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Differences in the Throughput Performance of the Warehouse Depending on the Quality of the Calculation Parameters

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***Abstract*—This article explores the quality level of the parameters that are used to determine the throughput performance of the warehouse. In our model case, this is a rack warehouse where the storage and picking of goods is ensured by forklifts. All kind of goods are stored on pallets. The aim of our research is to assess to what extent the quality level (accuracy) of the description of warehouse processes influences the accuracy of the determination of the throughput performance of the warehouse. In the first part of the article, we defined the parameters and the ways in which different levels of quality can be obtained for the values of these parameters. These include, for example, acceleration and deceleration values of the forklift truck and the speed of the forklift, with and without the goods. To obtain these values, measurements were taken directly in the warehouse. In the next part of the paper, attention is paid to the value of the difference in the results in the determination of the throughput performance assuming the different quality of the description of the warehouse processes. In particular, the relationship between the significance of the difference and the difficulty of obtaining exact parameters with a higher level of quality level is investigated. This relationship will help in practice to determine the extent to which inventory processes need to be described as accurately as possible and where different forms of simplification can be used without the resulting throughput performance being determined with a significant error or deviation. By comparing the level of process description quality, it is also possible to identify the parameters that influence the accuracy of the throughput performance more closely.**

Keywords—throughput, performance, warehouse

I. Introduction

Optimizing the internal layout of the warehouse and the activities that take place there is undoubtedly a very demanding activity. Individual optimization methods are created with regard to the characteristics of the warehouse and the technology used to store and receive goods in the warehouse. Optimization methods differ from each other, among other things, in what optimization criteria are included in them and what is the level (quality) and the depth of description of the individual processes in the warehouse. The quality of process descriptions for the purposes of this article is, for example, the use of average values (low level of description) or values defined by probability distribution with an appropriate level of reliability (high level of description). Thus, it is clear that using one optimization method the different results can be obtained depending on the accuracy of the description of ongoing processes. But the question remains whether the difference between these results will be significant or not. In other words: Does the increase in the level of process description mean a significant improvement in the value of optimization criteria and thus some savings (financial, time, etc.)?

The topic of warehouse performance is devoted to several authors. The reference [1] is focused on how to use a forklift truck in terms of energy consumption. Among other things, he concluded that the acceleration and deceleration value had the greatest impact on energy consumption. The movement of the forklifts describes as a succession of acceleration, driving at almost constant speed and deceleration. However, he did not examine how the calculated value of the energy consumed would change if the detailed description of the driving characterization was replaced, for example, by the average speed with the neglect of the acceleration and deceleration phases. Authors of [2] deals with the time of movement and consumption of energy in storage with the AS/RS system. For a warehouse with forklifts, this calculation needs to be adjusted. In the [3], it is possible to find the principle of minimizing energy consumption in the warehouse using genetic algorithms. The genetic algorithm is used to create batches and track routes in warehouse at order picking so that the total energy consumption is as small as possible. The speed of forklift trucks was used to determine energy consumption, but with neglect of acceleration and deceleration in the start and end phases.

II. Theoretical Basis

A. Decomposition of the Handling Time

The method of determining the permeability of the warehouse depends on many factors. The main factors include, in particular, the type of stored goods, the type of handling units, the picking method and the type of handling equipment. In our case, the goods are stored exclusively on pallets that are manipulated by forklifts. The pallets are stored in shelves in which six positions are available vertically. The pallets are handled from the front of the forklift. To retrieve or store the pallet, it is therefore necessary to turn the forklift 90 degrees relative to the direction of travel.

In order to determine the permeability of the warehouse, it is necessary in this case to determine the time for which the pallet is picked up from or stored on its storage position. By this time, it is possible to determine the total amount of pallets that can be processed during work shift or during another period. Pallet handling time is expressed as the sum of the time needed to perform partial tasks. It can be expressed by the equation

$$T_r = t_{mt} + 2t_t + 2t_l + t_{mf} \tag{1}$$

where T_r is the total time required to pick up the pallet without including external influences, t_{mt} is the travel time from the depot to the pallet storage position, t_t is the time of the curve facing the rack and when the forks are inserted under the pallet (possibly lifting the forks with the pallet), t_l is the lifting time or pallet laying and t_{mf} is driving time back to the depot. Equation (1) can be completed with the amount of time t_{lu} needed to reach the required level of the rack in the upward direction and t_{ld} to lower the forks to the driving position. These two times, however, are not counted in the total time because the lifting or lowering of the forks usually takes place at the same time as slowing down and turning to the shelf or by turning from the rack and accelerating. To count the time of concurrent activities, it is possible to use the coefficient γ, which expresses how many percent of the duration of the action takes place concurrently with another act whose duration is counted in its entire length. In this case, we use the γ_u and γ_d coefficients one for the lifting and the other for the lowering the fork. Both coefficients can take values from the interval <0; 1>, where 0 means that the whole operation is performed in less time than the time required to complete the concurrent activity and value 1 is used when the operation is performed independently without concurrent with another activity. Equation (1) then looks like this

$$T_r = t_{mt} + 2t_t + \gamma_u t_{lu} + 2t_l + \gamma_d t_{ld} + t_{mf} \tag{2}$$

Equations (1) and (2) apply if the carriage departs from a depot without pallet directly to the picking point and, after loading, returns directly to the depot. However, it is also possible to consider the case where the pallet is transported out of the depot to the store position, and after this operation, another pallet is picked up and brought into the depot. Formula (2) will then be modified as follows:

$$T_r = t_{mt} + 4t_t + \gamma_u \Sigma t_{lu} + 4t_l + \gamma_d \Sigma t_{ld} + t_{mb} + t_{mf} \tag{3}$$

where t_{mb} is the driving time from the unloading position to the loading position. Coefficients γ are considered constant for individual segments.

All of these partial times are dependent on other parameters, such as the distance between the depot and the storage position, the velocity of the movement and the acceleration or deceleration, the trip with or without the load, the height of the storage position, etc. Only in the case of the turn time t_t and the lifting or laying time of the palettes t_l is the difference between turn with a palette and without a palette at the measurement accuracy boundary. Therefore, this time is considered to be constant and independent of other actions.

B. Dependencies of Individual Parameters

In terms of the share of individual times in the total time of manipulation T_r, the most important parameters are the times t_{mt} and t_{mf}. Many authors state that they only use the maximum speed and distance when calculate this time, and for the sake of simplicity, they are counting at the maximum speed from the start of the journey. Similarly, this is also the case for stopping. The starting and braking phase at the start and at the end of the movement is thus omitted. Also the effect of curves (in most rectangular warehouses) on driving time, the effect of passage of junctions in the warehouse and other movements of persons or means of transport in the warehouse is also eliminated.

The driving time t_{mt} or t_{mf} can be expressed on the basis of the motion equation as follows:

$$t_{mt} = \frac{v_{max}}{a_a} + \frac{s_r}{v_{max}} + \frac{v_{max}}{a_d} \tag{4}$$

where v_{max} is the maximum speed at which the forklift moves, a_a is the value of acceleration at start, a_d is the value of acceleration (deceleration) in braking, and s_r is the distance at which the forklift moves at maximum speed. The distance s_r is determined by:

$$s_r = s - \frac{v_{max}^2}{2a_a} - \frac{v_{max}^2}{2a_d} \tag{5}$$

Where s is the total distance from the depot to the storage position. This calculation is closer to reality as it involves both starting and braking. The speed of the forklift is thus not reached immediately, but only after the corresponding time, depending on the initial acceleration.

According to the above equations, it is possible to determine the driving time that is not affected by any external factors. For more accurate calculation, it is also necessary to include cornering passages in which the forklift moves below the maximum speed. Including the one-turn passage extends the calculated driving time by the Δt_c time. This value is determined as the difference between the time at which the curve can be driven through at maximum speed and the time, including the deceleration before curve to decrease the speed, curving through the curve at reduced speed and acceleration to the maximum speed behind curve. The magnitude of the acceleration and deceleration values is considered the same as for starting and stopping the truck at the start and end of the journey. In the case of multiple turns' passage from the depot to the storage position, the time difference is counted as $n_c\Delta t_c$, where n_c is the (average) number of curves on the route.

It is also necessary to consider the crossing of the junctions for the calculation. As in the case of curves, when crossing the junction, the driving time is increased by Δt_{xp}, which represents the difference between the maximum speed throughput and the reduced speed for passing through the intersection. According to the number of intersections, the total time required for their passage is equal to $n_x \Delta t_{xp}$, where n_x is the (average) number of crossings on the route. In the event that a crossing is passed in a non-direct direction, it is necessary to decide which of the Δt_c or Δt_{xp} time increments will be included in the calculation. If we consider the same reduced speed for the passage through the curve and the crossing through the intersection ($v_{rc} = v_{rx}$), only one of the extras is counted. For different speeds, the greater of the Δt_c and Δt_{xp} values will be included in the total time.

In some cases, it is necessary to stop at the junction and wait for the free passage. The total travel time is then extended by Δt_{xs}. However, this surcharge can not be included in the calculation according to the number of intersections. Determining the Δt_{xs} value depends on the average wait time at one junction. Thus, the Δt_{xs} time is determined based on the probability distribution of the waiting times at the junctions, which must be determined experimentally by the direct measurement in the warehouse. Since there is no need to wait at the junction every time it is passed, the time Δt_{xs} is not counted in the total time according to the number of intersections, but it is based on probability that the forklift will stop at intersection. This probability is dependent on the intensity of movement of other means of transport within the warehouse. At greater intensity (the greater the number of moving carts in the warehouse), the probability of stopping at the junction will be greater. This dependency has not been determined for the purpose of this article and has been replaced by the mean value of the stopping number at the junction. The time Δt_{txs} was used to calculate the total driving time, which includes both the probability of waiting at the junction (mean number of stops at the junction) and the mean waiting time at the junction.

It is also possible to influence the driving time of the forklift by considering that the free passage through the aisle between the shelves is not always guaranteed. It is possible to manipulate another forklift in the aisle, which cannot be traversed due to the aisle width and the second forklift must be stopped. There may also be a case of overtaking another forklift at a reduced speed. The total time offset Δt_{tb} is then determined similarly to the transition and stop at the intersection with probabilities. Also, in this case, the intensity of the movement of other means of transport in the warehouse and the frequency of their handling in the aisles affects the Δt_{tb} value.

The total travel time T_t to pick up one pallet with all influences is determined by the following equation:

$$T_t = T_r + n_c \Delta t_c + n_x \Delta t_{xp} + \Delta t_{txs} + \Delta t_{tb} \tag{6}$$

The last, not mentioned parameters in (2) are the time t_{ld} and t_{ld}, which represent the time of lifting or lowering the forks to the storage position in the rack. As has been mentioned, part of this time can take place simultaneously with the ride, which is expressed by the coefficient γ. The value of the t_{ld} and t_{ld} parameters depends primarily on the maximum lifting or lowering speed and usually reaches about 0.7 m/s for forklift trucks. The second factor that affects the value of t_{lu} and t_{ld} is the height of the storage position in the rack. The particular location of the pallet depends primarily on the way the warehouse is organized for warehousing. Thus, it is clear that if the maximum storage permeability should be as high as possible, it is advisable to set these parameters to low values. Thus, if goods with different turnover speeds are stored in the warehouse, it is appropriate that the goods that are removed more frequently are placed in the lower shelf positions. The issue of choosing a warehouse position is described by many authors and is not focused in this article.

III. Determination of Parameter Values

The values of some of the above mentioned parameters can be determined by their direct measurement in the warehouse, others need to be determined based on the probability distribution, which can also be based on the measurement set directly in the warehouse. For the purposes of this article, a direct measurement of the acceleration and deceleration values of the forklift truck was made.

To carry out the measurements, it was first necessary to construct a measuring device (accelerometer). As an optimum with regard to accuracy and cost, the Arduino development platform was selected to which the ADXL 345 accelerometer module was attached. This module includes a three axis accelerometer. In our case, only to measure the acceleration in the direction of the longitudinal axis of the forklift is needed. Values for the other two directions were not recorded. A module for connecting a SD card was also connected to the Arduino platform. The measured values were stored in a text format on a memory card, and later were processed on the computer.

Before the measurement was started, it was necessary to decide what the sensitivity of the measuring module would be set. The used module allows to set four acceleration measurement ranges: ± 2g, ± 4g, ± 8g and ± 16g. Due to the assumed acceleration values of the forklift, a measurement range of ± 2g has been selected, This range can fully cover the measured values. In addition, it was necessary to select the measurement frequency. This was selected at 10 Hz with respect to the duration of the measurement and to the volume of recorded data. The measuring device was attached to the trolley in exact horizontal position and in the direction in which the measured acceleration direction was identical to the longitudinal axis of the forklift. Horizontal stowage is very important because the accelerometer module also measures Earth's gravitational acceleration. If the measured direction is not perpendicular to the gravitational acceleration direction of the Earth, non-zero values would be recorded at rest.

At the same time, a video was taken along with the measurement, which was used to identify the forklift mode when processing the measured data. During the measurements, a normal work activity was carried out with the forklift, i.e. picking up the pallet and storing the pallet at the storage site. The measurement was followed by the processing of measured data. First, a correction factor has been determined to eliminate the not exactly accurate horizontal placement of the measuring device. In the rest position, an acceleration value of 0.02 m/s^2 was measured. This value was then used as correction for all measured data.

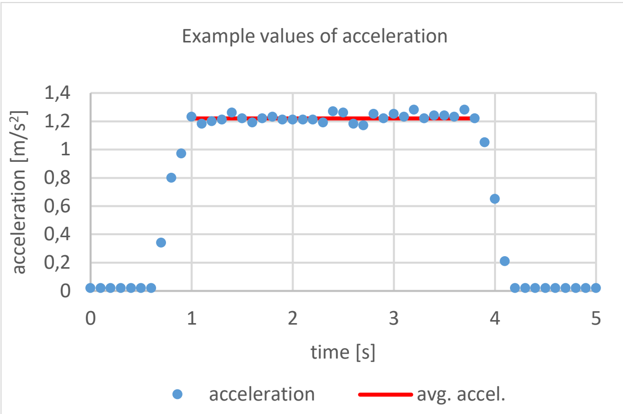

Fig. 1. Example of measured values

Further, there have been identified areas in which acceleration or deceleration occurred in the measured direction. The measured acceleration was not completely linear, so the average was determined for the values. An example of a portion of the measured data is shown in Fig. 1. According to the measurement, the value 1,2 m/s^2 for acceleration and 1,5 m/s^2 for deceleration was determined. Based on these two values, the part of throughput performance was calculated.

Similarly, deceleration of braking and other parameters were determined. No sufficient data was accumulated so far to determine the parameters based on the probability distribution, since only a very short time for the measurement in the warehouse was negotiated. The values of these parameters were determined based on the recorded video and averaged.

IV. Comparing the Results with Respect to the Used Parameters

In the following section, model calculations are made for the total time required to pick up one pallet. Individual parameters are added to each calculation to refine the result. For the model case, the total path from the depot to the storage position and back to 260 m was determined. The maximum speed the carriage moves is 3.8 m/s. If we consider the immediate maximum speed of the forklift, the driving time for the given distance is about 68.4 seconds. This time is taken as a starting point for further comparison. With an acceleration of 1.2 m/s^2 and a deceleration of 1.5 m/s^2, the resulting time will be 71.3 seconds, which is 2.9 seconds more than the calculation without the acceleration considered. This time difference is not dependent on the total distance.

Let us consider the following theoretical situation: the forklift carries a full shift (8 hours) without a break on a route with a distance of 260 m. The total pallet handling time (without driving) is 6 seconds. During the shift the 387 trips is done (to the warehouse position and back). Only 372 runs is made if we count the acceleration. During the shift, the 15 pallets less can be dispose. Depending on the total number of forklifts in the warehouse, the difference in the number of processed pallets would be a multiple. The lower number of processed pallets corresponds more to reality.

If we include a reduced cornering speed in the calculations, the above difference will be even higher. Consider that there are four curves on the route that are driven at a reduced speed. The time increment per turn is 2.5 seconds when cornering at a speed of 2 m/s and includes braking before cornering and acceleration after cornering. For the entire route, the driving time is longer about 10 seconds, meaning that only 329 pallets will be handled by the forklift. When we count one crossing with the same parameters as cornering, we get 320 unloaded pallets, which is about 18% less than in the simplified case. Values from the above considerations are summarized in Table 1.

TABLE I. Differencies in Calculations

Type of calculation	Trip time	# of pallets	Difference
simplified	68,4 s	387	-
+ acceleration only	71,3 s	372	- 4 %
+ lower speed in turns	81,3	329	- 15 %
+ delay on crossway	83,8	320	- 18 %

V. Conclusion

These results show that a detailed description of all the processes that take place in the warehouse is important for determining the permeability of the warehouse. In some cases, it is possible to use a certain degree of simplification and omission of some parameters, but the resultant storage permeability may be more or less distorted. It is also important to set the values for each parameter correctly (e.g. based on direct measurement). All of the parameters listed in this article should be included in the calculation of warehouse throughput by computer simulation. Thanks to this, other factors can be included in the calculations to obtain more accurate results. The parameters listed here should form the minimum basis for calculating of warehouse throughput.

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