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EFFICIENCY INDICATORS FOR BENCHMARK AND IMPROVEMENT OF ENERGY EFFICIENCY ON AUTOMATED MATERIAL FLOW SYSTEMS

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Abstract: *Rising energy costs as well as ecological goals put energy efficiency on a significant level of interest in most industries. Industrial Logistics operates a huge number of devices and is characterized by high over all energy consumption. Therefore, contemporary industrial applications require solutions, which are (re)designed for high energy efficiency.*
Currently no general guidelines or standards exist regarding how energy efficiency is represented in relation to logistic output. The paper presents the basis for a benchmark system for energy efficiency of automated in-plant systems. Through the use of Energy Efficiency Indicators (EEI), efficiency is becoming quantifiable. Comparisons and optimization tasks on systems can be worked out and evaluated. The focus here is on conveyor systems for unit loads as they are commonly used for the transportation of goods in typical logistics applications.
The common structures and basic operation functions of material flow technology are explained. Starting with a basic definition of energy efficiency, the mathematical derivation of Energy Efficiency Indicators is performed by the use of basic characteristics of conveyor systems. All process steps necessary for determining the energy efficiency indicators are described. Finally, the validity and clarity of the EEIs is verified by an application example.

Key words: *energy efficiency, industrial logistics, green logistics, benchmark system, efficiency indicator, material flow system, conveyor system.*

1. INTRODUCTION, MOTIVATION

Energy efficiency is becoming highly important, due to both economic reasons and the overall goal of environmental sustainability [1–3].

Material Flow Systems (MFS) are main components in most in-plant logistic systems. The numbers of installed automated MFS have increased progressively over the last decades, as well as their energy consumption.

Today, no standardized methods for benchmarking energy consumption of MFS, in relation to characteristic operations, are available. The available standards for determining losses and efficiency apply only to single components like electric drives (EN 60034).

Therefore, at the Institute of Logistics Engineering a research project (titled effMFS) was arranged and started in March 2011 in close cooperation with the industrial partner SSI Schäfer PEEM GmbH – funded by FFG Austrian Research Promotion Agency.

The research project focuses on two main areas of interest. The first focal point is the overall optimization approach for automated MFS [4]. The second core area is presented in this paper: The design of a standardized and generalized model of characteristic values in order to make it possible to compare energy efficiency of MFS, independent from manufacturers and technical solutions.

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1.1. Energy Efficiency in Material Flow Systems

Figure 1 basically illustrates aspects of the three levels of MFS that can be optimized: Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), device/component (field).

The previously published research findings concerning energy consumption of Material Flow Systems (MFS) and their efficiency mainly focus on transportation problems. In general, these results are not transferable to intra-logistics.

1.2. Need of a Benchmark System (EEI-MFS)

Improvement of the energy efficiency of MFS becomes possible if efficiency factors are available in relation to current orders, loads and modes of operation. The specific power consumption at nominal system performance (payload, throughput …) is not a sufficient indicator. There are no standards available for measuring and calculating characteristic energy efficiency indicators (EEI) for MFS.

In this paper we present the project results for a standardized energy efficiency indicator system. The basic approach, the specifications, the equations for calculations and two examples are illustrated.

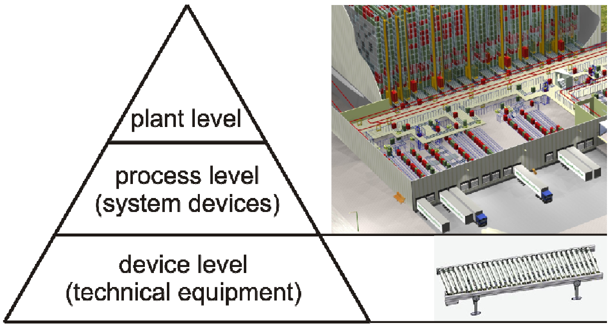

Fig. 1. Levels of MFS and EEI.

2. OVERVIEW OF MFS, TECHNOLOGY

2.1. Levels of MFS

The comprehensive approach of the EEI benchmark system was developed with consideration of classified system levels of material flow systems (MFS) [4]. Different degrees of complexity of intra-logistic systems as well as the depth of details are represented.

The approach specifies three levels of MFS as shown in Fig. 1. A conveyor system is an example for the device level. The process level includes groups of devices of the same or of more than one types, e.g. conveyor plus automated warehouse systems plus order picking units of a distribution center.

The plant level represents the overall facilities at the location but this will not be addressed in this project.

At device level, the actual physical technology, components and elements of devices must be investigated to calculate EEI, e.g. conveyor systems, sorters, automatic storage and retrieval systems, etc.

2.2. Conveyor Systems Technology

Continuously operated conveyors for load units (LU) are standard components of in-plant logistic systems. Their task is to transport load units, containing packaged goods and freight, from a point A to a point B.

Conveyors are characterized by their given route of line and have a defined length. Load units are conveyed in a continuous way from the loading point to the discharging point, with a given distance or with given cycle times between load units.

Typical conveyors work with a defined conveying velocity, depending on the application, at a range of 0.3 and 2 m/s.

Different types of load units are used in common industrial applications, depending on the weight and the characteristics of the transported goods. The following classification of the rated load is distinguished:

- up to 50 kg (boxes);
- 50 kg – 200 kg;
- 200 to 2 500 kg (palettes).

Depending on the nominal load, different types of commonly used conveyor systems in MFS are

- Roller conveyors;
- Belt conveyors (Fig. 2);
- Chain conveyors.

The basic structure is similar in all applications. One or more drive units operate the transport system of the conveyor, i.e. rollers, belts, or chains, and transport the load units (Fig. 2).

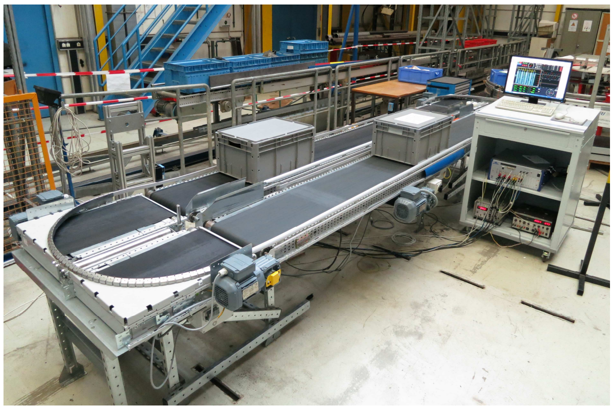

Fig. 2. Belt conveyor for load units, located at ITL laboratory.

3. ENERGY EFFICIENCY INDICATORS (EEI) OF CONVEYOR SYSTEMS

The benchmark system is based on indicators, which describe and quantify interested situations of processes [5]. Furthermore, standardized specifications and conditions are necessary to determine the EEI and ensure these EEIs are also comparable.

As a basis for the introduction of an energy efficiency indicator for conveyor systems, the general definition of the efficiency of the EU directive [6] is used.

3.1. Definition of Energy Efficiency

The definition of efficiency is characterized by the ratio of output to input of a process. Thus, efficiency describes the amount/quantity of an output size of a process, based on its input ratio.

$$\eta = \frac{Output}{Input}\,. \tag{1}$$

At energy efficiency E_{eff}, this definition is expanded and describes the ratio of a general definable output of performance, service, goods or energy, depending on the application, and is set to an input of energy [6]. The input of energy represents the energy demand respectively consumption of the considered process/application.

$$E_{eff} = \frac{Output\ of\ \ a\ performance\ or\ process}{Input\ of\ \ Energy}\,. \tag{2}$$

3.2. Characteristics of Conveyor Systems

The main characteristic values of a conveyor system are:

- Throughput Λ_N [LU/h];
- Conveyor velocity v [m/s];
- Loading m of the boxes (LU) [kg];
- Length of the conveyor L [m];
- Nominal Power of drive unit P_D [kW].

The achievable throughput Λ_N indicates the maximum number of LU per time unit which can be transported by the conveyor system. This is done with the assumption of a constant conveying speed v.

The LU are charged with the loading m, and applied on the conveyor at a distance e between the LU (Fig. 3).

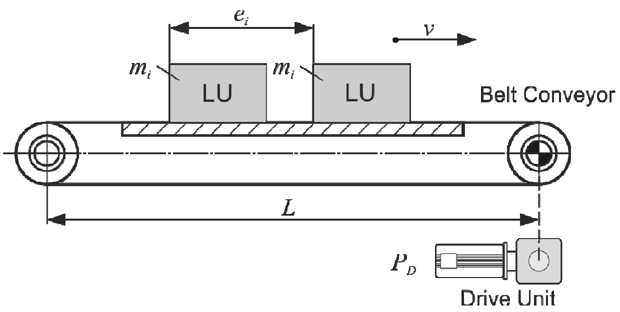

Fig. 3. Schematic representation of a conveyor.

During its operating time the conveyor demands the electrical power P. This power consists of the installed power of the drive P_D (including actuator/control unit) per module and the rated demand of the control system. This results in the energy demand required to operate the conveyor system.

These values are needed in the following section to develop the Energy Efficiency Indicators.

3.3. Standardized Boundary Conditions

In order to determine respectively measure the characteristic values needed for the efficiency indicators, a load collective is defined, which is composed of all possible operating states,

- nominal load,
- partial load (turndown),
- no load,
- stoppage (standby).

These reference loads are proportionally combined and define a standardized representative operation cycle (ROC), which describes a typical load situation on conveyors (Fig. 4).

Reference loads, combined to a representative operation cycle, are commonly used for the calculation and dimensioning of material handling components, such as lifting appliances [7, 8]. Hence, this approach can also be applied to the determination of the energy consumption of a conveyor system.

With these given conditions the energy demand is determined by power measurement. The total duration of the representative operation cycle ROC is defined by T_N.

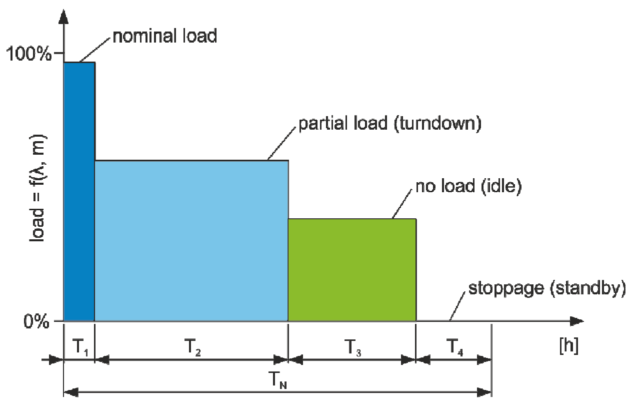

Fig. 4. Representative operation cycle (ROC).

Table 1

Coefficients of Representative Operation Cycle

i	**Operation state**	**Time slice** t_i	**Through-put** λ_i	**Load** m_i	**Velocity** v_i
1	Nominal load	20%	90%	90%	100%
2	Partial load	50%	50%	50%	100%
3	No load	20%	0%	0%	100%
4	Stoppage (standby)	10%	-	-	-

The time units T_i are calculated from the operating states using the relative percentage of time t_i

$$T_i = t_i \cdot T_N \,. \tag{3}$$

Table 1 contains the coefficients, which define the respective proportions of the representative operation cycle.

Different throughput rates, corresponding to the respective load conditions of the ROC, are considered via the weighting λ_i in percent. With the load dependent Λ_i the throughputs are calculated as follows

$$\Lambda_i = \lambda_i \cdot \Lambda_N \,. \tag{4}$$

The loading m also has an effect on each operating state. The conveying velocity is, if stoppage is not considered, the nominal velocity v of the conveyor system.

In order to determine the EEI, the specific values of the energy consumption of the entire system have to be measured by considering the conditions of the ROC, at the specified measurement point (Fig. 5).

All other required values can be calculated.

3.4. Energy Efficiency Indicators (EEI)

In technical applications, indicators are commonly used as specific values, which relate a basic parameter (the input of a process) to a reference value such as mass, length, or area. In case of logistics engineering, a combination of several basic parameters as a reference is recommended. This combination is referred to as "logistic performance" and represents the output of a logistic process.

For internal investigations, calculations and to transfer the results from a single device to a system, the introduction of a specific energy demand is recommended. This specific energy demand refers the input of energy to the "logistic performance" as a reference for processes in logistics. The specific energy demand of a conveyor system is obtained formally from the reciprocal of the energy efficiency (2), as follows

$$E_C = \frac{1}{E_{eff}} = \frac{E_E}{W_L} \,, \tag{5}$$

E_C – specific energy demand of conveying process;
E_E – energy input;
W_L – logistic performance (output).

- **Logistic performance**

Compared to complex systems at the process level, the output on the device level can be defined in a simple way due to its corresponding task.

The basic function of a conveyor is to transport load units from a point *A* to a point *B*, wherein the distance between these two points is L_F. Thus, the "logistic performance" would be, in the simplest case, the distance of the transported freight itself. However, the logistic performance is more meaningful when the number of transported load units is also considered.

The logistic performance W_L is then given by the product of the distance L_F with the sum of the transported load units x_{ges}. It represents a form of work performed by the conveyor within a certain period of time. The weight of transported LU's, which certainly has an effect on the logistic performance, is omitted at this first step. The definition of logistic performance W_L for a load unit conveyor is

$$W_L = x_{ges} \cdot L_F = \sum_{i=1}^{n} x_i \cdot L_F \quad [\text{LU·m}]. \tag{6}$$

The number of transported load units x_i can be determined in a practical manner, by counting all units passing a measurement point in the period T_i of the respective operating state *i*. Furthermore, the number can be calculated theoretically with the use of the throughput Λ_i of a material handling conveyor. This throughput is multiplied by the percentage of time values T_i, given by the representative operating cycles/states (ROC), Table 1.

$$x_i = \Lambda_i \cdot T_i \,. \tag{7}$$

As a result, the logistic performance is as follows

$$W_L = \sum_{i=1}^{n} \Lambda_i \cdot T_i \cdot L_F = \Lambda_N \cdot T_N \cdot L_F \cdot \sum_{i=1}^{n} \lambda_i \cdot t_i \quad [\text{LU·m}]. \tag{8}$$

The previous definition (6) and (8) of the logistic performance was formulated without consideration of the weight of the LU. However, for other types of conveyors, like systems for bulk transport, it is more useful to consider the transported weight and not load units. The logistic performance of the transported mass M_{ges} over the distance L_F is then obtained:

$$W_L = M_{ges} \cdot L_F = \sum_{i=1}^{n} x_i \cdot M_i \cdot L_F \ [\text{kg·m}]. \tag{9}$$

On the other hand, the calculation can also be made by the use of the nominal throughput Λ_N of the conveyor.

$$W_L = \sum_{i=1}^{n} \Lambda_i \cdot T_i \cdot M_i \cdot L_F = $$
$$= \Lambda_N \cdot T_N \cdot M_N \cdot L_F \cdot \sum_{i=1}^{n} \lambda_i \cdot t_i \cdot m_i \ [\text{kg·m}]. \tag{10}$$

Currently, two different types of logistic performance have been defined to refer to the energy input and create a specific value. Later, this results in two different types of EEI depending on the type of conveyor, for comparison and evaluation.

- **Energy Input**

The energy input of the system has to be determined. Therefore, the power consumption P_i of each individual operating state *i* of the conveyor, corresponding to the ROC (specified in chapter 3.3), must be determined and combined to form a representative energy demand.

Based on the representative operation cycle (ROC), the average power P_i of each operating state is measured. Multiplying these benefits P_i with the corresponding percentage of time T_i from the load spectrum, results in the energy input E_E. This energy demand is specific to the investigated conveyor and indicates the quantity of energy which is necessary to fulfill the material handling function, based on the given ROC.

$$E_E = \sum_{i=1}^{n} P_i \cdot T_i = P_1 \cdot T_1 + P_2 \cdot T_2 + \cdots + P_n \cdot T_n =$$
$$= T_N \cdot \sum_{i=1}^{n} P_i \cdot t_i \qquad [Ws, kWh] \tag{11}$$

By the use of the logistic performance and the energy input, the specific values of energy consumption (EEI) can be defined. As shown above, it is possible to define different indicators for conveyors, as result of the two different considerations of logistic performance.

- **Energy Efficiency Indicator 1 (EEI 1)**

The logistic performance used is the product of the number of transported units x_{ges} and the distance L_F in the reference period. This results in the first EEI

$$E_{C/(LU,s)} = \frac{E_E}{W_L} = \frac{\sum_{i=1}^{n} P_i \cdot t_i}{\Lambda_N \cdot L_F \cdot \sum_{i=1}^{n} \lambda_i \cdot t_i} \left[\frac{\text{Ws}}{\text{LU} \cdot \text{m}}\right]. \tag{12}$$

This allows the description of the energy demand referring to the transport of one load unit LU and based on a meter of transport distance.

- **Energy Efficiency Indicator 2 (EEI 2)**

The total transported mass M_{ges} and the distance L_F in the reference period are used as logistic performance. So, the second EEI is

$$E_{C/(M,s)} = \frac{E_E}{W_L} = \frac{\sum_{i=1}^{n} P_i \cdot t_i}{\Lambda_N \cdot M_N \cdot L_F \cdot \sum_{i=1}^{n} \lambda_i \cdot t_i \cdot m_i} \left[\frac{\text{Ws}}{\text{kg} \cdot \text{m}}\right]. \tag{13}$$

This indicator allows the description of the energy demand referring to the transported mass in kg, based on a unit length of the transport line, independently of T_N.

The focus of investigations in the research project effMFS is on conveyor systems which transport piece goods (LU), and not on bulk materials. Therefore, only the EEI 1 is considered in the example in section 5 of this paper.

4. PROCESS OF DETERMINING EEI

The process for determining the Energy Efficiency Indicators is arranged in three main steps

- Preparation,
- Measurement,
- Analysis (Calculation, Evaluation), Documentation.

All necessary process steps for determining the EEI are illustrated in Fig. 5.

Also, the information flow of each specific input/output value during the process is given and illustrated until the EEI are finally calculated.

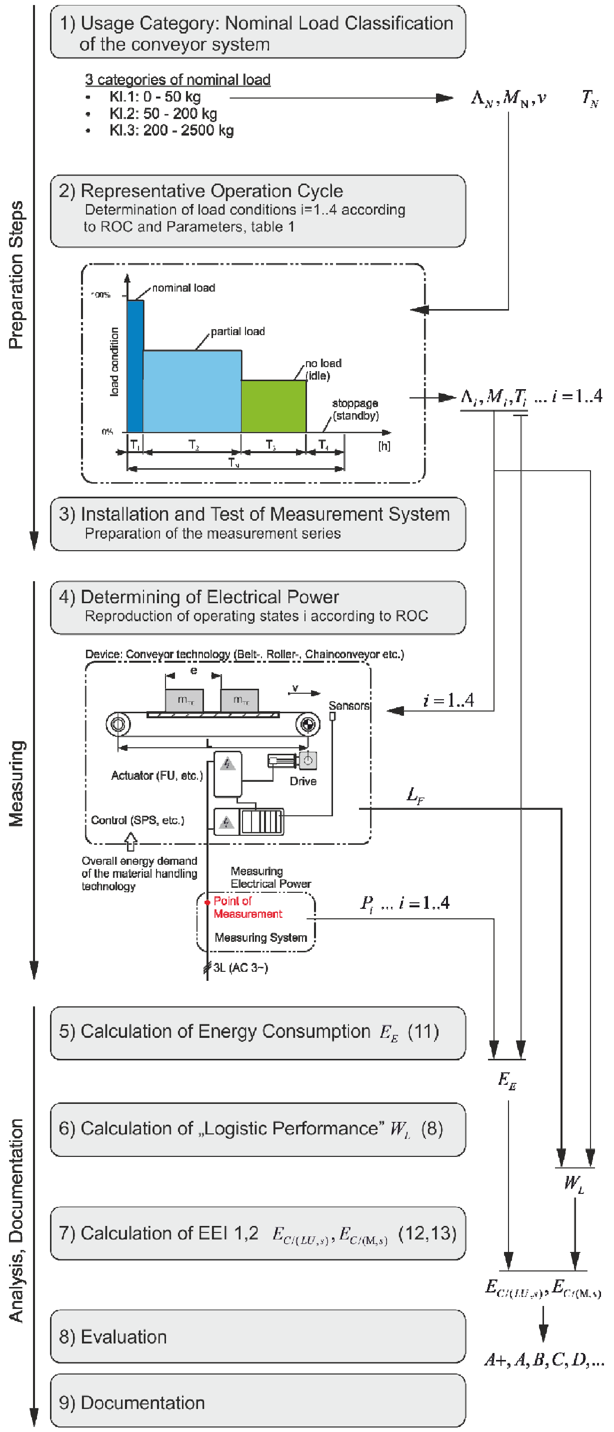

Fig. 5. Process steps of determining EEI.

In addition, steps of evaluation and documentation are also required for a complete and significant statement of energy efficiency.

The EEI have to be determined under standardized conditions. Only in this way, the comparability of the EEI can be guaranteed. This is achieved by the given loading conditions of the ROC, which are reproduced on the conveyors during the power measurement. This ensures that comparable EEI are determined, regardless of manufacturer or the respective testing laboratories.

5. EXAMPLE

A roller conveyor, located at the institute's laboratory, operated with an internal flat belt drive system is investigated. The conveyor was operated in two different load situations, situation A and B (Fig. 6). Then, the original drive was replaced with an energy-saving drive and operated again in both situations. The results of these four scenarios are determined and compared.

5.1. Situation, initial Parameters

The investigated roller conveyor is 2.6 m long and has a maximum load capacity of 50 kg per load unit (LU). The conveying velocity is 0.6 m/s. The original installed drive has an overall efficiency of approx. 30% [4]. The energy-saving drive has, depending on the load situation, an overall efficiency of 50−60 %.

The realized load intensities on the conveyor are shown in Table 2 (percentage values of electrical power rated on nominal load). Table 3 shows the running times for each operating state of the ROC load spectrum.

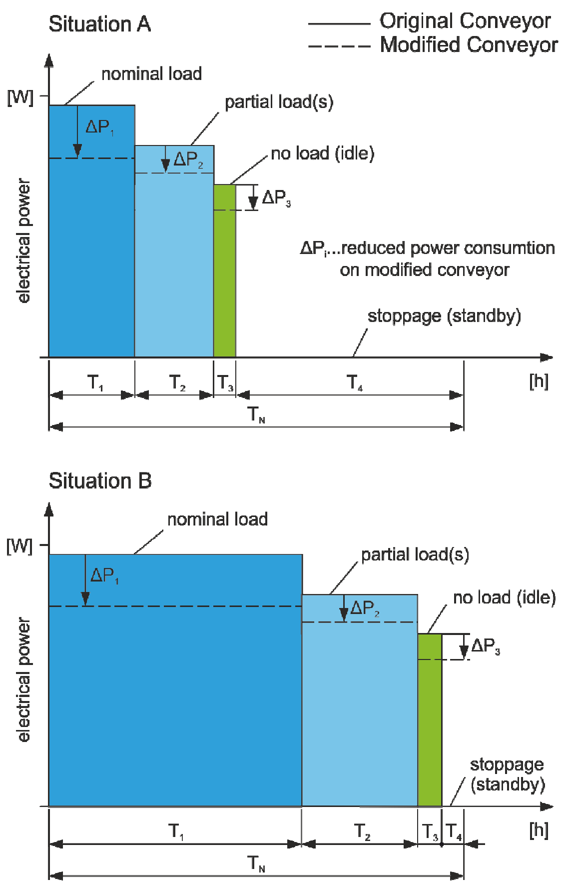

Fig. 6. Situations for EEI calculation.

Table 2

Load intensity of each operating state (relative)

	Nominal load	**Partial load**	**No Load**	**Stoppage (standby)**
Load	100%	80%	65%	0%

Table 3

Running times of operating states (relative)

	Nominal load	**Partial load**	**No Load**	**Stoppage (standby)**
Situation A	20%	20%	5%	55%
Situation B	60%	30%	5%	5%

Table 4

Calculated EEI 1: $E_{C/(LU,s)}$

	Original Conveyor	**Modified Conveyor**
Situation A	$48.25\frac{Ws}{LU \cdot m}$	$43.52\frac{Ws}{LU \cdot m}$
Situation B	$36.14\frac{Ws}{LU \cdot m}$	$31.82\frac{Ws}{LU \cdot m}$

5.2. Results

With the power values and the corresponding running times (Table 3), the calculation of the EEI 1 $E_{C/(LU,s)}$ is performed. The results are presented in table 4.

Different situations A + B. The specific energy consumption is lower in system B, although the loading of the conveyor is significantly higher due to longer operation times on full load and part load. The conveyor in situation B has a far higher energy consumption. This is of course trivial due to the higher time weighting of nominal- and part-load states in the collective B. However, the conclusion that the conveyor in situation B is less efficient is wrong. The conveyor provides a correspondingly higher logistical performance; it transports more load units in the same observation period (2760 LU instead of 1120 LU). Regarding the specific energy consumption, the number of load units conveyed is now being considered. Therefore, the specific energy consumption in situation B is about 25.10% lower than that of situation A.

Modified conveyor. In addition to a plant-specific comparison, a before-after comparison can also be carried out. The recalculated EEI provide information on the currently achieved energy savings.

Due to the higher proportions of full and part load, the suspected savings might be higher in system B. In fact, the specific energy demand in B is reduced by ~11.9%. Here, the use of a more efficient drive component is reasonable. However, a similarly high savings effect is also achieved in system A, which was not expected. Here, the current savings effect for the standard conveyor is ~9.8%.

The specific energy consumption of all considered situations has now a minimum value in system B, due to the use of the efficient component. That means that this configuration here has formally the highest energy efficiency. This is obvious because of the reduced energy demand and the higher available logistic performance.

6. CONCLUSIONS, OUTLOOK

An approach of a benchmark system for determining energy efficiency of material flow systems has been introduced. This includes the implementation of efficiency indicators to describe and quantify the energy efficiency of continuous operating conveyor systems. Furthermore, all specifications and standardized boundary conditions for determining the indicators have been developed. In addition, process steps for determining the energy efficiency indicators have been described. It is therefore possible to compare devices in terms of energy consumption.

At the device level (Fig. 1), the structure of the benchmark system can be transferred to other devices of material flow technology, such as automated storage and retrieval systems. An interesting task is the transfer of the benchmark system away from individual devices (device level), to entire processes, i.e. picking, at the process level. This extension of the performance of the benchmark system up to the process level is aspired and is currently in progress. Furthermore, statements concerning the carbon footprint of in-plant material systems, by the use of the EEI, are interesting.

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