Benchmarking the Energy Efficiency of Diverse Automated Storage and Retrieval Systems

Thomas Stöhr
Research Assistent
Institute of Logistics Engineering (ITL)
Faculty of Mechanical Engineering
and Economic Sciences
Graz University of Technology
Austria

Michael Schadler
Research Assistent
Institute of Logistics Engineering (ITL)
Faculty of Mechanical Engineering
and Economic Sciences
Graz University of Technology
Austria

Norbert Hafner
Assistant Professor, Deputy Head
Institute of Logistics Engineering (ITL)
Faculty of Mechanical Engineering
and Economic Sciences
Graz University of Technology
Austria

Automated Storage and Retrieval Systems (AS/RS) are core components of intralogistics systems. Revealing the potentials regarding energy efficiency and further optimizing these systems are of importance.
A benchmarking procedure for AS/RS was developed to characterize parameters and specifications in order to derive energy efficiency indicators. The benchmarking procedure for AS/RS has recently been varified. A comprehensive test series was conducted to rate the energy efficiency of three AS/RS systems that are available on the market: Miniload-Crane, Horizontal Carousel- and Shuttle-Systems.
This paper presents the investigation methods as well as the final results for the energy efficiency of all three AS/RS types based on comparable logistic performance.

Keywords: *energy efficiency, Material Flow System, AS/RS, miniload, horizontal carousel, shuttle,*

1. INTRODUCTION

The high energy consumption of material handling and storage systems in intralogistics is due to the fact that these systems operate a large amount of electrical devices. Only little knowledge about specific potentials to reduce the energy consumption and few standards to calculate or measure energy efficiency were available. In order to close the gaps, standardized procedures to measure and calculate values indicating the energy efficiency of Material Flow Systems (MFS) and Automated Storage and Retrieval Systems (AS/RS) were developed [6-10].

Up to now the benchmarking of conventional MFS like conveyors has already been investigated in detail and the method and procedures used to rate the energy efficiency can easily be applied to different technical solutions [cp. 8-10].

This was not the case for AS/RS. Although systems like miniload systems, horizontal carousel systems and shuttle systems essentially perform the same tasks, their technical nature is very heterogenous. A basic concept of a method to evaluate the energy efficiency of different AS/RS using a common denominator was introduced in [6]. The benchmarking method for AS/RS has recently been varified. This paper presents the application of the benachmarking method as a reference and provides the results of the evaluation.

2. ENERGY EFFICENTCY BENCHMARKING FOR DIVERSE AS/RS

The benchmarking concept of AS/RS that was published in [6] can be used as a step-by-step procedure to rate the energy efficiency of three AS/RS systems namely: miniload-, horizontal carousel-, and shuttle-systems.

An overview of the benchmarking method is depicted in Figure 1.

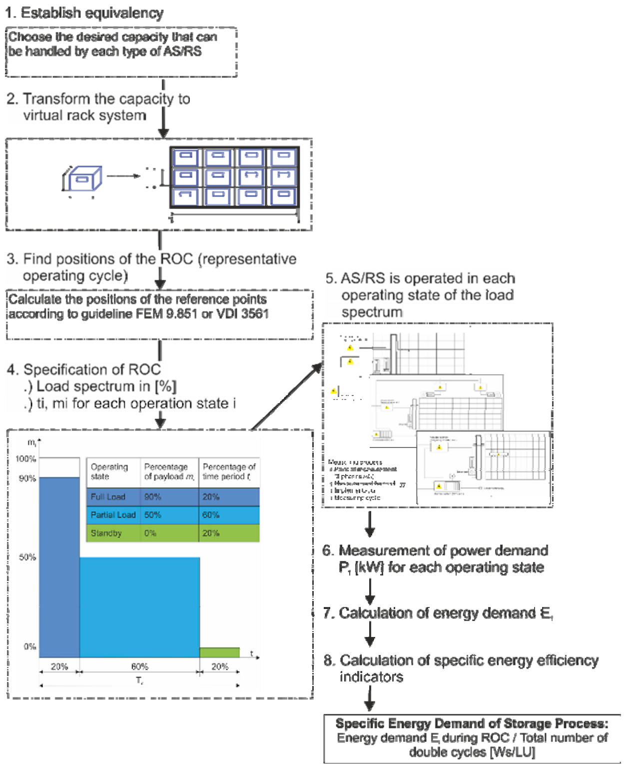

Figure 1: Overview - benchmarking method for AS/RS [6]

The benchmarking method provides an energy efficiency indicator e_s that confronts the electrical energy demand with a logistical performance (see Formula (1)).

$$e_s = \frac{\sum_{i=1}^{n} P_i * t_i}{\sum_{i=1}^{n} \Lambda_i * t_i}, \left[\frac{Wh}{double\,cycle} \right] \quad (1)$$

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Correspondence to: Dr.techn. Norbert Hafner
Institute of Logistics Engineering, Inffeldgasse 25e,
8010 Graz - Graz University of Technology
E-mail: norbert.hafner@tugraz.at
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To evaluate the energy demand, the power usage of each system is measured over time while the system is operated in a pre-defined Representative Operating Cycle (ROC). This cycle is defined by a load spectrum that consists of several operating states (full load, partial load and standby) and specific reference points according to standard guidelines [1-4] that are approached by the storage and retrieval machines during the test operations.

2.1 Reference application of the benchmarking method

To verify the benchmarking method for AS/RS the procedures have been exemplarily conducted on three different types of AS/RS systems that are available on the market. Table 1 lists the most important charac–teristics of the AS/RS systems that have been chosen for the energy efficiency benchmarking.

Table 1: Characteristics of chosen AS/RS systems

	MLC	Shuttle system	HCS
Storage capacity of the system [#]	1.056	800	400
Storage capacity of single aisle rack [#]	240	200	400
Levels [#]	11	10	10
Columns [#]	24	20	40
Length [m]	15.50	10.00	9.80
Height [m]	4.10	4.5	3.9
MLC … miniload crane HCS … horizontal carousel system			

Specification of the virtual rack and the reference points: The specification of the virtual rack dimensions as outlined in [6] is based on the capacity of the smallest AS/RS. In the presented case the horizontal carousel system is only equipped with a storage capacity of 400 unit loads. The storage capacity of the HCS was used to calculate fictitious virtual rack dimensions of a single-aisle miniload crane and Shuttle system.

This virtual racks are necessary to ensure comparability as the compared systems are equal in terms of their logistical functionality. The virtual rack dimensions conserve the ratio height/length of each rack in order to provide the same geometrical and dynamic conditions of the real systems.

The following guidelines that are suggested in [6] were chosen to define the reference points:

1) Miniload systems: VDI 3561 [2]
2) Shuttle system: Kartnig & Oser [5]
3) Horizontal carousel systems: VDI 4480-3 [4]

The calculated virtual rack systems and the specified reference points are also depicted in Figure 2.

Specification of the Representative Operating Cycle

The load spectrum is defined for double cycle operation and consists of the following three phases: full load operation, partial load operation and standby. The total amount of time used for all recommended operating states sums up to $T_N = 1\ h$. Each period is a percentage of T_N and can be calculated according to Formula (2).

$$T_i = t_i * T_N \qquad [s] \tag{2}$$

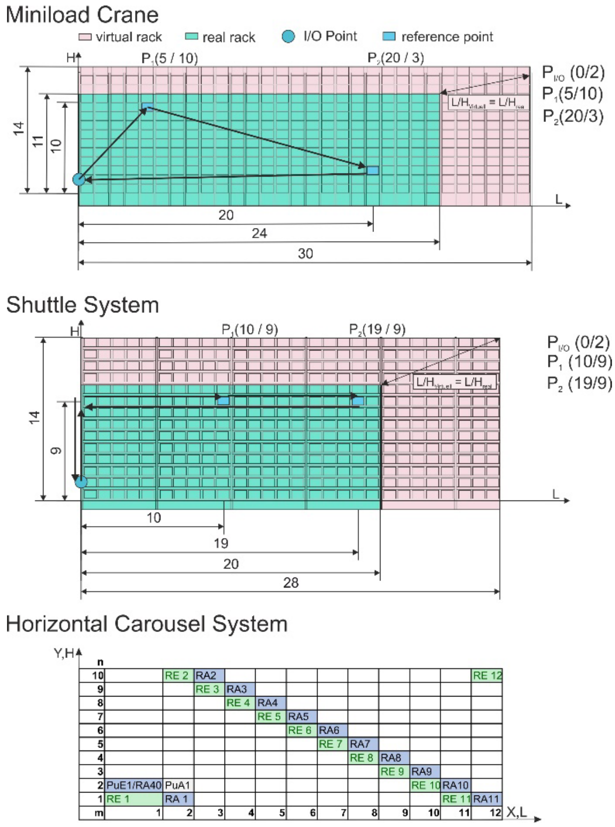

Figure 2. Virtual rack systems and reference points

The different payloads within the load spectrum are defined by the relative loading m_i of the nominal load $M_N = 25kg$. During full load operation 90% of the unit load's payload and during partial load operation 50% of the unit load's were used. The time period for full load operation resembles 20% of the total time used for the measurement, while partial load operation consumes 60%. Standby operation corresponds to 20% of the total time. Figure 3 outlines the defined load spectrum.

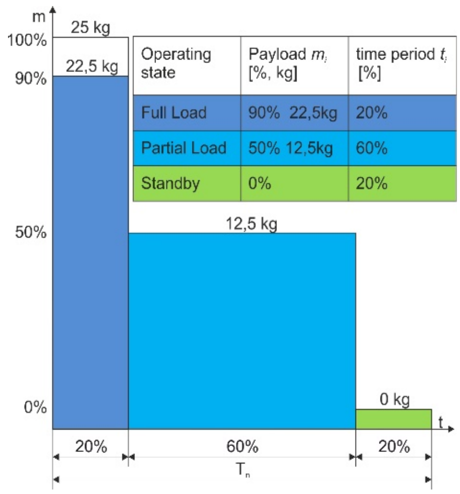

Figure 3. Load spectrum and operation states

Since horizontal carousel systems are dynamic warehouses, the same coefficients were used for each operating state with regards to the percentage of the total system payload.

2.2 Measurement of the energy consumption

Point of measurement and measurement system

In order to conduct proper power measurements to determine the electrical energy demand, the system boundaries of each system have to be defined. The system boundaries include the complete construction ranging from drive trains, regulator control elements to control systems, and thus contain everything necessary to store a unit load. The measurement includes all electric appliances of the AS/RS system.

Further the measurement system and setup was chosen considering the complexity of electrical power measurement. Due to the high number of converters and power adapters a significant portion of the power consumption occurs at high frequencies (Figure 4). To record such electrical loads, the entire measurement equipment has to feature high sample rates. The chosen measurement system is a computer-based *Dewetron 800* and includes the sensors listed in

Table 2. A sample rate of 100 kHz was used throughout the benchmarking tests.

Figure 5 illustrates the measurement system applied to the point of measurement of a MLC system.

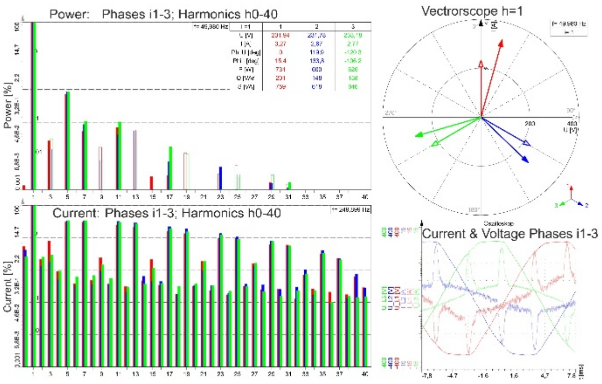

Figure 4. FFT analysis of reactive power and corresponding currents (3 phases, harmonics 0-40)

Table 2: Specification of the measurement system

Measurement system for current:		
Sensor	Prosys CP300	Current clamp Measuring range 300A Sample rate 100 kHz Accuracy class 0,05 ±10V analog signal
Data acquisition	Dewetron DAQP-LV	Low-voltage data acquisition Input range+/- 50mV to +/- 50V Sample rate 300 kHz Accuracy class 0,05
Measurement system for voltage:		
Sensor	Dewetron DAQP-HV	High-voltage data acquisition Measuring range 1400 V Sample rate 300 kHz Accuracy class 0,05

To measure the energy demand of AS/RS while operating in a specific Reference Operating Cycle without hassle, it is favourable that the systems runs repeatedly in an automated way. Unfortunately the tested AS/RS systems weren't able to provide such automated mode. A manual trigger of each movement from the control panel was required and lead to system downtime. This circumstance was taken into account while processing the data later on. The downtime and the corresponding energy consumption during these phases was subtracted. The adjusted data is outlined below.

To exclude specific behaviour during the warm-up phase of each system and to ensure repeatability of the test results, a thermal conditioning of each system was conducted prior to the measurements. The throughput of each operating phase was measured by simply counting the unit loads.

Figure 5. Measuring the electrical energy consumption of a miniload crane that is used in a field application

2.3 Data processing and results

The acquired data was processed using the power mea–surement toolbox that is included in the software *Dewe–soft X2*. The electrical energy and power consumption was calculated using the three phases of current and voltage and considers the full sample rate according to Formula **Error! Reference source not found.**.

$$E = \int_{\tau=0}^{T} P(t)\,dt \quad [Wh] \tag{3}$$

In the following the results for the three types of AS/RS are presented separately:

Miniload crane (MLC):

The double cycles within the Representative Operating Cycle (ROC) were measured ten times for each load state. Figure 6 exemplarily illustrates the energy and power demand while operating a double cycle com–mand. The figure also shows the movements of the crane that can be identified easily.

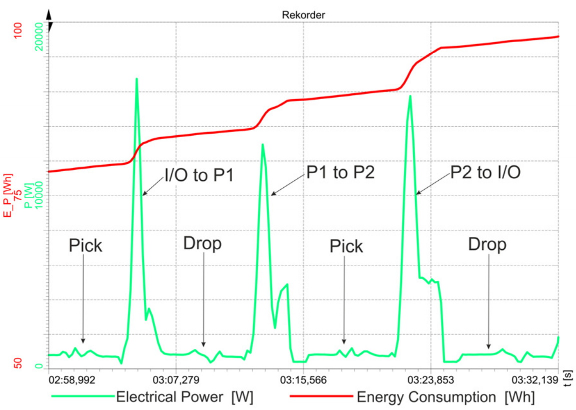

Figure 6. Energy and power consumption of MLC while executing a double cycle

As can be seen in the offset of the cummulated energy consumption, the horizontal acceleration of the crane causes a considerable amount of electrical energy. The results of the measurement and the calculation of the specific energy demand is listed in Table 3. All numbers are mean values whereas all numbers in round brackets represent the standard deviation.

Table 3: Energy consumption and cycle times of a MLC

Operating state	E_i [Wh/DC]	t_i [min]	DC/t_i [#]	t/DC [s/DC]
Full load	19.14 (0.46)	12	23.35	30.84 (0.66)
Partial load	18.79 (0.94)	36	71.07	30.39 (0.41)
Standbyload [W]	316.85 [W] (2.69)	12	-	-

Below the calculation of the specific energy demand of the MLC is outlined according to the proposed definition in [6], Table 3 and Formula (1):

$$e_s = \frac{19.14 \cdot 23.35 + 18.79 \cdot 71.07 + 316.84 \cdot \frac{12}{60}}{23.35 + 71.07 + 0}$$

$$e_s = 19.55 \frac{Wh}{DC}$$

Horizontal Carousel System (HCL):

The double cycles within the Representative Operating Cycle were measured ten times for each load state. As already stated, the same coefficients specifying the load spectrum were used to define the percentage of the HCS's total payload within each operating state. According to the manufacturer's data the total payload of the chosen HCS is 4.800 kg.

Due to limitations of the tested HCS, which is used in a field application, the prescribed payload for each operating state of the ROC deviated during the measurements. The mathematical correction of this deviation is shown in Table 4.

Table 4: Nominal and corrected payload of the HCS

Average mass of stored LU [kg/LU]	5.79
Storage capacity HCS [#]	400
Filling level	96%
Payload stored [kg]	**2.223,6**
Payload according to ROC [kg]	**4.800**
Deviation [kg]	**2.576,4**

Also the energy consumption of the system has to be adjusted due to the deviation of the real payload to the proposed payload of the ROC. The adjustment was done by assuming a linear dependency between the energy demands of the moving parts and the load states.

The correction was done using the ratio that is shown in Formula (5).

$$cf_{payload} = \frac{4800}{2576.40} \tag{4}$$

Table 5 provides the results of the measurement and the calculation of the specific energy demand including the correction.

Figure 7 depicts the electrical power demand and the cumulated energy consumption of ten double cycles. The Figure also shows the movements of the HCS. As can be easily seen in the peaks of the electrical power, the movement of the carousel's lift consumes a considerable amount of electrical energy, whereas the horizontal movement does not.

Table 5: Terms of the energy consumption of a HCS

Total measured time of ROC (RE1-RE10) [s]	230,665
Measured time without idles [s]	216,86
Energy demand (216,86s) [Wh]	72,18
Standbyload [W]	911,29
Energy demand of standybyload during ROC [Wh]	54,895
Energy demand of moving part in ROC [Wh]	17,283
Adjusted energy demand moving part [Wh]	37,312
Adjusted energy demand of ROC (RE1-RE10) [Wh]	**92,207**

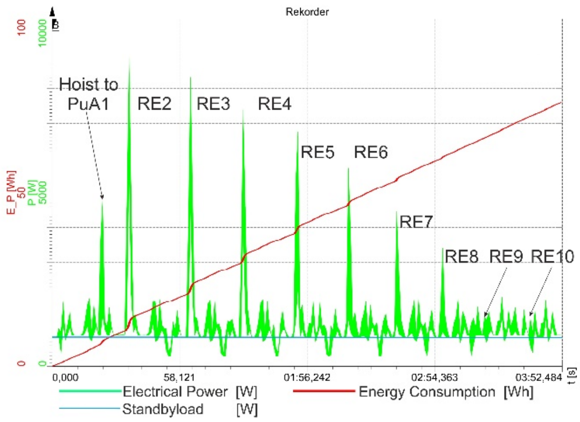

Figure 7. Energy and power consumption of a HCS while executing ten double cycles

The results of the measurement and the calculation of the specific energy demand is listed in Table 6. All numbers in the first row represent the measured values while numbers listed in the second row (blue) are adjusted results derived from the data processing.

Table 6: Energy consumption and cycle times of a HCS

Operating state	E_i [Wh/DC]	t_i [min]	DC/t_i	t/DC [s/DC]
Full and parital load	7.22 (-)	48	132.80	21.69 (-)
Full and parital load adjusted	9.22 (-)	48	132.80	21.69 (-)
Standbyload [W]	911.29 W (1.45)	12	-	-

Below the calculation of the specific energy demand of the HCS is outlined according to the proposed definition in [6], Table 6 and Formula (1):

$$e_s = \frac{9.22 \cdot 132.80 + 911.29 \cdot \frac{12}{60}}{132.80 + 0}$$

$$e_s = 10.59 \frac{Wh}{DC}$$

Shuttle System:

The movements of the elevator and the movements of the shuttle were measured separately as these move–ments are executed independently in practice. Further–

more, the control panel of the investigated system was only able to manually trigger the movements of one subsystem. The energy consumption and the cycle times of the elevator and the shuttle while operating in the ROC were computed linearly in the data processing step.

The benchmarked shuttle system is composed of ten storage levels each equipped with one shuttle. Since the power measurement of only one shuttle is of interest, all other shuttles either have to be removed from the system or their electrical standby-load needs to be compensated mathematically. This can be done by dividing the measured standby-power by ten and subtracting the constant power consumption of nine shuttles from the total power consumption.

Figure 8 depicts the total electrical power and cumulated energy consumption of the elevator. Figure 9 illustrates the total electrical power and cumulated energy consumption of one shuttle and also quanti–tatively shows the subtracted standby load of nine non-operating shuttles.

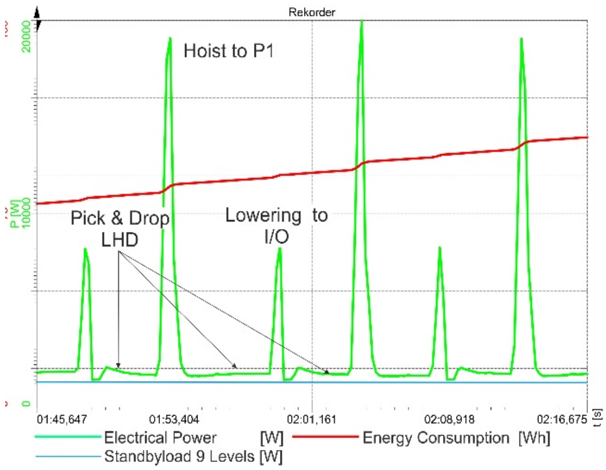

Figure 8. Energy and power consumption of the elevator performing a double cycle

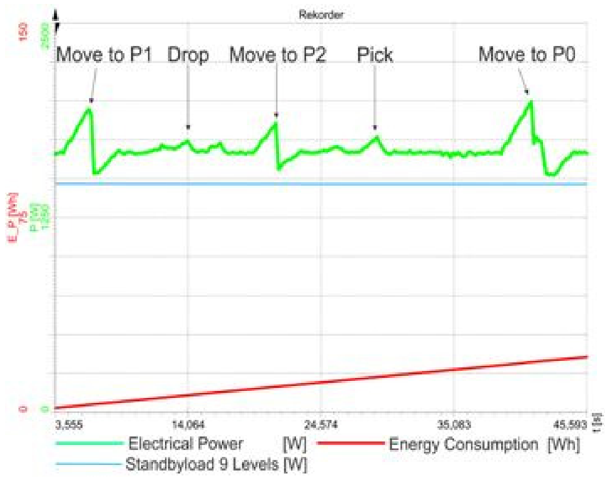

Figure 9. Energy and power consumption of one shuttle performing a double cycle

The results of the measurement and the calculation of the specific energy demand is listed in Table 7. All numbers in the first two rows represent the measured values while numbers listed in the blue rows are adjusted results derived from the data processing.

Table 7: Energy consumption, cycle times and standyload of a Shuttle system

Operating state	E_i [Wh/DC]	t_i [min]	DC/t_i	t/DC [s/DC]
Full load	37.53 (2.29)	12	9.90	72.72 (4.30)
Partial load	35.54 (1.46)	36	31,02	69.63 (2.99)
Full load adjusted	7.94 (0.48)	12	9.90	72.72 (4.30)
Partial load adjusted	6.74 (0.28)	36	31.02	69.63 (2.99)
Standbyload [W]	911.29 W (1.45)	12	-	-

Below the calculation of the specific energy demand of the Shuttle system is outlined according to the proposed definition in [6], Table 7 and Formula (1):

$$e_S = \frac{7.94 \cdot 9.90 + 6.74 \cdot 31.02 + 1627.51 \cdot \frac{12}{60}}{9.90 + 31.02 + 0}$$

$$e_S = 7.83 \frac{Wh}{DC}$$

<u>Benchmarking results:</u>
Finally the individual results of each system are to be compared to conclude the energy efficiency benchmarking process. The energy efficiency indicators e_S of the tested AS/RS systems are shown in Figure 10. The graph clearly reveals the potentials of savings in electrical energy.

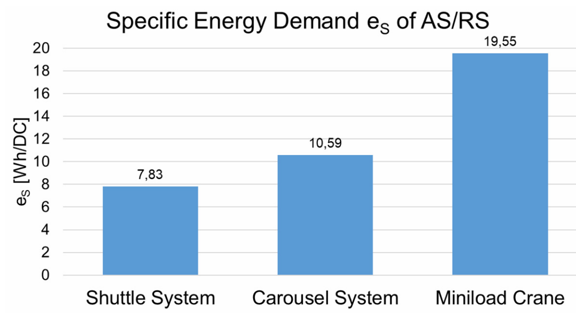

Figure 10. Specific energy demands of different AS/RS systems

2.4 Conclusion and outlook of AS/RS benchmarking

A direct comparison of different types of material handling and storage systems is of complex nature.

It is a challenging task to fulfil all requirements necessary for accurate measurements – such as automated operation of the ROC, exact loading of an HCS according to the defined load spectrum or repetition of load cycles just to name a few. More times there was the need to calculate the data by post processing significantly to ensure comparability. These adjustments for the measurement as well as calculation tasks need to be done carefully in order not to interfere repeatability.

The results in this investigation are reliable findings that compare miniload cranes, shuttle system and horizontal carousel systems regarding their energy efficiency.

The following general statements can be recapped:

- The specific energy demand, which was chosen as an indicator, is a quantitative rating that enables the benchmarking of different technical implemen–tations of AS/RS.
- The consequent consideration of the comparable logistical performance, based on the standardised double cycle of miniload cranes, as a function of the energy input was processed.
- The following main factors have relevant influence on the electrical energy consumption and efficiency of the individual systems:
  - General: The dynamic movement of equipment results in high power peaks.
  - General: The standby operation has a relevant impact on the cumulated energy consumption.
  - Miniload crane: The acceleration/deceleration of the crane for horizontal movements causes the highest power peaks as well as share of energy consumption.
  - Horizontal carousel system: The acceleration/de-celeration of the lift for vertical movements causes the share of energy. The effective mass stored in the HCS has a low impact on the energy consumption while moving the carousel horizontal.
  - Shuttle systems: The standby power consumption of non-operational shuttles is highly significant.

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УПОРЕДНА ПРОЦЕНА ЕНЕРГЕТСКЕ ЕФИКАСНОСТИ РАЗЛИЧИТИХ СИСТЕМА АУТОМАТСКОГ СКЛАДИШТЕЊА РОБЕ

Т. Штуа, М. Шадлер, Н. Хафнер

Системи аутоматског складиштења и проналажења ускладиштене робе (AS/RS) представљају главне компоненте интралогистичких система. Откривање потенцијала за енергетску ефикасност и даљу оптимизацију ових система је од великог значаја. Поступак упоредне процене за системе AS/RS је развијен у циљу карактеризације параметара и спецификације индикатора енергетске ефикасности. Недавно је овај поступак и верификован. Извршен је низ испитивања у циљу процене енергетске ефикасности три система AS/RS који се могу наћи на тржишту: мини лоад, хоризонтални карусел и шатл. Приказане су методе истраживања и резултати који се односе на енергетску ефикасност сва три наведена система, који су засновани на упоредивим логистичким перформансама.