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Isoenergetic Shelves of Automatic Small Parts Warehouses

Isoenergetische Fächer automatischer Kleinteilelager

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To improve the energy efficiency of automatic small parts warehouses (ASPWs) not only the drives and other technologies must be improved, but the strategies must be configured more energy-efficient, as well. For this purpose the single movements must be analyzed in detail. At the Institute of Logistics and Material Handling Systems an ASPW is available for such analysis. It is able to analyze movements over time in terms of power input. From the first experiments the so-called isoenergetic shelves were deduced. The isoenergetic shelves are the shelves which can be reached with the same amount of energy needs. Furthermore existing storage strategies were analyzed concerning the average energy needs.

Um die Energieeffizienz von Automatischen Kleinteilelagern (AKLs) zu verbessern, sind nicht nur die Antriebe und andere Technologien zu verbessern, sondern auch die Strategien energieeffizienter zu gestalten. Ein erster Schritt dazu liegt in der Detailanalyse der Einzelbewegungen. Am Institut für Logistik und Materialflusstechnik steht für solche Untersuchungen ein AKL zur Verfügung, mit dem die Bewegungen hinsichtlich der Leistungsaufnahme über der Zeit analysiert werden können. Aus den ersten Experimenten wurden die sogenannten isoenergetischen Fächer hergeleitet, also die Fächer, die jeweils mit dem gleichen Energieeinsatz zu erreichen sind. Weiterhin wurden bestehende Lagerstrategien hinsichtlich ihres durchschnittlichen Energiebedarfs untersucht.

[Keywords: Energy Efficiency, Automatic Small Parts Warehouses, Isoenergetic Shelves, Storage Strategies]

1 RELEVANCE OF ENERGY EFFICIENCY IN THE (INTRA-)LOGISTICS

The Federal Government of Germany has high objectives concerning the reduction of greenhouse gases. The objective is a reduction of carbon dioxide (CO_2) emissions of 40% based on 1990 because CO_2 is considered as biggest driver of global warming [UBA07]. To reach this objective each branch of industry must make a contribution.

In 2007 the logistics sector was the third largest branch of industry in Germany following the automotive industry and the trade sector. Its turnover accounted for 210 billion € with 2.6 million employees [BDI08]. The logistics sector has a share of 25% in the energy and resource consumption in Germany. Thereof 76% account for external transport and 24% for the intra-logistics [Kra08]. The energy needs of an average logistics center splits into 40% heat demand, and 60% electricity requirement (about 36% of the total requirement are caused by heating, ventilation, and air conditioning). In an average automated logistics center the materials-handling technology, to which storage and retrieval vehicles (SRVs) class with, accounts for 8% of the energy needs on average. Therewith the material-handling systems have the same share of the total requirement as illumination (see Figure 1).

The absolute energy need of a warehouse or logistics center respectively particularly depends on the size of the hall, the throughput, and the degree of automation. The higher these parameters are the higher the absolute total energy need. For highly-automated warehouses the sectors material handling technology, storage and picking technologies contribute up to 50% to the energy costs (heating, ventilation, and air conditioning technologies account for 35% and lighting 15%) [Kra08]. In a benchmark in the context of the BVL (Bundesvereinigung Logistik - Federal Association of Logistics) working group "Sustainable Production Logistics" it turned out that the electricity requirement per m^2 of a logistics center makes up about one third of the total energy requirements but accounts for about 50% of the costs (see Figure 2). Across all compared logistics centers in the benchmark it showed up that the total energy need per m^2 and year ranges between 40 kWh and 130 kWh per m^2 according to the case of application [Sues11]. Furthermore the peak load depends on the particular case of application, as well, e. g. stint system, hours of operation, throughput, degree of automation etc. Hence it is not derivable in general how high the absolute energy need is and when load peaks occur. This must be verified for each individual case. In an example of the benchmark the power input of a logistics center amounted to about 250 kW in the base load, but was twice as high during the peak periods.

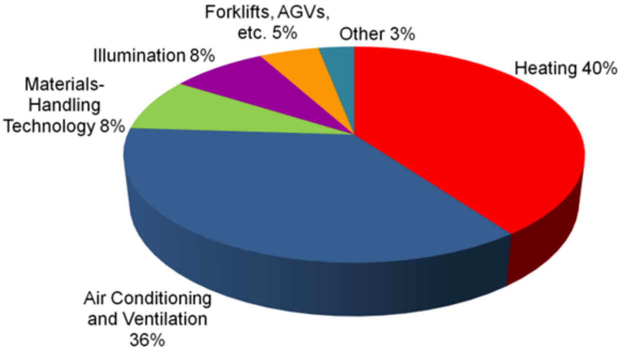

Figure 1. Energy needs structure of an average-automated logistics center (compare [Sues11] and [Beck11])

1.1 STATE OF THE ART

In the past the focus of the intra-logistics sector was particularly put on the maximization of the throughput and the system performance. However, the growing public pressure and the stricter legislation regarding the energy efficiency resulted in a change of thinking of producers and operators of intra-logistics equipment. Sustainability and thus energy efficiency more and more attract attention. Energy efficiency means "to create a desired benefit (products or services) with a preferable low use of energy or to make the most benefit out of a given use of energy" [Muel09, p. 2]. The European Commission defines energy efficiency as follows: "Technically, energy efficiency means using less energy inputs while maintaining an equivalent level of economic activity or service" [EU11, p. 2].

Besides technical measures which relate to the building itself or the energy production at the location (compare [Zor11] and [Fen11]) various technological measures exist in the field of intra-logistics which contribute to the improvement of energy efficiency. Among others these include energy-efficient electrical drives, lightweight construction, low rolling friction material combinations at wheel and rail, electric grid recovery systems, direct current intermediate circuit linkage (use of the energy released while braking or lowering the drives for the other drive), throughput-optimized vehicle operation, intelligent driving curve control (for example avoidance of a simultaneous start of to SRVs) or counter-balanced pallet lifters [Muhl11]. The use of energy-saving drives of the class IE2 or IE3 is not suitable for SRVs because a high starting torque must be hurdled. In comparison this would lead to a higher energy need due to the frequently occurring starting and braking processes.

1.2 RESEARCH NEEDS

So far single operation cycles could not be examined regarding the influence of different parameters on the energy needs of intra-logistics systems. As earlier described above it could be determined in practice that the reduction of the speed, the optimization of a drive's starting point dependent on the other one, or a workload management can lower the energy needs of these systems. However, it is not defined yet how the parameters should be set in which specific situation. This article shall provide first insights to this.

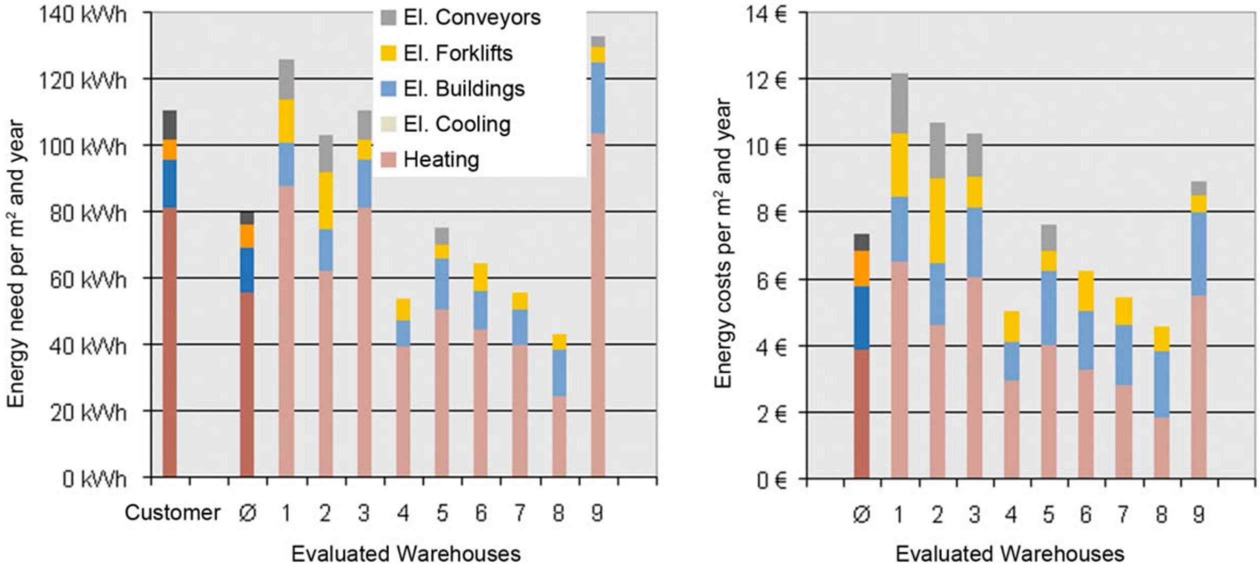

Figure 2. Energy needs and costs per m^2 and year of different automated warehouses in comparison [Sues11]

2 THE EXPERIMENTAL LABORATORY AUTOMATIC SMALL PARTS WAREHOUSE AT THE INSTITUTE

At the Institute of Logistics and Material Handling Systems (ILM) at the Otto-von-Guericke University Magdeburg an ASPW was built in 2010 (see Figure 3). With this ASPW the energy efficiency of such systems shall be studied with a practical orientation.

Figure 3. The Automatic Small Parts Warehouse at the Institute of Logistics and Material Handling Systems at the Otto-von-Guericke University Magdeburg

For the studies a 10 m long and about 7.5 m high rack lane and box-handling technology (which represents the pre-storage area and the storage and retrieval point respectively) are available. In the ASPW at the ILM (ILM-ASPW) theoretically 840 boxes may be stored (2 racks, 20 shelves horizontally, 21 shelves vertically). However, because one rack is exclusively used for the storage and the other one only for experiments 420 boxes are situated in the system. The maximum speed of the driving unit is 5 m/s at an acceleration of 3 m/s². Due to a limitation of the change of the acceleration over the time by the drive technology term jolt of r= 6 m/s³ acceleration and braking distances of 4 m in each case arise as a result. The driving unit transports 1.996 kg in total. The lifting unit with a weight of about 215 kg (180 kg lifting sledge, 35 kg load handling device) and a maximum load capacity of 100 kg can be moved with a maximum speed of v= 4 m/s at an acceleration of a= 4 m/s² (r= 8 m/s³). The acceleration and braking distances are about 2 m each. In addition during braking and lowering processes the system is able to either use the university-internal energy recovery system or to provide the released energy to the other drive by the direct current intermediate circuit linkage.

The ASPW exhibits unique features in its functionality. In practice storage, stock transfer, and retrieval jobs are automatically transferred and executed to the SRV by a warehouse management system. In contrast, at the ILM-ASPW jobs can be individually set up and executed. Thereby not only single transport orders can be created, but also order sequences, e. g. consecutive transport orders. Furthermore as default settings of the experiments it is possible to vary the speeds and the positive and negative accelerations of each drive, e. g. driving unit, lifting unit, fork, and belt, independently of one another. In addition the starting point of driving and lifting unit can be set dependent on the driving and lifting distance of the other drive (in % of the driving and lifting distance).

The result data of the experiments contains information about the current position of all drives (for coordinates see Figure 4) and their current power input over the experiment's time. The sampling rate is 20 ms. Hence the SRV's covered distances, the speeds, the accelerations, and the power inputs (in kWs) or the recovered power respectively, are depicted. First results show that the energy recovery rate compared to the electric energy input of the drives measures up to about 45-60% at the driving unit and about 60-70% at the lifting unit.

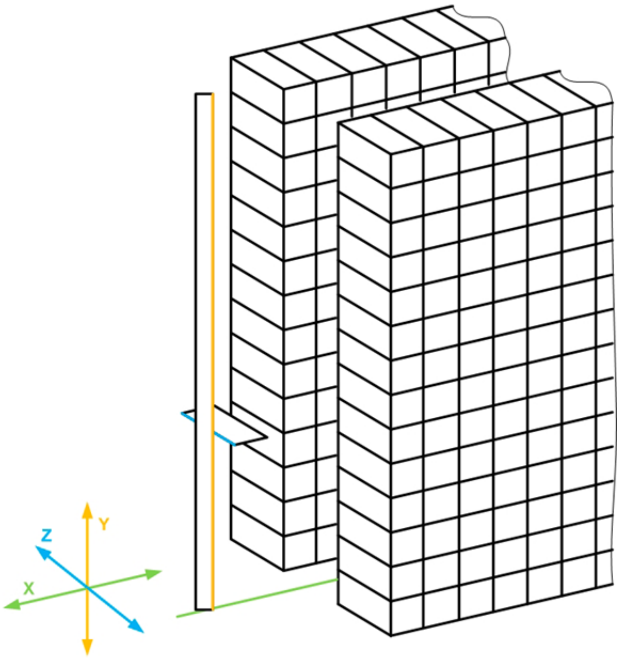

Figure 4. Coordinates of the ILM-ASPW

3 THE INFLUENCE OF THE STARTING POINT OF EACH DRIVE

In section 1 it was already described that modern intra-logistics systems have two different options for the energy recovery: the recovery into the public or company-internal grid or alternatively the use of the energy by another drive of the machine. In the case of automated warehouses with multiple SRVs it is also possible that the energy released during braking and lowering processes is used by another SRV. Theoretically it is even possible that the energy is directly used by other equipment in the warehouse.

Since losses always emerge during a recovery into the grid it is most efficient for SRVs to directly use the released energy for the other drive of the SRV. When the movements of each drive of the SRV are not synchronized then especially during the acceleration phase more electric power must be taken from the grid, for example when the SRV's driving unit accelerates and simultaneously the load is lifted by the lifting unit (see Figure 5). Besides, the energy released during the braking of the drive unit and the lowering of the lifting unit respectively must then be fed into the grid when the other drive has no need for the electric power at the same time. Thus the movements should be synchronized concerning the energy efficiency in that way that the lifting unit does not start to lift the load until the driving unit recovers energy during the braking phase (see Figure 6) or that the drive unit does not accelerate until the lifting unit lowers the load and recovers energy. At the ILM-ASPW it is possible to adjust one drive's (driving or lifting unit) starting point dependent on the covered distance of the other drive. In first studies regarding the driving unit it was observed that as a result of losses, for example friction resistances, about 80% of the electric energy input arrive in the system as kinetic energy.

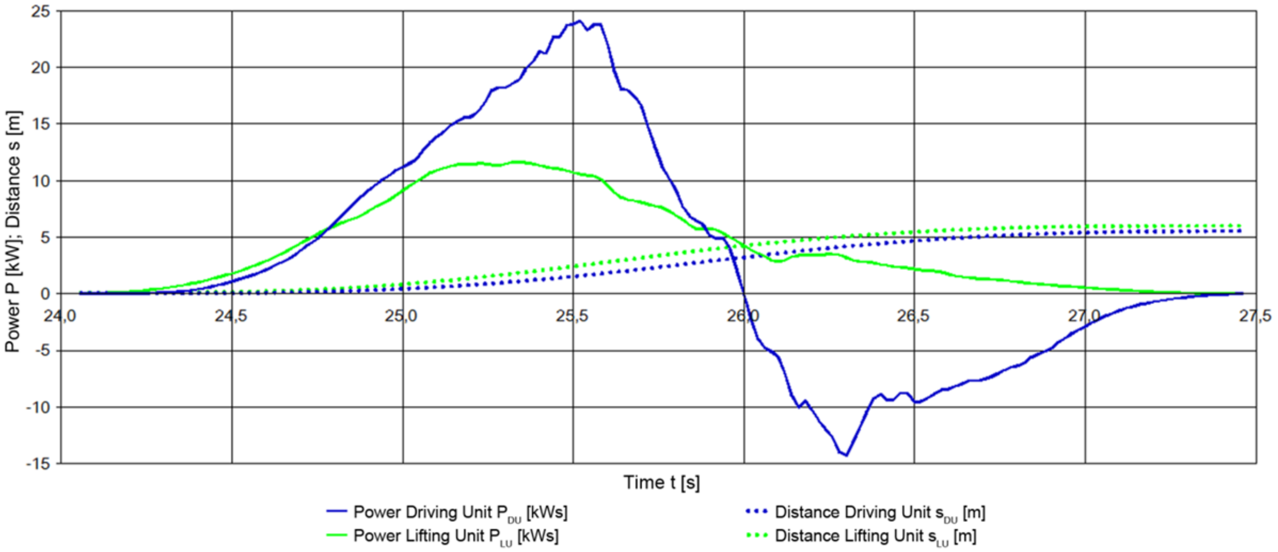

Figure 5. Power input and recovery of a SRV for a simultaneous start of the drives

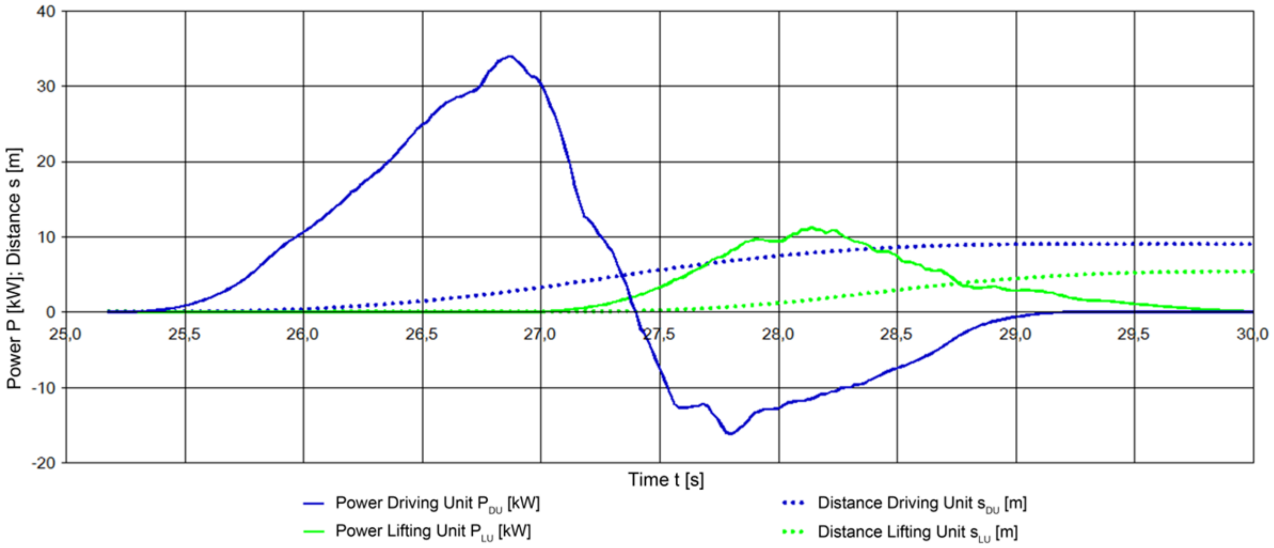

Figure 6. Power input and recovery of a SRV for a delayed start of the lifting unit

4 ISOCHRONAL AND ISOENERGETIC SHELVES

First results of the so far executed experiments are the so-called ***isoenergetic shelves*** of an automated warehouse. This term was developed based on the isochronal shelves. Isochronal shelves are exactly these shelves which can be reached within the same amount of time. In theory this is dependent on the particular speeds of the driving unit (v_x) and the lifting unit (v_y). Hence the isochronal line results from the quotient of lifting unit speed and driving unit speed, multiplied with the distance covered in x-direction. In the case of the ILM-ASPW this equation correlates to $y = -4/5 \cdot x$ for the maximum speeds. The shelves are 0.5 m wide and 0.3 m high. Thus for example while moving to the 6th shelf in x-direction in the same amount of time the 8th shelf in y-direction can be reached (see Figure 7). All other shelves on the horizontal and on the vertical line (l_x and l_y) have the same transit time. These are the isochronal shelves. However, the speeds are adjustable as already mentioned. In addition it must be noted that the equation of the isochronal line neither takes the accelerations nor the jolt into account. Consequently the isochronal shelves in practice do not necessarily correspond to these calculated in theory.

Based on the isochronal shelves the isoenergetic shelves of automated warehouses are defined as the shelves which can each be reached with the same energy input. Out of the single experiments models were developed with which the energy need for single movements can be calculated, e. g. the models calculate how much energy is needed for the movement of a box from one shelf to another. This is done by matching the distances (measured in the amount of shelves) in x- and y-direction with the energy needs. For the modeling the ASPW is defined as cuboid-shaped object with the edge length X (driving distance of the SRV), Y (operating range of the lifting unit), and Z (storage side and storage depth of fork and belt). The electric energy needs and recoveries of representative operation cycles are determined punctiform in the system. The models rely on these experiments and are able to approximate and to interpolate between the sampling points. The transferability of the results from the research object to other construction types and sizes of ASPWs is another research goal.

The total energy need thereby results from the sum of the driving unit's electric energy input and recovery and

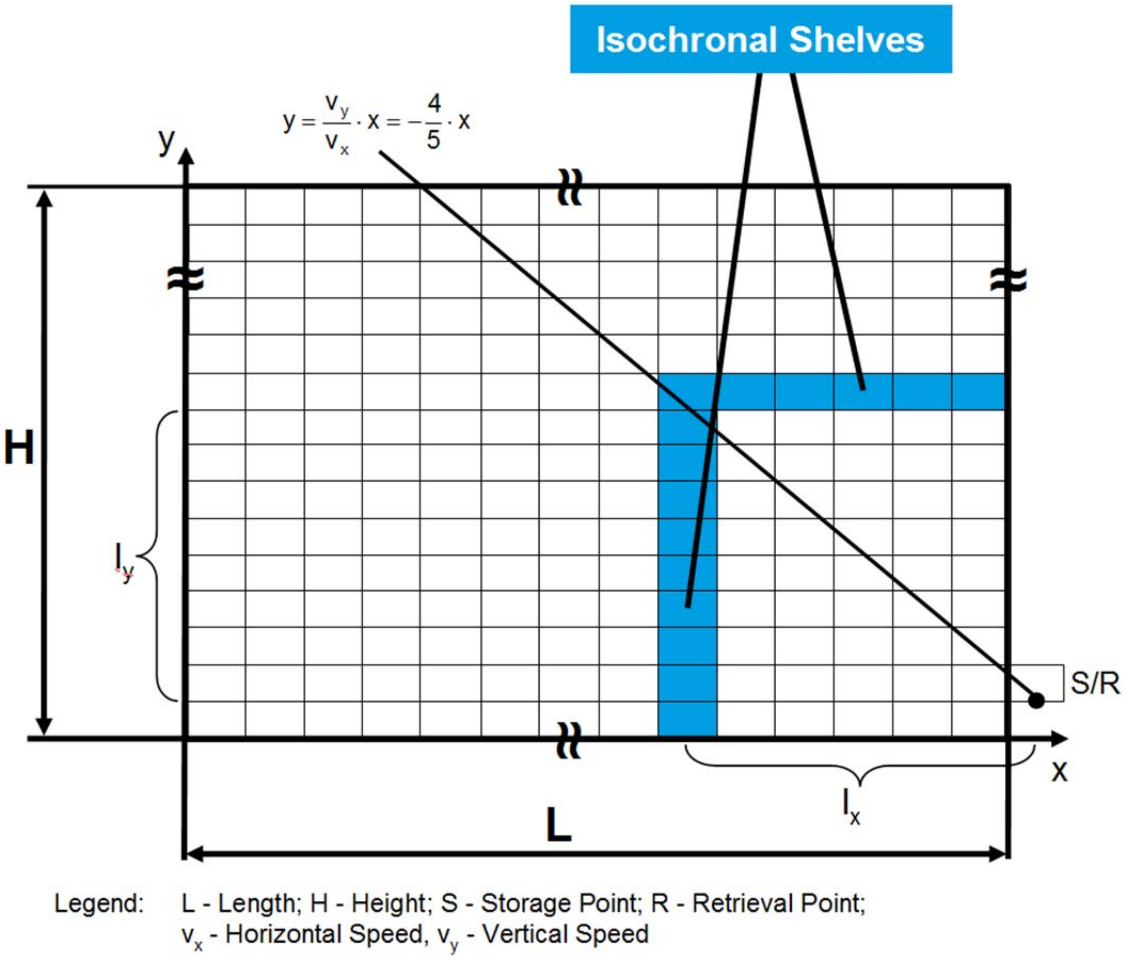

Figure 7. Isochronal shelves of the ILM-ASPW at maximum speeds

the lifting unit's electric energy input and recovery respectively. The energy needs of the fork and the belt are considered as negligibly low. The isoenergetic shelves vary depending on where the starting point of the movement of the SRV is located. Exemplarily the isoenergetic shelves are shown for the SRV's movements starting from the point X01Y01 (see Figure 8) and from the point X20Y21 (see Figure 9). For both figures a ΔE of 5 kWs was chosen. However, this ΔE is adjustable, so that the illustration can also be made more detailed. At the ILM-ASPW the isoenergetic shelves may change as well when the speed of the driving unit or the lifting unit's transported mass are varied. In larger high rack pallet warehouses the transported mass has an influence on the driving unit's energy need, as well.

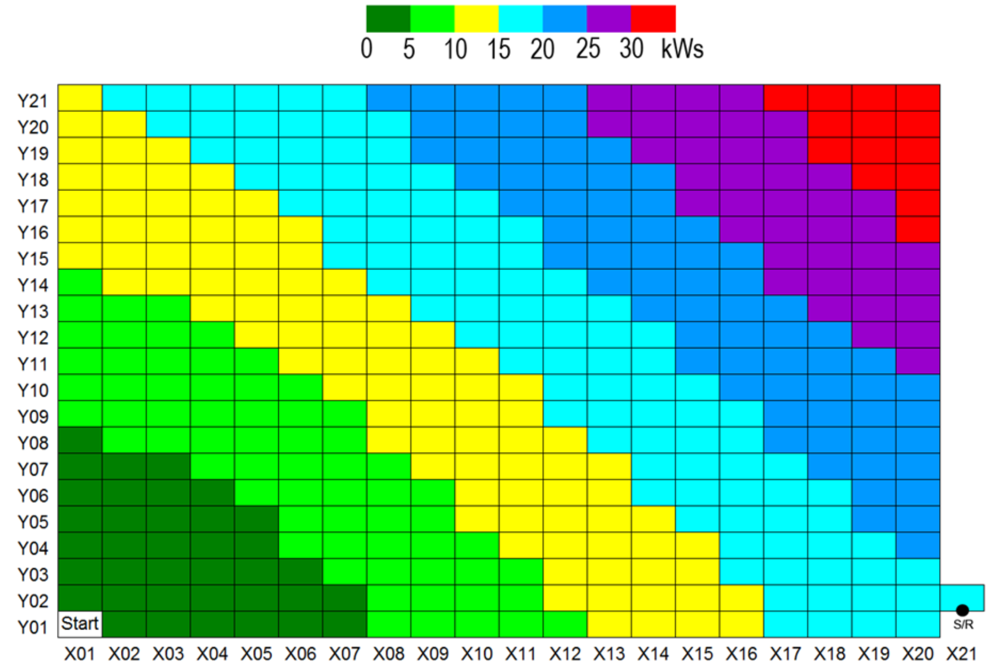

Figure 8. Isoenergetic shelves for the SRV's movements starting from X01Y01

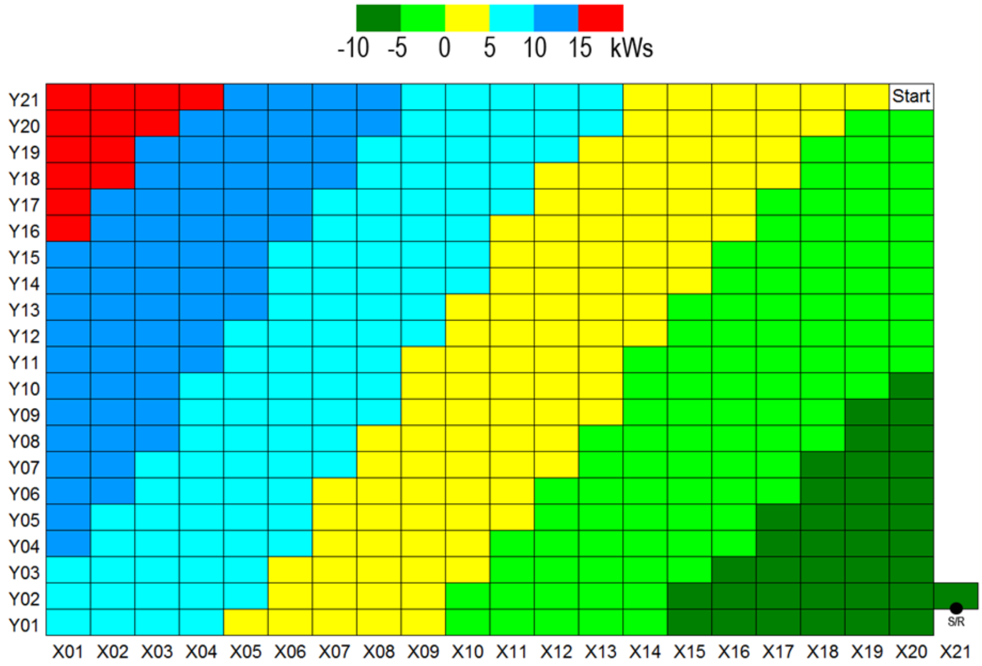

Figure 9. Isoenergetic shelves for the SRV's movements starting from X20Y21

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4.1 INFLUENCE OF THE S-/R POINT'S POSITION ON THE ENERGY NEED

As can be seen in Figure 8 and Figure 9 the total energy balance is lower at the same driving distance due to the lowering of the lifting unit because during the lowering the energy is recovered by the lifting unit. Consequently it must be reflected at which position of the rack the storage and retrieval point (S-/R point) should be located so that the ASPW may be operated as energy-efficient as possible. Because the position of the storage point and the retrieval point do not necessarily have to be identical, a first assumption suggests that the boxes should first be lifted (which could be done by a vertical conveyor at the lane entrance that requires relatively low energy), stored in the top level, and the retrieval point should be located in the lowest level. A concept in which several transfer points exist in the rack lane is conceivable as well (compare [Lant11]).

Depending on which position of the rack the transfer points are located the ABC areas change. However, In the future these should not exclusively be designed based on criteria like access frequency or share of turnover but should also be oriented towards the energy need that arises during the approach of the shelves. Therefore it still has to be validated which strategy, for example a fast mover strategy or the shortest travel time rule, respectively, really represent the most energy-efficient storage strategies.

4.2 INFLUENCE OF THE SPEED ON THE ENERGY NEED

It is already known that in general a reduced driving unit's speed of a SRV result in a lower energy need. This knowledge is particularly used in the workload management of automated warehouse systems (compare [Aber11] and [Muhl11]) when the systems are not being operated with the maximum performance across the day. It is not investigated yet which influence the speeds have in detail on the energy need of such systems. The research of this correlation is possible with the ILM-ASPW.

To obtain first results the same experiment was therefore executed each with different speeds. In this experiment a single operation cycle was executed with one box that is moved from the point X01Y01 to the point X20Y21, e. g. the maximum distance is approximately covered.

First experiment results confirm the perceptions of the industry: the lower the driving unit's speed, the lower the electric energy need on the covered distance (see Figure 10). However, it still must be clarified which speeds and accelerations have to be chosen in which situation (dependent on the work load at a specific time) to minimize the energy need under consideration to execute the orders in time.

4.3 INFLUENCE OF THE MASS ON THE ENERGY NEED

Another parameter that has influence on the energy need of automated warehouses is the transported mass. In general the more the transported mass, the higher the energy need ($E_{kin} = ½·m·v^2$ and $E_{pot} = m·g·h$). On the other hand due to the opportunity of the energy recovery the potential for the recovery is high at larger transported masses. Especially at automated pallet warehouses a relatively high percentage of the energy saved in the system can be recovered due to the large transported mass.

In the specific example of the ILM-ASPW only boxes with a maximum load weight of 30 kg are transported and stored. With a total SRV weight of 2.3 t the influence on the driving unit's energy need is merely minimal and hence negligible. At the lifting unit (permanent weight about 215 kg) the influence on the energy need for the lifting movement and the recovery

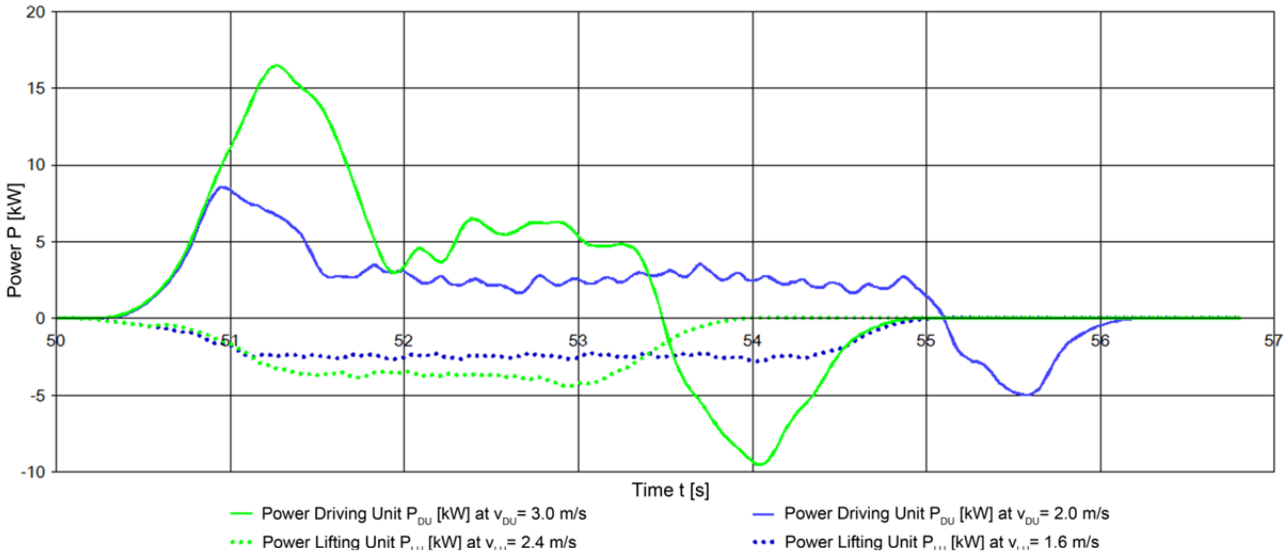

Figure 10. Speed-dependent power input and recovery of a SRV

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potential during the lowering movement is higher. How the load weight makes an impact on the energy need is not studied experimentally yet. This must still be analyzed. The results will be able to give evidence about the possible position of the storage and retrieval point for a more energy-efficient storage strategy. It is expected from an additional result whether a higher transport weight entails a higher energy need or a better utilization of the energy recovery in total.

5 THE ENERGY NEED OF DIFFERENT STORAGE STRATEGIES

Because the storage strategy is predetermined on a higher level, selected strategies were examined regarding their energy efficiency. For most static storage control strategies it is not possible to measure the average energy need because the transport orders are not predictable. This applies for example to the fixed box location, the transverse distribution, FIFO, or LIFO. In contrast the energy need of the ABC zoning, of single and double operation cycles, as well as of the driving distance optimization is ascertainable on average.

5.1 THE ENERGY NEED AT A COMPLETELY CHAOTIC BOX LOCATION ATTRIBUTION

The average energy need of the completely chaotic box location attribution inside a rack lane can be calculated using the area balance point. This point lies in the shelve X11Y11 at the start from the S-/R point in the case of the ILM-ASPW. The energy need was calculated for a single operation cycle and amounted to 18.1 kWs on average.

5.2 THE ENERGY NEED OF AN ABC ZONING

To determine the average energy need of an ABC zoning the position and size, respectively, of each zone in the rack and the percentage distribution of the operation cycles over the zones are required. With this data the average energy need can be ascertained similar to the chaotic box location attribution over each zone's area balance point. Because the B and C zone each consist of two rectangles two area balance point are defined each. Thus five area balance points arise in total. The experiment sequence and the arrangement of the zones are depicted in Figure 11. The five representative box locations were thereby approached with single operation cycles. By using the 80-20 rule based on the amount of storage and retrieval operations the energy need for a single operation cycle in the ABC zoning accounted for 9.8 kWs on average. Nevertheless, how the following passage shows, this value can be reduced even more with the application of double cycle operations.

5.3 SINGLE AND DOUBLE OPERATION CYCLES

It is generally known that with double operation cycles in comparison to single operation cycles time is saved and hence the system performance (the throughput) increases. Double operation cycles need less electric energy though compared to single operation cycles, as well. For a representative example test drives for single and double operation cycles were executed based on the FEM standard 9851 (compare [FEM9851, p. 9]). Since representative shelves are displayed for calculating a mean cycle time, in this context it is used for calculating a mean energy need as well. In this experiment a box shall be stored in the shelf X16Y14 and another box shall be retrieved from the shelf X06Y05. The S/R point is located on X21Y02. As a result for both single operation cycles 37.8 kWs were needed in total, including the energy recovery, and for the double operation cycle 26.8 kWs were needed. By using the driving and lifting distance optimization instead of the free double operation cycles strategy the energy need can be reduced even more.

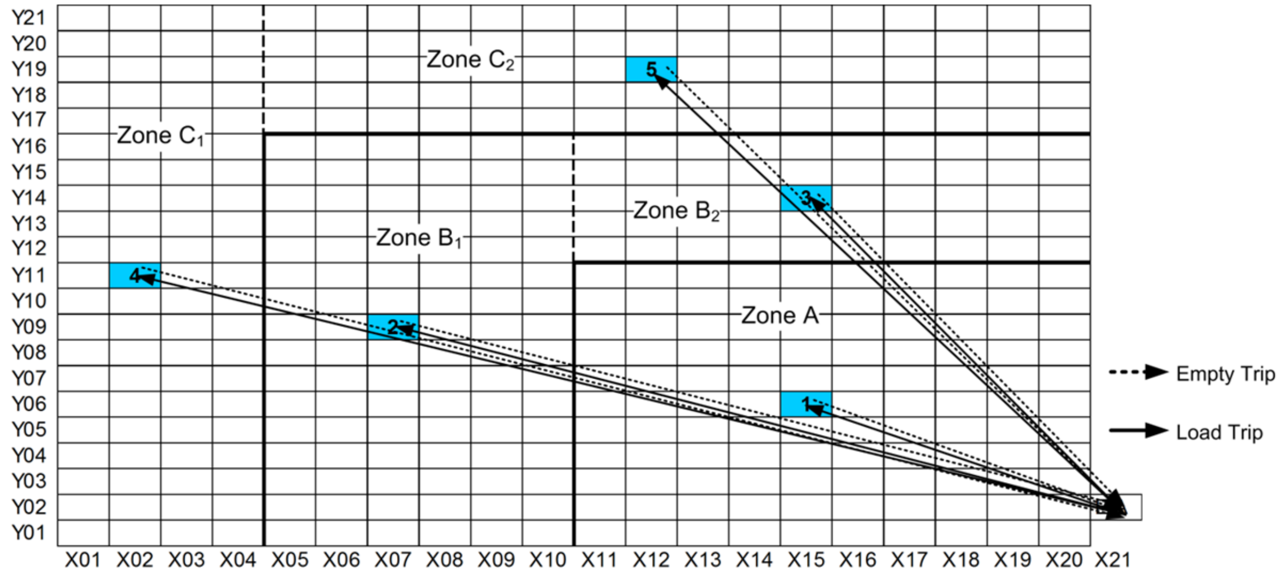

Figure 11. Experiment sequence of the ABC zoning

6 SUMMARY AND OUTLOOK

Despite newly developed technical measures a high potential regarding the energy efficiency still exists in automated warehouses, particularly in high rack storages and automatic small parts warehouses (ASPWs). Due to the energy recovery and the direct current intermediate circuit linkage a big step was already taken. However, these measures are only targeted on the single movements of a storage and retrieval vehicle (SRV) and do not take into account the applied storage strategy. Thus the objective must be to develop a storage strategy which considers the energy efficiency as well as the system performance, e. g. the throughput. To develop an energy-efficient storage strategy it is though initially important to know which parameters have which influence on the throughput and the energy need. With the experimental laboratory at the Institute of Logistics and Material Handling Systems (ILM) at the Otto-von-Guericke University Magdeburg this is now possible. An ASPW is available with which transport orders can be arbitrarily created and executed. In the orders it is possible to vary the starting point, the speeds, and the accelerations of the driving and lifting units.

First research results are the ***isoenergetic shelves*** of automated warehouses. The isoenergetic shelves are the shelves which can each be reached with the same energy input. Since modern SRVs have the ability of the energy recovery into the grid and the direct current intermediate circuit linkage, the energy recovery is introduced into the calculation of the shelves' energy balance. Several parameters such as the position of the storage and retrieval point(s), the selected speed, and the transported masses have influence on the isoenergetic shelves.

The isoenergetic shelves are the basis for further investigations regarding storage strategies. It must now be analyzed which influence the described parameters have on the total energy balance. The basis therefore is the single movements of the SRV. The energy needs can subsequently be transferred to the storage strategies. From these results a new more energy-efficient storage strategy may arise or one of the existing storage strategies may be confirmed as most energy-efficient, respectively.

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Hartmut Zadek was born 1968 in Berlin, Germany. 1987 until 1993 he studied Industrial Engineering at the Technical University Berlin. There he operated as a research assistant between 1993 and 1998. 1999 he finished his Ph.D. studies with the Dr.-Ing. and was honored with the Konrad Mellerowicz price. Between 1999 and 2002 Hartmut Zadek was active in project management at the consultant company ZLU GmbH, Berlin. The Visality Consulting GmbH was co-founded by him in 2003. Until 2007 he acted as a partner there, as well. Between 2003 and 2008 he was a member in the promotion advisory board of the BVL (Federal Association of Logistics). Since 2008 he holds the Chair of Logistics at the University Magdeburg “Otto-von-Guericke”. Furthermore, Hartmut Zadek is a member in the logistics advisory board of the federal state Saxony-Anhalt.

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