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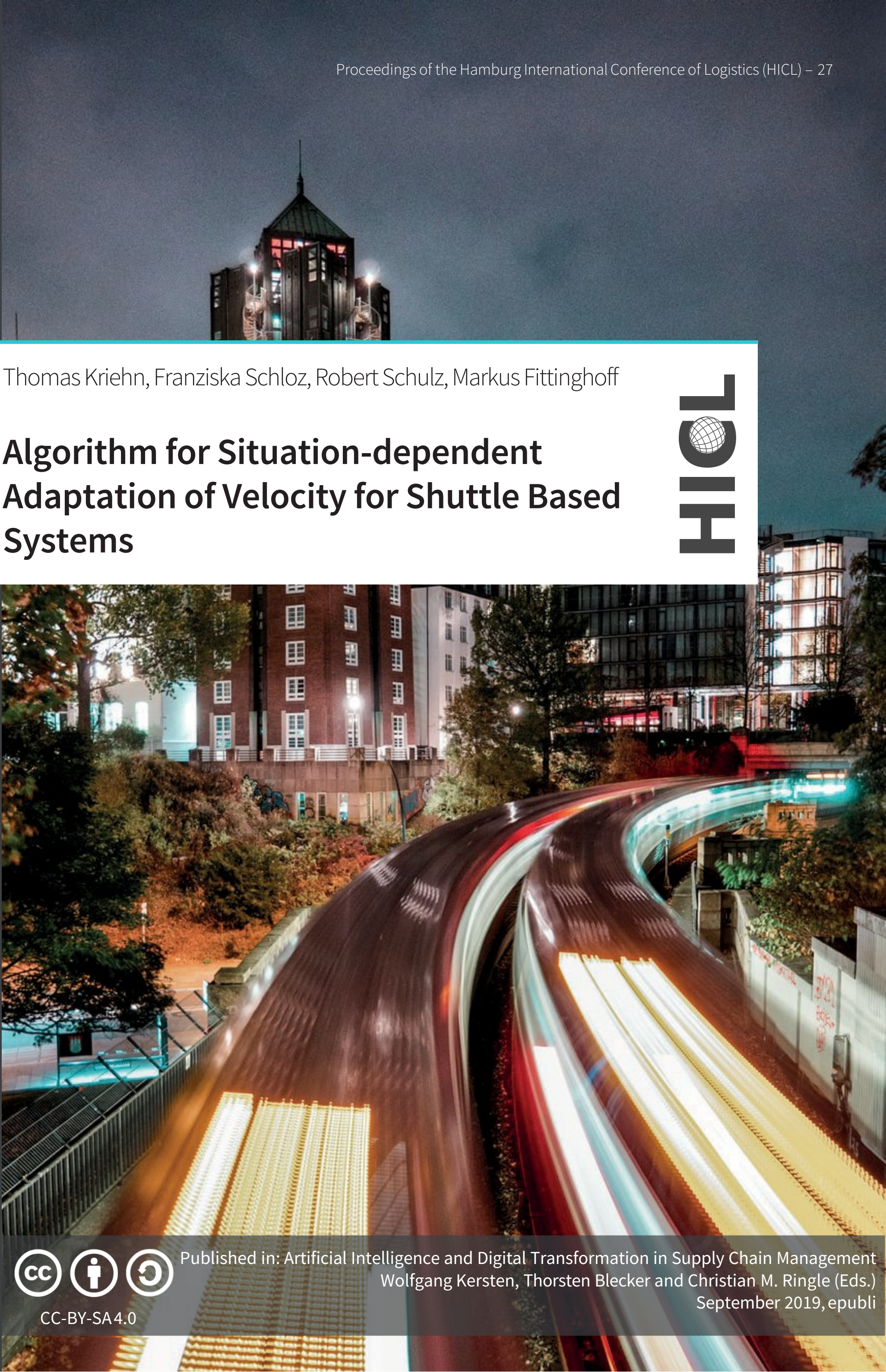

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Algorithm for Situation-dependent Adaptation of Velocity for Shuttle Based Systems

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Purpose: Shuttle based storage and retrieval systems (SBS/RS) are suitable for applications which require a high throughput. Many times, however, the maximum performance of SBS/RS is not required. For example, when customers initiate a large number of retrieval requests at a specific time, or when a large number of storage requests enter the system at fixed times due to scheduled inbound deliveries. This article presents and discusses an algorithm that is based on closed-loop-control.

Methodology: A situation-dependent adaptation of the velocity to the currently required throughput or the number of currently awaiting orders requires an algorithm which needs to be implemented in the control of the SBS/RS. A simulation model of a SBS/RS will be introduced, which contains the control of the shuttle carriers and elevators as well as a model for calculating the energy requirement.

Findings: The results of this paper is the quantified energy saving by the application of the algorithm for situation-dependent adaption of velocity for SBS/RS

Originality: To our knowledge this is the first paper that introduces a situation-dependent adaption of velocity for SBS/RS.

Keywords: Shuttle Based Systems, Simulation, Energy Consumption, Velocity Adaption

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1. Introduction

SBS/RS consists of one or more shuttle carriers, at least one elevator, a rack structure and a control system (VDI-2692, 2015). Systems with aisle- and tier-captive shuttle carriers are often used for high troughput demands. Tier-to-tier shuttle carriers cannot change the aisle, but the tiers. In such cases, the shuttle carrier uses the elevator to change tiers. This usually leads to throughput-reducing waiting times (Kriehn, 2017). It is also possible to combine both systems. The combination is same as a tier-captive SBS/RS with an additional elevator for shuttle carriers.

Aisle- and tier-captive SBS/RS use a shuttle carrier for each tier, which cannot leave the tier. The shuttle carrier and the elevator use buffer locations at each tier to store or retrieve totes. As a result, the horizontal and vertical transport is largely decoupled from one another. Accordingly, aisle- and tier-captive SBS/RS can often achieve a higher throughput than tier-to-tier SBS/RS (Kriehn, 2017).

Figure 1 shows an aisle- and tier-captive, tier-to-tier and a combined SBS/RS.

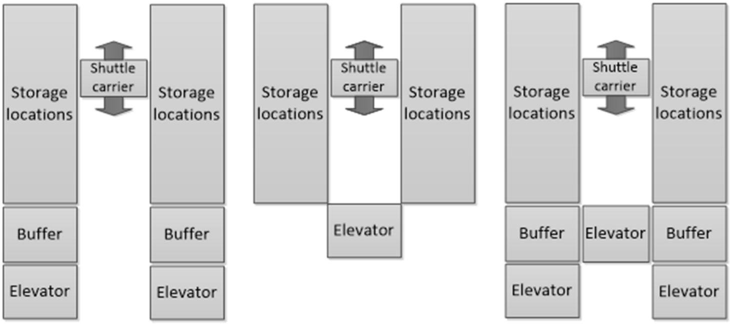

Figure 1: Tier-captive (left), tier-to-tier (middle) and combined (rigtht) SBS/RS, top view

The energy consumption of a SBS/RS can be decreased by reduced velocity of the shuttle carriers. But if the velocity is reduced permanently, the throughput also decreases. Therefore, the velocity should be lowered or increased depending on the situation. By reducing the velocity, no or only a small reduction of the throughput and the retrieval request processing time should occur. Therefore, the velocity should be adapted to the current situation in the SBS/RS. With only a few retrieval requests, the velocity should be relatively low, with many requests, the velocity should be relatively high. This paper presents an algorithm for that purpose.

We compare the energy consumption (calculated in Joule), the troughput (measured with a simulation model in totes per hour) and the retrieval request processing time (in seconds) with and without applying the algorithm for situation-dependent adaptation of velocity. The energy consumption of an SBS/RS consists of the energy consumption for elevators, shuttle carriers and tote handling attachments as well as the constant (standby) energy consumption. The throughput of an SBS/RS is the number of totes that are stored or retrieved in a certain time, e.g. in one hour. The retrieval request processing time is the time that a retrieval request spends in the SBS/RS. The time starts as soon as the retrieval request is received by the SBS / RS, and it ends as soon as the corresponding tote leaves the SBS/RS.

This paper is structured as follows: Chapter 1 gives an introduction. Chapter 2 contains an explanation of the existing literature on papers that deal with energy consumption for SBS/RS (2.1), the description of the analytical model for the calculation of the energy consumption (2.2) and the simulation model (2.3) as well as the algorithms for situation-dependent adaptation of velocity for shuttle carriers. (2.4). Chapter 2 ends with the results received by the applied algorithm (2.5). Chapter 3 contains a summary of the paper.

2. Models and algorithms

2.1 Literature

In (Ekren, 2018; Eder, 2017; Borovinsek, 2017; Akpunar, 2016; Lerher, 2016) models for calculating the energy consumption of SBS/RS are shown. In (Ekren, 2018; Borovinsek, 2017; Akpunar, 2016; Lerher, 2016) the power of the elevators and shuttle carriers are calculated with friction coefficients and multiplied by the travel time. This leads to the calculation of the energy consumption. With these analytical models, it is possible to show the potential in decreasing the velocity of shuttle carriers. With appropriate analytical models for calculating the throughput, e.g. in (Eder, 2017; Lerher, 2016), can also be shown how the achievable throughput decreases by lowering the velocity. It is also possible to measure the throughput with a simulation model, as we do in this paper.

In (Eder, 2017) the energy consumption is calculated on the basis of the law of conservation of energy. Coefficients of friction for horizontal movement are taken into account, but only for traveling with constant velocity. Our approach is the calculation of the energy consumption on the basis of the balance of forces. We consider for our model coefficients of friction for the entire route (acceleration, traveling with constant velocity, deceleration). The friction coefficient thus also increases the consumption of energy during the acceleration and reduces the recuperation of energy during the deceleration.

In this paper the reduction of energy consumption without or with very little loss of throughput is shown by applying the developed algorithm. The algorithm decreases and increases the velocity of the shuttle carriers depending on the number of retrieval requests. To our knowledge there is no other situation-dependent adaptation of the velocity of shuttle carriers published.

2.2 Analytical model to calculate energy consumption

The energy consideration includes the following motion processes:

- Movement lift,
- movement shuttle carrier, and
- movement tote handling attachement.

The movements can be divided into two movement patterns:

- Movement with only acceleration and deceleration (case 1) and
- movement, with acceleration, deceleration and a constant velocity component (case 2).

Figure 2 shows the movement sequence for case 1.

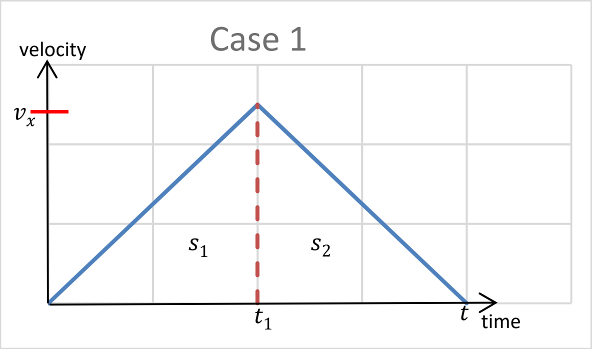

Figure 2: Movement sequence, case 1

s_1 is the distance traveled from the beginning to the end of the acceleration. s_2 is the distance traveled from the beginning to the end of the deceleration. The length of the distance s_1 has the numerical value of the area below the function line to t_1. t_1 is the time to reach v_x. t is the time required for the movement, from the beginning of the movement to the standstill of the mass. If acceleration and deceleration are identical, then s_1 and s_2 are equal ($s_1 = v_x \cdot \frac{t_1}{2} = s_2$). For different acceleration and deceleration values is $s_2 = v_x \cdot \frac{t_2 - t_1}{2}$. v_x is the achieved velocity. v_x is less than or equal to the maximum achievable velocity v.

Figure 3 shows the movement sequence for case 2.

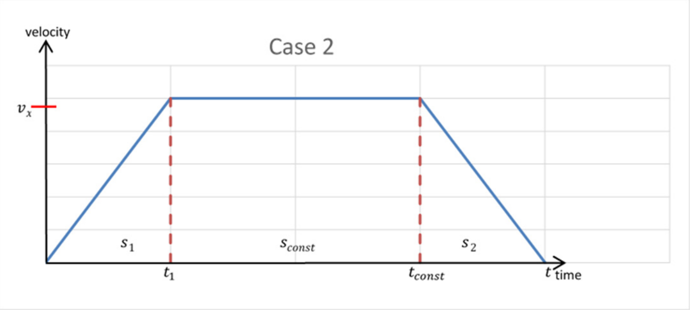

Figure 3: Case 2

s_{const} is the distance traveled at constant velocity.

Calculation of the critical distance to make a case distinction

Case 1 occurs when the distance to be traveled is less than or equal to the distance at which the maximum velocity is reached. Case 2 occurs when the distance to be traveled is greater than the distance at which the maximum velocity is reached. The distance required to reach the maximum velocity (and then immediately start with the deceleration) is referred to as the critical distance s_{crit}.

The critical distance is calculated as follows:

$$s_{crit} = \tfrac{a_1}{2}(t_1)^2 + \tfrac{a_2}{2}(t - t_1)^2$$

$$s_{crit} = \frac{a_1}{2}\left(\frac{v}{a_1}\right)^2 + \frac{a_2}{2}\left(\frac{v}{a_2}\right)^2$$

$$s_{crit} = \tfrac{1}{2}v^2\left(\tfrac{1}{a_1} + \tfrac{1}{a_2}\right) \tag{1}$$

a_1 denotes the acceleration, a_2 the deceleration.

Calculation of the travel time for case 1

It applies $s \leq s_{crit}$.

The travel time for case 1 is calculated as follows:

$$s = \frac{1}{2} {v_x}^2 \left(\frac{1}{a_1} + \frac{1}{a_2}\right)$$

$$v_x = \sqrt{\frac{2s}{\left(\frac{1}{a_1} + \frac{1}{a_2}\right)}}$$

$$t = \frac{v_x}{a_1} + \frac{v_x}{a_2}$$

$$t = \left(\frac{1}{a_1} + \frac{1}{a_2}\right) \sqrt{\frac{2s}{\left(\frac{1}{a_1} + \frac{1}{a_2}\right)}} \tag{2}$$

Calculation of the travel time for case 2

It applies $s > s_{crit}$.

The travel time for case 2 is calculated as follows:

$$t = \frac{v}{a_1} + \frac{v}{a_2} + \frac{s - s_{crit}}{v}$$

$$t = \frac{v}{a_1} + \frac{v}{a_2} + \frac{s - \frac{1}{2} v^2 \left(\frac{1}{a_1} + \frac{1}{a_2}\right)}{v}$$

$$t = \frac{v}{2}\left(\frac{1}{a_1} + \frac{1}{a_2}\right) + \frac{s}{v} \tag{3}$$

Calculation of the energy consumption of the vertical movement (elevator)

For the calculation of the energy consumption of the elevator movement, it is assumed that the elevator needs energy when moving upwards, and that it can maybe recover energy while moving downwards. If no energy can be recovered, since no recuperation is used, the recuperation efficiency is 0 percent, so no energy is consumed and none is recovered for moving downwards.

The energy consumption of an elevator movement upwards is calculated as follows:

$$E_{Elevator,up} = \frac{1}{\eta_{Elevator}} (m_{Elevator} + m_{Shuttle} + m_{Tote}) \cdot g \cdot s_{Elevator} \quad (4)$$

$\eta_{Elevator}$ is the efficiency factor of the elevator. $m_{Elevator}$ is the moving mass of the elevator. $m_{Shuttle}$ is the mass of the shuttle carrier. For tier-captive SBS/RS applies $m_{Shuttle} = 0$, since no shuttle carriers are transported by the elevator. m_{Tote} is the mass of the tote. If no tote is transported by the elevator, then m_{Tote} = 0. g is the gravitational acceleration. $s_{Elevator}$ is the vertical distance traveled.

The energy demand of an elevator movement downwards is calculated as follows:

$$E_{Elevator,down} = -\eta_{Elevator,Rekup} \cdot (m_{Elevator} + m_{Shuttle} + m_{Tote}) \cdot g \cdot s_{Elevator} \quad (5)$$

$-\eta_{Elevator,Rekup}$ is the recuperation efficiency factor of the elevator. If no recuperation is used, $-\eta_{Elevator,Rekup} = 0$. A negative value for the energy consumption corresponds to an energy recovery.

Calculation of the energy requirement of the horizontal movement (shuttle carrier or tote handling attachement) for case 1

Figure 4 shows the balance of forces of the horizontal movement during the acceleration process. The air resistance is neglected, due to low estimated impact.

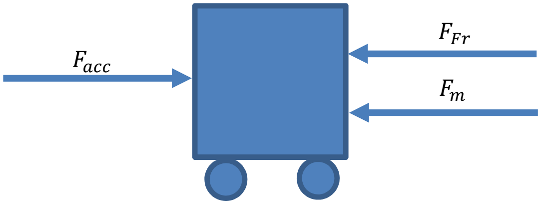

Figure 4: Balance of forces horizontal mass movement during acceleration

F_{acc} is the force needed to accelerate the mass. F_{Fr} is the friction force. F_m is the force of mass inertia.

The friction force is calculated as follows:

$$F_{Fr} = \mu_r \cdot F_N = \mu_r \cdot F_G = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g$$

$\mathrm{m_H}$ denotes the mass of the tote handling attachment (only the moving mass of it). μ_r denotes the coefficient of friction. When calculating a movement with a shuttle carrier, μ_r uses the coefficient of friction for the shuttle carrier, and when there is movement of the tote handling attachment, the coefficient of friction is applied to the tote handling attachment. When a movement of the tote handling attachment is calculated, then $\mathrm{m_{Shuttle}} = 0$. If there is no tote on the shuttle carrier unit during the move, then $\mathrm{m_{Tote}} = 0$.

The force of mass inertia is calculated as follows:

$$F_m = (m_{Shuttle} + m_{Tote} + m_H) \cdot a_1$$

The balance of forces of horizontal acceleration gives:

$$F_{acc} = F_m + F_{Fr} = (m_{Shuttle} + m_{Tote} + m_H) \cdot a_1 + \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g$$

The energy requirement for horizontal acceleration thus results:

$$E_{acc} = F_{acc} \cdot \mathrm{s}_1$$

$$E_{acc} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot s_1 + (m_{Shuttle} + m_{Tote} + m_H) \cdot a_1 \cdot s_1$$

$$E_{acc} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot s_1 + (m_{Shuttle} + m_{Tote} + m_H) \cdot a_1 \cdot \frac{1}{2} a_1 {t_1}^2$$

$$E_{acc} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot s_1 + (m_{Shuttle} + m_{Tote} + m_H) \cdot a_1 \cdot \frac{1}{2} a_1 \frac{{v_x}^2}{{a_1}^2}$$

$$E_{acc} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot \mathrm{s}_1 + \frac{1}{2}(m_{Shuttle} + m_{Tote} + m_H){v_x}^2$$

Ancillary calculation to express s_1 as a function of acceleration and deceleration and total distance traveled:

$$v_x = \sqrt{\frac{2s}{\left(\frac{1}{a_1} + \frac{1}{a_2}\right)}}$$

$$s_1 = \frac{1}{2} a_1 {t_1}^2$$

$$t_1 = \frac{v_x}{a_1}$$

$$s_1 = \frac{1}{2} a_1 \frac{{v_x}^2}{{a_1}^2}$$

$$ {v_x}^2 = \frac{2s}{\left(\frac{1}{a_1} + \frac{1}{a_2}\right)} = 2s \cdot \frac{a_1 \cdot a_2}{a_1 + a_2}$$

$$s_1 = \frac{1}{2} \frac{\left(\sqrt{\frac{2s}{\left(\frac{1}{a_1} + \frac{1}{a_2}\right)}}\right)^2}{a_1}$$

$$s_1 = \frac{1}{2} \frac{\left(\frac{2s}{\left(\frac{1}{a_1} + \frac{1}{a_2}\right)}\right)}{a_1}$$

$$s_1 = \mathrm{s} \frac{\left(\frac{1}{\left(\frac{1}{a_1} + \frac{1}{a_2}\right)}\right)}{a_1}$$

$$s_1 = \frac{s}{1 + \frac{a_1}{a_2}}$$

$$s_1 = s \frac{a_2}{a_2 + a_1}$$

Thus, the energy consumption of the acceleration can be formulated as follows:

$$E_{acc} = \mathrm{\mu_r} \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot s \frac{a_2}{a_1 + a_2} + (m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot \frac{a_1 \cdot a_2}{(a_1 + a_2)}$$

If we substitute $a = \frac{a_1 \cdot a_2}{(a_1 + a_2)}$, then follows:

$$E_{acc} = (m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot a \cdot \left(\mu_r \cdot g \cdot \frac{1}{a_1} + 1\right) \tag{6}$$

With consideration of an efficiency factor η_h, the energy requirement is:

$$E_{acc,h} = \frac{1}{\eta_h}(m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot a \cdot \left(\mu_r \cdot g \cdot \frac{1}{a_1} + 1\right) \qquad (7)$$

When a movement is calculated for a shuttle carrier, the efficiency factor for the shuttle carrier is used, when a movement of the tote handling attachement is calculated, the efficiency factor of the tote handling attachement is used.

In the following, the energy recovery during the deceleration is calculated. Figure 5 shows the balance of forces of horizontal mass movement during braking. Air resistance is neglected.

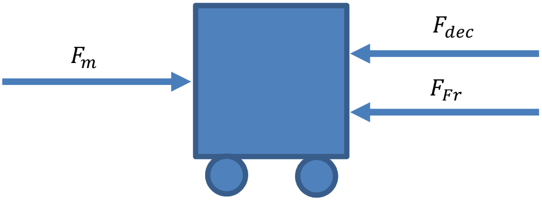

Figure 5: Force balance horizontal mass movement during deceleration

The balance of forces of the deceleration gives:

$$F_{dec} = F_m - F_{Fr}$$

The energy recovery of the deceleration thus results in:

$$E_{dec} = (F_m - F_{Fr})s_2$$

$$E_{dec} = (m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot a - \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot s \frac{a_1}{a_1 + a_2}$$

$$E_{dec} = (m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot a \cdot (1 - \mu_r \cdot g \cdot \frac{1}{a_2}) \qquad (8)$$

With consideration of the efficiency of the recuperation $\eta_{h,r}$, the energy recovery results in:

$$E_{dec,h} = \eta_{h,r}(m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot a \cdot (1 - \mu_r \cdot g \cdot \tfrac{1}{a_2}) \tag{9}$$

The total energy consumption for case 1 is calculated as follows:

$$E_{case1,h} = E_{acc,h} - E_{dec,h}$$

$$E_{case1,h} = \frac{1}{\eta_h}(m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot a \cdot \left(\mu_r \cdot g \cdot \frac{1}{a_1} + 1\right) -$$

$$-\eta_{h,r}(m_{Shuttle} + m_{Tote} + m_H) \cdot s \cdot a \cdot (1 - \mu_r \cdot g \cdot \frac{1}{a_2})$$

$$E_{case1,h} = (m_{Shuttle} + m_{Tote} + m_H) s \cdot a \left(\tfrac{1}{\eta_h}\left(\mu_r \cdot g \cdot \tfrac{1}{a_1} + 1\right) - \eta_{h,r}\left(1 - \mu_r \cdot g \cdot \tfrac{1}{a_2}\right)\right) \tag{10}$$

Calculation of the energy consumption of the horizontal movement (shuttle carrier or tote handling attachement) for case 2

In the case of the accelerated movement, in case 2, the achieved velocity is known (maximum velocity), therefore, the formulas for calculating the acceleration and the deceleration can be simplified as follows.

The energy consumption for the acceleration is calculated as follows:

$$E_{acc} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot \mathrm{s}_1 + \frac{1}{2}(m_{Shuttle} + m_{Tote} + m_H)v^2$$

$$E_{acc} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot \frac{v^2}{2a_1} + \frac{1}{2}(m_{Shuttle} + m_{Tote} + m_H)v^2$$

$$E_{acc} = \frac{1}{2}(m_{Shuttle} + \ m_{Tote} + m_H)v^2 \cdot \left(\mu_r \cdot g \cdot \frac{1}{a_1} + 1\right) \tag{11}$$

With consideration of the efficiency factor η_h, the energy consumption of the acceleration results:

$$E_{acc,h} = \frac{1}{2\eta_h}(m_{Shuttle} + \ m_{Tote} + m_H)v^2 \cdot \left(\mu_r \cdot g \cdot \frac{1}{a_1} + 1\right) \tag{12}$$

The energy recovery of the deceleration is calculated as follows:

$$E_{dec} = \frac{1}{2}(m_{Shuttle} + \ m_{Tote} + m_H)v^2 \cdot (1 - \mu_r \cdot g \cdot \frac{1}{a_2}) \tag{13}$$

Including the efficiency factor of the energy recovery $\eta_{h,r}$ of the deceleration results in:

$$E_{dec,h} = \frac{\eta_{h,r}}{2}(m_{Shuttle} + \ m_{Tote} + m_H)v^2 \cdot (1 - \mu_r \cdot g \cdot \frac{1}{a_2}) \tag{14}$$

The energy consumption of the constant velocity movement is calculated below. The balance of forces is shown in Figure 6.

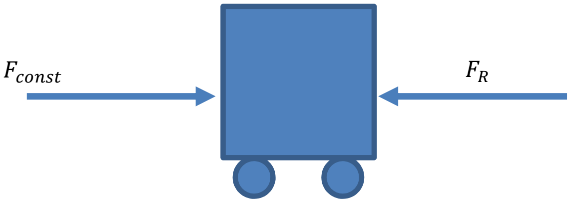

Figure 6: Balance of forces horizontal mass movement during constant velocity motion

The balance of forces results:

$$F_{const} = F_R$$

The energy consumption of the movement with constant velocity results in:

$$E_{const} = F_R \cdot \mathrm{s}_{const}$$

$$E_{const} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot s_{const}$$

$$E_{const} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot (s - s_1 - s_2)$$

$$E_{const} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot \left(s - \frac{v^2}{2}\left(\frac{1}{a_1} + \frac{1}{a_2}\right)\right) \qquad (15)$$

Taking into account the efficiency factor η_h results in the energy consumption:

$$E_{const,h} = \frac{1}{2\eta_h}\mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot \mathrm{g} \cdot \left(s - \frac{v^2}{2}\left(\frac{1}{a_1} - \frac{1}{a_2}\right)\right) \qquad (16)$$

The following summarizes the energy consumption of accelerated motion and constant motion:

$$E_{acc} + E_{const} = \mu_{roll} \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot s_1 + \frac{1}{2}(m_{Shuttle} + m_{Tote} + m_H)v^2 + \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot s_{const}$$

$$E_{acc} + E_{const} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot (s_1 + s_{const}) + \frac{1}{2}(m_{Shuttle} + m_{Tote} + m_H)v^2$$

$$E_{acc} + E_{const} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot (s - s_2) + \frac{1}{2}(m_{Shuttle} + m_{Tote} + m_H)v^2$$

$$E_{acc} + E_{const} = \mu_r \cdot (m_{Shuttle} + m_{Tote} + m_H) \cdot g \cdot (s - \frac{v^2}{2a_2}) + \frac{1}{2}(m_{Shuttle} + m_{Tote} + m_H)v^2$$

$$E_{acc} + E_{const} = (m_{Shuttle} + m_{Tote} + m_H)\left(\mu_r \cdot g \cdot \left(s - \frac{v^2}{2a_2}\right) + \frac{1}{2}v^2\right) \quad (17)$$

With consideration of the efficiency factor η_h, the energy consumption is:

$$E_{acc,h} + E_{const,h} = \frac{1}{2\eta_h}(m_{Shuttle} + m_{Tote} + m_H)\left(\mu_r \cdot g \cdot \left(s - \frac{v^2}{2a_2}\right) + \frac{1}{2}v^2\right) \quad (18)$$

The total energy consumption for case 2 is:

$$E_{case2,h} = E_{acc,h} + E_{const,h} - E_{dec,h}$$

$$E_{case2,h} = \frac{1}{2\eta_h}(m_{Shuttle} + m_{Tote} + m_H)\left(\mu_r \cdot g \cdot \left(s - \frac{v^2}{2a_2}\right) + \frac{1}{2}v^2\right) - \frac{\eta_{h,r}}{2}(m_{Shuttle} + m_{Tote} + m_H)v^2 \cdot \left(1 - \mu_r \cdot g \cdot \frac{1}{a_2}\right)$$

$$E_{case2,h} = (m_{Shuttle} + m_{Tote} + m_H)\left(\frac{1}{2\eta_h}\left(\mu_r \cdot g \cdot \left(s - \frac{v^2}{2a_2}\right) + \frac{1}{2}v^2\right) - \frac{\eta_{h,r}}{2}v^2 \cdot \left(1 - \mu_r \cdot g \cdot \frac{1}{a_2}\right)\right) \quad (19)$$

2.3 Simulation Model

The simulation model was developed as part of the research project SmartShuttle. This paper focuses is on the description of the situation-dependent adaptation of velocity for SBS/RS. The simulation model, however, includes other storage management policies, such as class-based storage, sequencing of retrieval requests, dwell point strategies, and warehouse reorganisation. The model can be configured online (http://smartshuttle.hs-heilbronn.de), the simulation run is started after entering the configuration data (size of the warehouse, velocity of elevators and shuttle carriers, etc.) on the server. The user receives the results automatically after the simulation run is completed. This takes approximately five to thirty minutes.

The simulation model can be used for tier-captive and tier-to-tier SBS/RS, see Figure 1. In addition, a combined version can also be simulated by adding an elevetator in the middle of the aisle for transporting shuttle carriers to an originally tier-captive SBS/RS, see also Figure 1 (then not all tiers need to be occupied by shuttle carriers). In the combined version, the elevator in the middle is only responsible for transferring unloaded shuttle carriers to another tier on the basis of corresponding requests. The simulation is based on the software AutoMod. The visualization of the simulation model is three-dimensional. Figure 7 shows a visualization example of the simulation model with a tier-to-tier configuration.

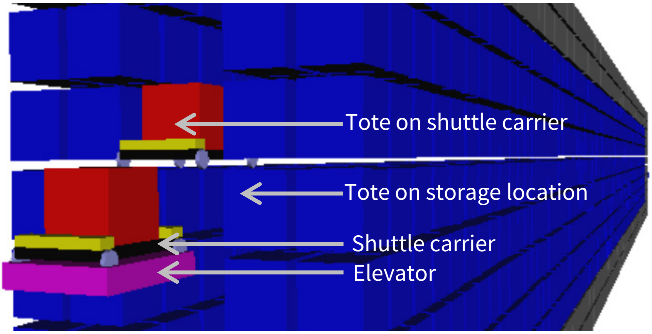

Figure 7: Visualization of the simulation model

For the simulations performed for this paper, the capacity of the elevator and shuttle carriers is one. This paper uses the simulation model for tier-to-tier SBS/RS. The simulation model can simulate single- and double-deep SBS/RS. Also retrieval requests can be given as input, over a period of twenty four hours. The retrieval requests entered per hour are equally distributed during the hour in the SBS/RS. As soon as a retrieval request has been completed by the SBS/RS, it waits for a configurable time before it is sent to the SBS/RS as a storage request. Elevator and shuttle carriers travel singe- or dual-command cycles, depending on the current request situation. An attempt will be made whenever possible to travel dual-command cycles. Each tier can accommodate a maximum of one shuttle carrier. Figure 8 shows the process of single- and dual-command cycles of elevator and shuttle carriers.

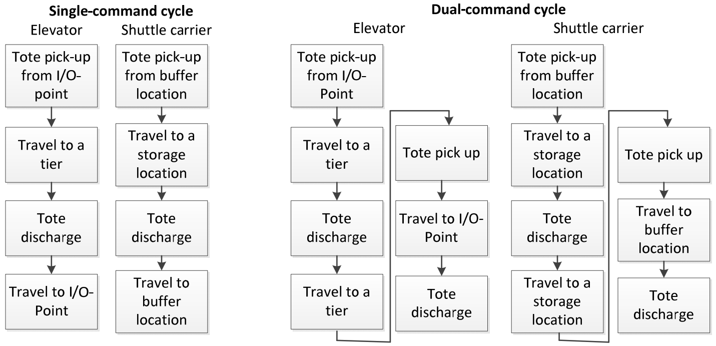

Figure 8: Single- and dual-command cycle of elevator and shuttle carrier

The following outputs of the simulation run were measured: energy consumption of the shuttle carriers, energy consumption of the entire SBS/RS, throughput of the SBS/RS (one aisle is considered) and retrieval request processing time. The energy consumption of all shuttle carriers is measured every hour over a simulation period of twenty four hours. The troughput of the SBS/RS and the retrieval request processing time is also measured every hour. The retrieval request processing time refers to a single position of an order. In result when a tote leaves the SBS/RS, the retrieval request processing time for it is measured. The retrieval requests are assigned to an order (positions of an order). The quantity of retrieval requests that belong to an order influences the retrieval request processing time, since the SBS/RS then simultaneously enters this quantity of retrieval requests at an equally distributed time within the hour. If there are many orders entering the system, then the retrieval request processing time increases. For this study, the amount of retrieval requests assigned to an order is equally distributed between one and nine. The storage management policy closest-location is used. Elevator and shuttle carriers travel to the closest possible location to store a tote. That leads to random storage assignment in the filled area of the aisle, because every tote in the SBS/RS is chosen with the same probability to be retrieved. In result totes that entering the SBS/RS could be stored in this (new) free storage locations. The dwell-point is point-of-service-completion (POSC). The retrieval request processing follows the first-in-first-out (FIFO) principle by the shuttle carriers within the tiers. The elevator also follows the FIFO-principle. However, in the case of many retrieval requests, some retrieval requests may have longer waiting times, since there is no shuttle carrier in the corresponding tier and the elevator travels to the closest location to transport a shuttle carrier to another tier.

2.4 Algorithm for adaption of velocity

The algorithm is based on a closed loop control with three-step controller with hysteresis, as described in the literature, e. g. in [1]. Figure 9 shows the controller output (velocity) depending on the controller input (waiting retrieval requests).

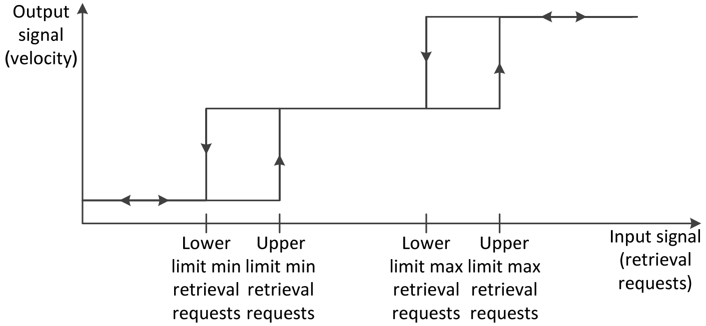

Figure 9: Output signal from the three-step controller, dependent from the input signal

The algorithm includes storage requests as another input signal. If the storage requests exceed a configurable limit, the highest velocity is issued, regardless of the number of waiting retrieval requests. This can prevent long queues forming at the entry point of the SBS/RS. The behavior of the three-step controller, as shown in Figure 9, only occurs as long as there are fewer waiting storage requests than the configured limit. In addition to the velocity adjustment, an adaptation of the acceleration and the deceleration takes place.

The algorithm is shown below:

```
if retrieval requests >= upper limit max retrieval requests or storage requests >= limit storage requests
    set velocity, acceleration, deceleration to max value
else
    if retrieval requests =< lower limit max retrieval requests and velocity = max) or (retrieval requests >= upper limit retrieval requests min and velocity = min)
        set velocity, acceleration, deceleration to middle value
    else
        if retrieval requests <= lower limit retrieval requests
            set velocity, acceleration, deceleration to min value
```

In the simulation model, the algorithm is executed after each completed cycle of the elevator and the variable values for velocity, acceleration and deceleration are set. The shuttle carriers check the variables before each travel and the values are updated.

2.5 Results

In the following, the influence of a situation-dependent adaption of the velocity on the energy consumption for different variants is shown.

Table 1 shows the constant parameter values of the simulated SBS/RS. Table 2 shows the variants.

Table 1: Constant parameter values

Parameter	**Value**
Distance between tiers [m]	0.4
Distance between first tier and I/O-point [m]	-1
Distance between aisle and first storage position in lane [m]	0.5
Distance between aisle and second storage position in lane [m]	1
Storage positions per tier	100
Distance between storage positions	0.5
Velocity tote handling attachment, unloaded	2
Velocity tote handling attachment, loaded	1
Acceleration and deceleration tote handling attachment, unloaded	2

Parameter	Value
Acceleration and deceleration tote handling attachment, loaded	1
Friction coefficient for shuttle carrier	0.06
Friction coefficient for tote handling attachment	0.5
Storage ratio [%]	95
Mass elevator	100
Mass shuttle carrier	100
Mass tote	50
Mass tote handling attachment	15
efficiency factor for energy consumption elevator [%]	70
efficiency factor for energy consumption shuttle carrier [%]	70

Parameter	Value
efficiency factor for energy consumption handling unit [%]	70
efficiency factor for energy recuperation elevator [%]	40
efficiency factor for energy recuperation shuttle carrier [%]	40
efficiency factor for energy recuperation tote handling attachment [%]	40
Time Gap until a retrieved tote enters the SBS/RS to be stored [s]	500 +-100
SBS/RS	Tier-to-tier, double-deep
Tiers	12
Velocity elevator	4
Acceleration elevator	4

Parameter	Value
Velocity shuttle carrier	7
Acceleration shuttle carrier	6
Pick-up and set-down time shuttle carrier	4
Velocity reduction middle [%]	60
Velocity reduction min [%]	90

Table 2: Variants

Variant	1	2	3	4	5	6	7	8
Retrieval requests per hour(	100, 70, 90, 150, 200, 300, 50, 30, 170,	100, 70, 90, 150, 200, 300, 50, 30, 170,	100, 200, 300, 150, 100, 50, 30, 10, 20,	100, 200, 300, 150, 100, 50, 30, 10, 20,	100, 200, 300, 150, 100, 50, 30, 10, 20,	100, 200, 300, 150, 100, 50, 30, 10, 20,	100, 70, 90, 150, 200, 300, 50, 30, 170,	100, 70, 90, 150, 200, 300, 50, 30, 170,

	120, 100, 50, 30, 140, 230, 120, 100, 90, 40, 30, 20, 10, 25, 10	120, 100, 50, 30, 140, 230, 120, 100, 90, 40, 30, 20, 10, 25, 10	30, 10, 20, 30, 100, 150, 120, 100, 90, 40, 30, 20, 10, 25, 10	30, 10, 20, 30, 100, 150, 120, 100, 90, 40, 30, 20, 10, 25, 10	30, 10, 20, 30, 100, 150, 120, 100, 90, 40, 30, 20, 10, 25, 10	30, 10, 20, 30, 100, 150, 120, 100, 90, 40, 30, 20, 10, 25, 10	120, 100, 50, 30, 140, 230, 120, 100, 90, 40, 30, 20, 10, 25, 10	120, 100, 50, 30, 140, 230, 120, 100, 90, 40, 30, 20, 10, 25, 10
Upper limit max retrieval requests	50	20	50	20	50	20	50	20
Lower limit max retrieval requests	40	10	40	10	40	10	40	10

Upper limit min retrieval requests	30	5	30	5	30	5	30	5
Lower limit min retrieval requests	20	2	20	2	20	2	20	2
Shuttle carriers	5	5	5	5	2	2	3	3
Pick-up and set-down time elevator	4	4	4	4	4	4	1	1

Figure 10 to 15 shows the energy consumption for the shuttle carriers (only for traveling, without tote handling), the throughput of the SBS/RS and the retrieval processing time for all variants. The retrieval request processing time is the average of all retrieval request processing times of one hour. It is calculated separately for each hour.

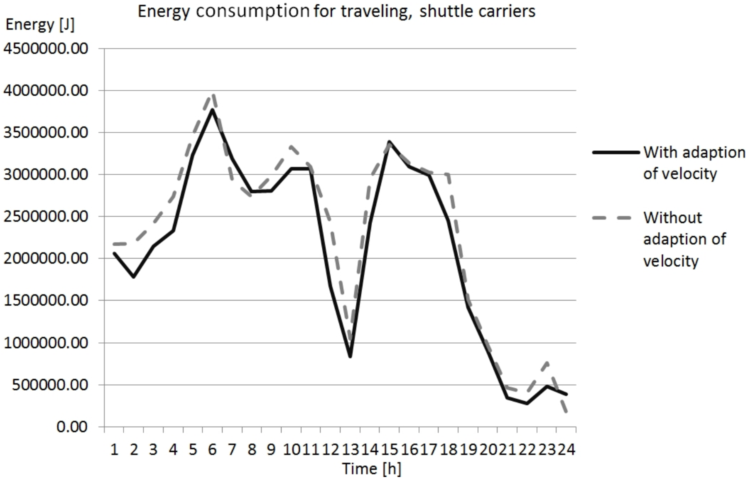

Figure 10: Energy consumption for traveling, shuttle carriers, variant 1

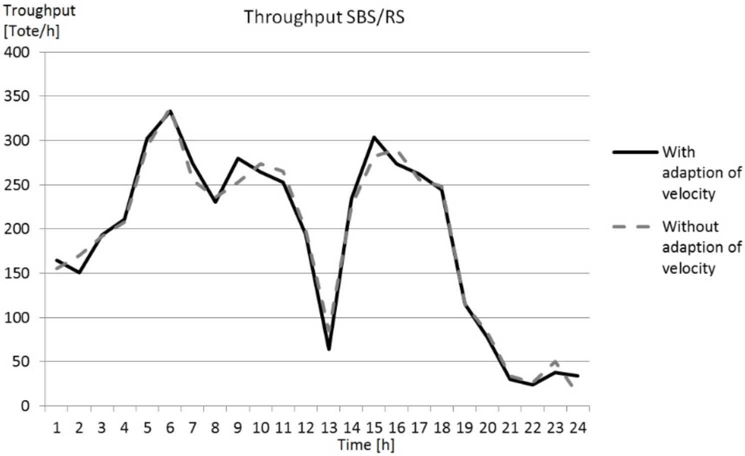

Figure 11: Throughput SBS/RS, variant 1

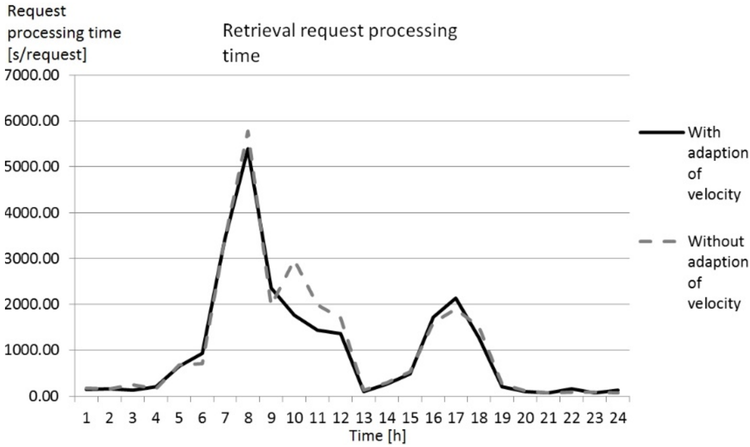

Figure 12: Retrieval request processing time, variant 1

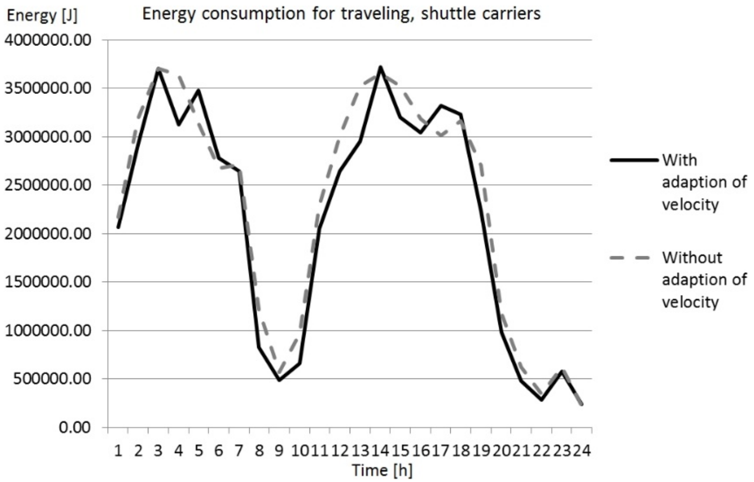

Figure 13: Energy consumption for traveling, shuttle carriers, variant 3

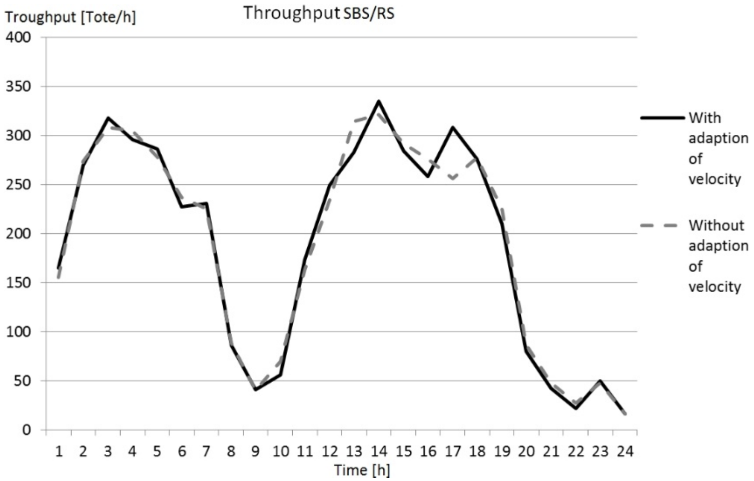

Figure 14: Throughput SBS/RS, variant 3

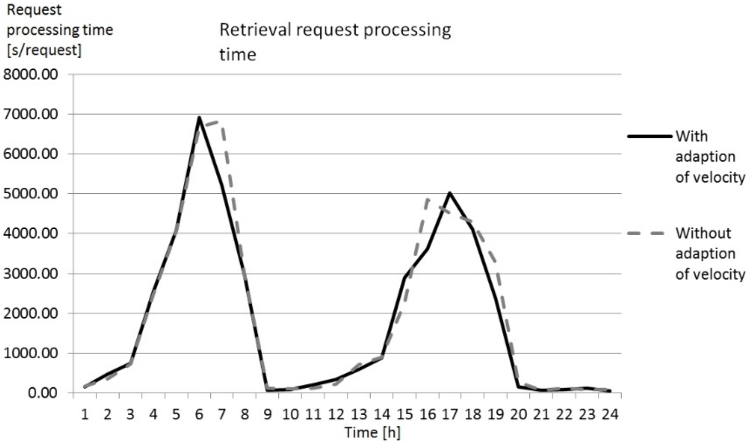

Figure 15: Retrieval request processing time, variant 3

Table 3 shows the energy consumption for the shuttle carriers and the SBS/RS (including tote handling, elevator and shuttle carrier traveling) without constant (or standby) energy consumption for elevator and shuttle carriers. Constant energy consumption is the consumption of energy that is independent from traveling or tote handling. Whether an elevator or shuttle carrier is active with traveling/tote handling or not, this value remains the same.

Table 3: Energy consumption of variants

	Energy consumption shuttle carriers [J/(24 h)]	Energy consumption for SBS/RS [J/(24 h)]	Reduction of energy consumption shuttle carriers [%]	Reduction of energy consumption SBS/RS [%]
Variant 1 with adaption of velocity	50918139	71377549	7.85	5.86
Variant 2 with adaption of velocity	51128641	71292362	7.47	5.97
Variant 1 and 2 without adaption of velocity	55258511	75817101		

	Energy consumption shuttle carriers [J/(24 h)]	**Energy consumption for SBS/RS [J/(24 h)]**	**Reduction of energy consumption shuttle carriers [%]**	**Reduction of energy consumption SBS/RS [%]**
Variant 3 with adaption of velocity	51647973	72075765	6.14	4.07
Variant 4 with adaption of velocity	52486542	72757432	4.62	3.17
Variant 3 & 4 without adaption of velocity	55028070	75137493		

	Energy consumption shuttle carriers [J/(24 h)]	Energy consumption for SBS/RS [J/(24 h)]	Reduction of energy consumption shuttle carriers [%]	Reduction of energy consumption SBS/RS [%]
Variant 5 with adaption of velocity	53132358	73301028	1.89	1.23
Variant 6 with adaption of velocity	53790160	74044842	0.67	0.23
Variant 5 & 6 without adaption of velocity	54153257	74217491		

	Energy consumption shuttle carriers [J/(24 h)]	**Energy consumption for SBS/RS [J/(24 h)]**	**Reduction of energy consumption shuttle carriers [%]**	**Reduction of energy consumption SBS/RS [%]**
Variant 7 with adaption of velocity	50094455	71169149	12.00	8.76
Variant 8 with adaption of velocity	52937432	74093209	7.00	5.01
Variant 7 & 8 without adaption of velocity	56925019	78000624		

As can be seen in the figures, throughput is only slightly changed by the adaptation of the velocity. In the first four variants, the lift is the major bottleneck, as the SBS/RS is equipped with five shuttle carriers. For variants five and six, the shuttle carriers are the bottleneck, since only two shuttle carriers are used. The retrieval request processing time increases slightly due to the velocity adaption during peak times for variants five and six. Variants five and six have an retrieval request entry that uses the SBS/RS with many retrieval request at peak times and rarely otherwise. Since only two shuttle carriers are available, the achievable maximum throughput is lower. This creates a long queue at the peak. The SBS/RS therefore runs at maximum velocity most of the time. Only when the queue is reduced, the velocity is reduced. Reducing of the queue takes longer than with variants three and four (which have the same hourly retrieval requests) due to fewer shuttle carriers in the SBS/RS. Since only very few retrieval requests are received between the two peaks, only a few retrieval requests are processed correspondingly at a reduced velocity.

Variant seven has the highest savings potential, here the retrieval request intake is rather evenly distributed, there are also two peaks, but in the meantime more retrieval requests are coming into the system. Accordingly, it is more often possible to travel at reduced velocity. Variation seven also has broader limits for the algorithm, so the velocity is reduced earlier respectively increased sooner. Nevertheless, the throughput and the retrieval request processing time is only slightly affected.

The influence of the broadened limits for the algorithm is most apparent when comparing variants five and six. Variant five has the broader limits and the retrieval request processing time is significantly higher at the second peak than at variant six, in which narrower limits are used.

Accordingly, the application of the algorithm depends on a suitable parameterization of the limits. The broader the limits, the more energy can be saved. At the same time, from a certain point on, a significant reduction in throughput and retrieval request processing time occurs. These should be avoided. Narrowed limits leads to less influence of the algorithm to save energy.

The retrieval request situation also has an impact on energy savings: if the SBS/RS receives more retrieval requests than it can handle, a long queue is formed. Then, the velocity cannot be reduced until the queuing is largely reduced. If there are subsequently no phases with request entries below the achievable throughput of the SBS/RS, there is little potential for saving energy. Velocity can only be reduced while the retrieval requests intake is less than maximum throughput.

The variants show that often energy savings of more than 5% are possible without having a significant effect on the throughput achieved and the retrieval request processing time. The energy consumption for the traveling of the shuttle carriers could be reduced in the variants up to 12 percent and the total energy consumption up to 8.76 percent.

3. Conclusion

This paper shows an analytical model for the energy calculation of SBS/RS and an algorithm for situation-dependent velocity adaptation. The analytical model is based on the balance of forces of the moving masses. For the horizontal movement the friction was considered. This model can be used to determine the energy consumption of the elevators, the shuttle carriers and the tote handling attachement. The algorithm is based on a three-step controller. The input signal is the number of retrieval requests. The output signal is one of the three velocity levels. The algorithm is configurable and can be adapted to a specific SBS/RS. If the limits for adjusting the velocity are chosen to be relatively high, a higher amount of energy can be saved. Excessive limits can lower throughput, however. The algorithm reduces the energy consumption, but at the same time the throughput is hardly influenced by proper parameterization. The algorithm and the energy model were applied within a simulation model of an SBS/RS. Results for energy saving and minimal impact on throughput and retrieval request processing time were shown.

Further interesting research topics for future work:

- The analytical energy model does not calculate energy savings by lowering the velocity of the elevator, so the velocity of the elevator was not lowered by the algorithm. By extending the model, it would be possible to calculate reductions of energy consumption by velocity regulation of the elevator. The algorithm allows shuttle carriers and elevators to reduce their velocity.
- The algorithm can be optimized in terms of energy savings, possibly by increasing the steps (multi-step controller) or another closed loop control.
- The input size for the algorithm can be changed. It does not necessarily have to be the quantity of retrieval requests that causes the velocity adaption, it may also be the waiting time of the shuttle carriers or the utilization of shuttle carriers. It is also conceivable to adjust the velocity to request-related priorities or specified deadlines.

- Methods of artificial intelligence, e.g. for deep reinforcement learning for adapting the velocity and optimize energy savings for SBS/RS.
- Furthermore, a velocity reduction also leads to less maintenance costs, and this relationship could be explored in the future.

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