, times such as the travel time between different storage locations in dual command cycles and pick-up and deposit times will be calculated by the simulation model to obtain the mean cycle time.

4.1. Modelling

The model consists of the rack, the S/R machine and conveyors to the I/O points for supply and removal of storage goods. The totality of the storage locations, characterized by its horizontal and vertical coordinates, form the rack. Since the S/R machine travels simultaneously in two directions, the travel time is given by the longer duration of the simultaneous travels in the two axis directions. For the calculation of the travel time in one axis direction, a distinction as to whether or not the maximum travel speed v_{max} will be reached has to be made. The maximum travel speed will be reached if the travel distance s satisfies the following condition (a corresponds to the absolute value of the acceleration and deceleration):

$$s \geq \frac{v_{\max}^2}{a} \qquad (1)$$

Depending on condition (1), the travel time can be calculated as follows:

$$\begin{cases} t = 2 \times \sqrt{\frac{s}{a}} & \text{for } s \leq \frac{v_{\max}^2}{a} \\ t = \frac{s}{v_{\max}} + \frac{v_{\max}}{a} & \text{for } s \geq \frac{v_{\max}^2}{a} \end{cases} \qquad (2)$$

Using equation (2) the travel times in the horizontal direction t_h and the vertical direction t_v can be calculated using the corresponding values for maximum speed and acceleration. The travel time T between two locations is given by the longer duration of t_h and t_v:

$$T = Max\left(t_h, t_v\right) \qquad (3)$$

The simulation model calculates the mean travel time by complete enumeration or Monte-Carlo-Simulation, depending on the desired operational strategies, using equations (2) and (3). I/O locations are selected according to the proposed strategies. Pick-up and deposit times are independent of the starting and target location and can be included afterwards to calculate the cycle time of an aisle.

The conveyors which connect the I/O points are modelled with constant conveying velocity with identical speeds for supply and removal of storage goods.

4.2. Implementation

The Siemens Plant Simulation software has been chosen for the implementation of the simulation model. The core of the model is a graphic visualization of the complete AS/RS with its storage locations, the S/R machine, the I/O points and the conveyors for the supply (see Figure 5) which has proven to be useful in the verification process and the analysis of the system's behaviour.

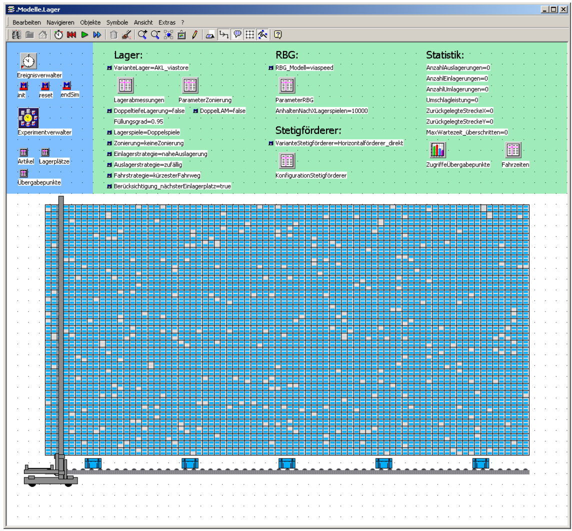

Figure 5: Graphic visualization of the simulation model

Result variables and diagrams as well as different user input tables and variables for the model configuration can be found in the upper part of the visualization window. The model and its graphical visualization are generated dynamically based on the user's input. Input parameters are:

- rack and storage shelf dimensions
- accelerations and speeds of the S/R machine
- pick-up and deposit times
- operational strategies for storage assignment and retrieval
- number, position and alignment of the I/O points (vertical, horizontal)
- speed of the supply conveyors

Tables are used for the management of the storage locations and their content as well as for the I/O points and their position.

Actions are triggered by the movement of the S/R machine. Each time the machine reaches a target position, the functions defining the following action are called. If desired, the software also offers the possibility to visualize the machine's movement in real-time.

4.3. Verification and Validation

To verify the implemented model, the travel times between specific locations have been controlled manually. The cycle time calculation has been validated comparing the results for different rack dimensions with a single I/O point calculated using the simulation model to those gained from the analytical expressions proposed by Bozer and White (1984). For this purpose, an S/R machine travelling with constant speed had to be used. As for the later experiments, a horizontal speed of 6 m/s and a vertical speed of 3 m/s have been selected as well as rack dimensions (LxH) of 20x10 m, 20x20 m and 40x10 m with a storage shelf size of 0.5x0.4 m. Table 1 shows the mean travel times between storage shelves and I/O calculated in both ways. The simulation model produces exactly the same results as the analytical calculation.

Table 1: Validation results

Rack size	Simulation	Analytical calculation	Deviation
20x10 m	2.22 s	2.22 s	0.0%
20x20 m	3.61 s	3.61 s	0.0%
40x10 m	3.61 s	3.61 s	0.0%

5. SIMULATION EXPERIMENTS

The aim of the simulation experiments is the evaluation of concepts and strategies for AS/RS with multiple I/O points in terms of cycle time. Target results are:

- cycle times for different AS/RS configurations with multiple I/O points
- influence of the different strategies on the cycle time
- influence of the number of I/O points on the cycle time
- required supply speed for the I/O points

5.1. Setup description

Three rack dimensions with a different width-to-height ratio are used to evaluate I/O configurations. This is necessary since the shown concepts with I/O points distributed on the rack surface are expected to show different gains depending on the ratio of the rack dimensions. Starting with a rack having 20 m length and 10 m height, a second rack with twice the height and a third rack with twice the length will be considered. Table 2 summarizes the rack dimensions:

Table 2: Rack dimensions

Rack name	Length [m]	Height [m]
Rack 1	20	10
Rack 2	20	20
Rack 3	40	10

The distance between the shelves is 0.5 m in the horizontal and 0.4 m in the vertical direction, assuming a mini-load AS/RS. For such systems, S/R machines with horizontal travel speeds up to about 6 m/s are available. Vertical travel speeds are typically lower. Table 3 shows the speeds and mean accelerations of the exemplary device used which represents the current state of technology:

Table 3: Speeds and mean accelerations of the S/R machine

	Horizontal direction	Vertical direction
Max. travel speed	6.0 m/s	3.0 m/s
Mean acceleration	3.0 m/s²	3.0 m/s²

To simplify the matter, it will be assumed that speeds and accelerations are independent of the lift height and the absolute value of the deceleration is equal to the acceleration in the same direction. Pick-up and deposit times are supposed to have an identical duration of 4 s.

Of the concepts with multiple I/O points (see section 3.1.2), configurations with a different number of I/O points will be examined. Preliminary studies showed that the relative gain will decrease for an increasing number of I/O points and become very small for more than two or three I/O points, depending on the AS/RS configuration. To verify this, I/O configurations with up to five I/O points will be considered.

5.2. Results and discussion

A first result of simulations with multiple I/O points was that for most of the examined configurations the speed of conventional conveyors is far from sufficient to supply all of the I/O points from the pre-storage area in time. For this reason, more than one storage unit has to be buffered at the I/O points in order to decouple the supply process from the storage process.

Travel times and cycle times in the following tables are always indicated in seconds.

5.2.1. Comparison of strategies

Table 4 shows the results for the comparison of the strategies introduced in section 3.2 using *Rack 1* (20x10 m) and an I/O alignment according to *Concept 1* with a different number of I/O points. The mean travel time between storage shelves and I/O points is denoted by $t_{shelves - I/O}$; the mean travel time in the opposite direction is denoted by $t_{I/O - shelves}$.

Table 4: Mean travel times for the different strategies

# I/O	Random selection		Nearest I/O		Travel time minimization	
	$t_{shelves - I/O}$	$t_{I/O - shelves}$	$t_{shelves - I/O}$	$t_{I/O - shelves}$	$t_{shelves - I/O}$	$t_{I/O - shelves}$
2	3.26	3.26	2.79	3.26	2.91	2.91
3	3.30	3.30	2.71	3.28	2.84	2.84
4	3.31	3.31	2.68	3.29	2.81	2.81
5	3.31	3.31	2.66	3.30	2.79	2.79

The time for the travel from a storage shelf across an I/O station to the next storage shelf consists of the sum of the two indicated times. As expected, the selection of an I/O point by minimizing the travel time between two targets and I/O will always lead to the shortest total travel time. The selection of the nearest I/O point shows an even shorter travel time between shelves and I/O at the expense of the travel time in the opposite direction. By randomly selecting an I/O point, additional I/O points are not an advantage. The travel time will even increase slightly for an increasing number of I/O points. This strategy is thus not suited for use with multiple I/O points.

Similar results can be expected for other I/O alignments and rack configurations. Therefore, for the following evaluation of different concepts, the travel time minimization strategy will be used.

5.2.2. Comparison of I/O configurations

Different I/O configurations will be compared based on the dual command cycle time. For a dual command cycle starting at I/O the cycle time consists of the following time components:

1. Pick-up time at I/O
2. Travel time from I/O to the storage location
3. Deposit time at the storage location
4. Travel time between storage and retrieval location
5. Pick-up time at the retrieval location
6. Travel time from the retrieval location to I/O
7. Deposit time at I/O (simultaneous to 1.)

With the applied strategy the mean travel times between I/O and storage or retrieval location are identical and thus calculated only once. The mean travel time between storage and retrieval location is independent from the I/O configuration but varies for the examined rack dimensions (see Table 5).

Table 5: Mean travel times between storage and retrieval location

Rack size	Mean travel time
20x10 m	3.06 s
20x20 m	3.79 s
40x10 m	4.19 s

Since both pick-up and deposit times are assumed to have a duration of 4 s and pick-up and deposit at I/O can take place simultaneously in subsequent cycles, a total of 12 s has to be added to the calculated travel times to get the dual command cycle time. Table 6 contains the results of the cycle time calculation for the four reference concepts as well as for the concepts with multiple I/O points in configurations with up to five I/O points for *Rack 1*. This rack is “square-in-time”.

Table 6: Dual command cycle time for different I/O configurations (rack 20x10 m)

I/O alignment	# I/O				
	1	2	3	4	5
Reference 1	22.64 100%	-	-	-	-
Reference 2	21.22 94%	-	-	-	-
Reference 3	22.18 98%	-	-	-	-
Reference 4	20.28 90%	-	-	-	-
Concept 1	-	20.88 92%	20.74 92%	20.68 91%	20.64 91%
Concept 2	-	19.78 87%	19.60 87%	19.52 86%	19.46 86%
Concept 3	-	22.08 98%	22.04 97%	22.04 97%	22.02 97%
Concept 4	-	20.12 89%	20.06 89%	20.04 89%	20.04 89%

The results for *Rack 1* (20x10 m) show that already a differently placed I/O point leads to a significant reduction of the cycle time. By shifting the I/O point towards half the length of the rack the cycle time can be reduced by 6% (*Reference 2*) or by even 10% placing the I/O point in the rack’s centre of area (*Reference 4*), compared to the most frequent I/O alignment in practical applications *Reference 1*. The cycle time is shorter than for some of the concepts with multiple I/O points. Those concepts (*Concept 1* and *3*) have the common ground of I/O points aligned alongside a border of the rack, which is expected to be easier to implement compared to I/O points distributed on the rack surface.

Multiple I/O points on the rack surface might be difficult to implement, but feature shorter cycle times than all of the concepts with a single I/O point (*Concept 2* and *4*). Compared to *Reference 1*, a reduction of the mean cycle time by up to 14% is possible with those concepts.

For all of the examined concepts with multiple I/O points the benefit of using more than two I/O points is very small. The benefit is typically less than 1% in relative terms. Therefore, two I/O points are sufficient for this AS/RS configuration with rack dimensions of 20x10 m. The results for the higher *Rack 2* (20x20 m) are shown in Table 7.

Table 7: Dual command cycle time for different I/O configurations (rack 20x20 m)

I/O alignment	# I/O				
	1	2	3	4	5
Reference 1	25.59 100%	-	-	-	-
Reference 2	24.87 97%	-	-	-	-
Reference 3	23.37 91%	-	-	-	-
Reference 4	21.95 86%	-	-	-	-
Concept 1	-	24.63 96%	24.57 96%	24.53 96%	24.51 96%
Concept 2	-	21.61 84%	21.47 84%	21.41 84%	21.37 84%
Concept 3	-	23.13 90%	23.01 90%	22.97 90%	22.93 90%
Concept 4	-	21.57 84%	21.37 84%	21.29 83%	21.25 83%

Due to the greater rack surface (20x20 m), cycle times are longer than for the first rack (20x10 m). Looking at the results for the reference concepts, it is noticeable that *Reference 3* with an elevated I/O point gives much better results for these rack dimensions than for the first examined rack using the same exemplary S/R machine. The reason for this is the increased rack height. *Reference 2* with an I/O point centred at the bottom of the rack surface has a much smaller advantage in comparison to the first rack. These results show that elevated I/O points are better suited to higher racks, using the same S/R machine. Comparing the results for the concepts with multiple I/O points will confirm this. *Concept 1* with the I/O points located at the bottom of the rack shows the smallest benefit while the other concepts, characterized by differently placed elevated I/O points, allow for cycle time reductions up to 17% compared to *Reference 1*.

Also the results for Rack 2 confirm that it is generally not convenient to use more than two I/O points. Table 8 contains the results for the last of the considered racks, the proportionally long *Rack 3* (40x10 m).

Table 8: Dual command cycle time for different I/O configurations (rack 40x10 m)

I/O alignment	# I/O				
	1	2	3	4	5
Reference 1	26.99 100%	-	-	-	-
Reference 2	23.77 88%	-	-	-	-
Reference 3	26.75 99%	-	-	-	-
Reference 4	23.31 86%	-	-	-	-
Concept 1	-	23.13 86%	22.87 85%	22.75 84%	22.67 84%
Concept 2	-	22.45 83%	22.15 82%	22.01 82%	21.91 81%
Concept 3	-	26.69 99%	26.67 99%	26.67 99%	26.67 99%
Concept 4	-	23.21 86%	23.17 86%	23.17 86%	23.15 86%

As expected, a comparison with the results of *Rack 2* shows that different concepts are suited to a proportionally long rack, always in combination with the given S/R machine. Whereas *Concept 1* offers only a small benefit for *Rack 2*, a noticeable reduction of the cycle time is possible for this rack. Adopting *Concept 2*, a further reduction of the cycle time by up to 19% compared to *Reference 1* will be possible, depending on the number of I/O points. In contrast, alignments with elevated I/O points at the border of the rack (*Reference 3* and *Concept 3*) don't show any significant benefit.

While the optimal strategy could be determined independently from the rack dimensions, the results for different I/O alignments vary for the examined rack dimensions. In particular, concepts with the I/O points aligned along a border of the rack are very sensitive to the rack dimensions. Therefore, a detailed analysis for a given application case is necessary for those concepts and the best suited concept as well as a reasonable number of I/O points have to be determined ad hoc.

6. CONCLUSIONS

In this paper, the idea of reducing the mean travel distance between storage shelves and I/O in an AS/RS by using more than one I/O points has been addressed. The paper proposes different concepts for the alignment of multiple I/O points in an AS/RS aisle. For those concepts, possible strategies for the selection of an I/O point were presented. After choosing an adequate strategy, I/O configurations with a different number of I/O points differently aligned were evaluated in terms of travel times. For this purpose, a simulation model has been developed. The evaluation has been done for three different sizes of rack face. As reference for the evaluation, four systems with differently placed single I/O points were defined.

The simulation results emphasize the benefit of the analyzed concepts. Although a reduction of the mean cycle time compared to an AS/RS with a single I/O point in the corner of the rack can already be achieved by placing the I/O point differently, the implementation of a concept with multiple I/O points yields a further reduction.

In addition, the outcome of the evaluation implies that by using a given S/R machine not every I/O configuration is suitable for a particular examined rack dimension. As a consequence, the obtainable cycle time reduction for a new configuration cannot be generalized but has to be calculated ad hoc using simulation. This is possible with reasonable effort using the developed configurable simulation model.

REFERENCES

Arantes, J. C., Kompella, S., 1993. Travel-time models for AS/RS with multiple I/O stations. *2nd Industrial Engineering Research Conference Proceedings*, IIE, Norcross, GA (USA), 405-409 – ISBN 0-89806-132-6

Bozer, Y. A., White, J. A., 1984. Travel time models for automated storage/retrieval systems. *IIE Transactions*, 16(4), 329-338 – ISSN 0470-817X

Eggert, M., Loschke, C., Schumann, M., 2010. Neuer Ansatz verspricht Effizienzschub. *f+h – Fördern und Heben 7/8*, 264-267 – ISSN 0341-2636

Gudehus, T., 1972a. Wohin mit der Kopfstation? *Materialfluß 2*, Nr. 4, 66-68

Gudehus, T., 1972b. Grundlagen der Spielzeitberechnung für automatisierte Hochregallager, *deutsche hebe- und fördertechnik Sonderheft*, 63-68

Gudehus, T., 2007. *Logistik 2*, Netzwerke, Systeme und Lieferketten. Berlin: Springer Verlag, 640

Knepper, L., 1980. Leistungsverbesserungen in Hochregallagern durch optimale Anordnung der Ein- und Auslager-Bereitstellplätze. *f+h – Fördern und Heben 30*, Nr. 12, 1096-1099

MHI, 2013. MHI glossary. Available from: http://www.mhi.org/glossary [accessed 13 June 2013]

Roodbergen, K.J., Vis, I.F.A., 2009. A survey of literature on automated storage and retrieval systems. *European Journal of Operational Research*, 194(2), 343-362 – ISSN 0377-2217

AUTHORS BIOGRAPHY

Lantschner Daniel, M.Sc., Ph.D. candidate and Research Assistant at the Institute of Materials Handling, Material Flow, Logistics, Technische Universität München. Daniel Lantschner was born in 1983 in Bolzano, Italy. Between 2003 and 2007 he studied Logistics and Production Engineering at the Free University of Bozen - Bolzano and afterwards Mechanical Engineering at the Technische Universität München until 2009.

Atz Thomas, M.Sc., Ph.D. candidate and Research Assistant at the same institute. Thomas Atz was born in 1985 in Bolzano, Italy. Between 2004 and 2007 he studied Logistics and Production Engineering at the Free University of Bozen - Bolzano and afterwards Mechanical Engineering at the Technische Universität München until 2009.

Günthner Willibald A., Prof. Dr., Head of the Institute of Materials Handling, Material Flow, Logistics, Technische Universität München.