MODEL FOR DETERMINING ENERGY CONSUMPTION USING MATERIAL FLOW SIMULATIONS

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ABSTRACT
Nowadays, automated material handling systems are indispensable and are of key importance for production and distribution. However, these systems also have a non-negligible energy consumption, which is an increasingly important factor due to climate change and rising energy prices. The question regarding the amount of the energy consumption of a system cannot usually be answered using common methods. This paper presents a way to determine the energy consumption of a pallet conveyor system using material flow simulation. To this end, a discrete event modeling approach is developed.

KEY WORDS
Energy, Material Flow Simulation, Energy Consumption, Material Handling System

1. Introduction
Material handling systems are key components in most logistics and manufacturing systems, particularly in automatic systems. For discrete goods and standard load units, conveyor systems are often used for transportation between fixed stations [1]. In particular, pallet conveyor systems transport load units (LU) up to 1,500 kg. Energy consumption is of great importance due to the huge size of most plants, of the transported weights and the high throughput. It represents an important aspect with respect to the efficient design and operation of the systems. In recent years, the demand for energy efficiency has become increasingly more important in light of the climate change and rising energy prices.

There is a variety of options to increase energy efficiency by using efficient components or material handling equipment [2, 3]. One example is the use of energy-efficient drives. However, using energy efficient drives involves additional expense, so a quantification of the monetary savings is required. However, the energy consumption issue is not taken into account in state-of-the-art planning approaches, and thus the economic potential cannot be estimated. For large and complex systems, material flow simulations are often used for throughput analysis due to the limits of analytical models.

These complex simulation models replicate the conveyor processes and thus the required factors for an energy consumption assessment very accurately, but there is no known approach for using such simulations for quantifying the energy demand. In order to quantify the energy consumption in the planning phase, a model must be developed. This model has to expand the existing material flow simulation models to allow for the energy consumption assessment. Such a model is presented in this paper, and the approach and model presented here can be used for various conveyors. In particular, the paper focuses on chain conveyors and roller conveyors, as those types are commonly used.

The paper is structured as follows: In Section 2, we describe various options to increase the energy efficiency of conveyor systems and present the results of a literature review on models for determining the energy consumption. Next, a model for quantifying the energy consumption is developed in Section 3. We then evaluate this model in Section 4 with the discrete event simulation environment Plant Simulation by Siemens PLM. The paper concludes in Section 5 with a summary and outlook on future research activities.

2. Energy Efficiency in Material Handling Systems

To determine the energy consumption of conveyors, their movement profiles have to be considered. Fig. 1 shows a typical pallet conveyor system consisting of chain and roller conveyors. It is obvious that there are several LU on a conveyor. The LU often have different weights. For functional reasons, the conveyor works in a start-stop operation with and without LU. For example, the following conveyor needs to accelerate before an LU can pass from the previous conveyor. Prior to the corner transfer, the LU needs to be separated, as the transfer segment’s capacity is one LU. Therefore, the conveyor with the LU accelerates and decelerates. Due to the different LU weights and operations, the electrical power required by the drive varies. Consequently, these aspects need to be considered in order to determine the energy consumption of material handling systems. The following sections show various ways to increase energy efficiency. To enable the assessment of these measures, the energy...
consumption has to be quantified in the planning phase. In Section 2.2, existing models for determining energy consumption are examined with regard to the previously described requirements.

Fig. 1. Example of a Pallet Conveyor System

2.1 Approaches for Increasing Energy Efficiency in Material Handling Systems

There are basically two approaches to increase the energy efficiency of conveyors. First, it is possible to use energy efficiency components (e.g. energy-efficient drives). An alternative is the use of control strategies (e.g. batch building).

Pursuant to EU Regulation No. 04/2014, there are minimum requirements for the efficiency of drives [4]. The regulation applies to AC motors with a rated power from 0.77 to 375 kW. Starting January 1, 2017, all motors have to reach at least the defined efficiency level of IE3. To meet the IE3 requirement, a 0.75 kW drive with 4 poles must have a degree of efficiency of 82.5%, whereas 72.1% is sufficient for IE1 [5]. As a result, the overall energy efficiency of conveyors can be expected to increase. Another high energy saving potential of up to 50% can be utilized by using gearless motors in conveyors [6]. These motors offer advantages in low-load operations where conventional motors often show low efficiency. However, the numerical value of the energy savings remains unclear, which prevents a monetary assessment.

One control strategy is the reduction of drives during runtime. Clément presents a study to increase the energy efficiency of pallet conveyors [3]. Using advanced analytical equations, it allows for the calculation of the optimal stopping time or sensor positions of the conveyor segments to reduce drives during runtime. However, it does not enable the quantification of the energy consumption and the quantification of the energy costs.

Hoppe et al. conducted studies on test stations to analyze the energy consumption of chain conveyors, which shows that an increase in speed leads to a reduction in energy consumption [7, 8]. This can be justified by the fact that asynchronous motors have significantly lower efficiency in the low load range than in the higher load range. It turns out that there are various approaches to increasing the energy efficiency of conveyor systems, but no approaches to determine the energy consumption. Therefore, the total saving potential of a material flow system remains unknown.

2.2 Models for Determining Energy Consumption

Energy consumption can be measured, calculated or simulated. In this section, we provide an overview of relevant research on the quantification of energy consumption.

Lottersberger et al. conducted a study of the energy efficiency of bin conveyors with a detailed analysis of the quantitative impact of the energy consumption [2, 6, 9]. In their studies, measures of both the energy efficiency rating of an individual conveyor [9] and of entire material flow systems were developed [6]. The energy consumption for the measure is quantified under consideration of different load situations by load collectives, wherein the load includes both the throughput and the LU weight. However, a model for quantifying the energy consumption over a long-term analysis period is not presented.

The measurements by Hoppe described in the previous section are not designed to be used during the planning phase [7, 8].

Schmidt & Schulze expand a discrete event simulation to determine the mechanical power of conveyors [10]. However, they do not model the electrical power, and thus not the energy consumption either. In the paper, they mention the advantage of state-based modeling, but the energy consumption is determined by sampling intervals (continuous). Continuous modeling quickly leads to considerable computational effort and is therefore regarded as ineffective.

For manufacturing machines, different energy consumption models have been developed that are transferable to other production machines and, to a limited extent, to conveyors as well.

Weinert presents a state-based method to determine the energy consumption at different levels of detail with so-called “Energy Blocks” [11, 12]. Weinert also describes connecting the model with discrete event material flow simulations. However, the determination of the energy consumption is done in a developed software tool, in which the interface to material flow simulations remains unclear. The model is very general and does not include specific conveyor aspects such as the modeling of a complete conveyor system. The model does not include a procedure for the delimitation of operating conditions based on various influencing factors. Overall, it can be stated that Weinert has developed a general approach to assessing the energy consumption of production systems. However, since it does not consider process parameters, such as the LU weight, the level of detail is too low for use in material handling systems.

A calculation method for determining the energy consumption of machine tools is provided by Dietmaier et al. [13]. In this case, the determination of the energy consumption is based on operating states. A constant energy consumption value is allocated to each state. However, this model does not consider the conveying specifics such as different sequences of states through
3. Model Development

As demonstrated in the previous section, discrete event models represent an appropriate modeling method for expanding material flow simulations to include energy consumption assessments. For this reason, a suitable model is developed, whereby a general procedure is applied in order to allow for the transfer to other conveyors and for modeling other KPIs (e.g. total running time of the conveyor).

1. Overall concept development
2. Study of the object under investigation
3. Identification of relevant factors and states for energy consumption assessment
4. Modeling of state-dependent power
5. Development of a modeling approach to identify the states within an discrete event material flow simulation

3.1 Overall Concept Development

The concept is intended to enable the expansion of simulation models of entire material flow systems. They consist of single conveyors that have to be combined in a modular form. However, there are close connections between the conveyors as a result of LU transfer and control strategies. Fig. 2 shows the overall concept to expand a material flow simulation to include the energy consumption assessment. On the left side, there is a common simulation model with the throughput and lead time as KPIs. On the right side, the simulation is expanded to include the energy consumption determination. The expansion is based on event state-based modeling for each conveyor. By determining relevant impact factors, the states and the corresponding transition conditions are derived (Section 3.3). A power value is assigned to each state (Section 3.4). Together with the determination of the start and end times of the states, the total energy consumption is determined.

3.2 Study of the Object under Investigation

In the study, we focus on the conveyor’s movement profile, which is required for assessing the energy consumption and a condition for state-based modeling. Chain conveyors and roller conveyors have a cyclic mode of operation. The beginning of a cycle is the acceleration of the conveyor without load, or in the case of an already running conveyor, the arrival of the first LU of the cycle. By decelerating the conveyor down to \( v = 0 \) or upon the arrival of the first LU of the next cycle, the cycle ends. A cycle includes a fixed number of LU, which is determined by the operating strategy. A frequently applied operating strategy is the batch strategy, where several LU are combined into a batch and then conveyed together. Fig. 3 shows the batch building of a 2-Batch (batch with two
The batch building is carried out on the (red) highlighted conveyor. After arrival of the first LU (1), the conveyor is delayed, followed by a subsequent waiting period for the following LU (2). Upon the arrival of the second LU on the previous segment (turn table) (3), the segment accelerates and the second LU overflows. The batch is thus complete (4) and can be conveyed to the next segment (5). In batch building, a timeout criterion can be used, according to which only LU with a time interval shorter than the timeout value are included in a batch. As a result, variable batch sizes can be formed and there are different modes of operation on the individual conveyor.

3.3 Modeling of States for Energy Consumption Assessment

The introduction of states enables the realization of the required discretization for the discrete event modeling of the power consumption. States represent time periods in which the electrical power of a conveyor can be described by a constant or by a function. To represent the characteristics of the electrical power, the states must be modeled with regard to the corresponding influencing factors. Therefore, it is necessary to identify the main influencing factors. The main influencing factors change over time, and thus have different values over time. Changing the time derivative of one of the main influencing factors results in a new state. The main influencing factors can be determined by reviewing the literature and evaluating measurements. All relevant information has to be included in the state definition, for example if a conveyor consists of several drives (e.g. turn tables).

Fig. 4 shows the profile of electrical power within an exemplary cycle with a batch consisting of two LU (2-Batch) for a chain conveyor. It allows for the identification of the relevant states. Taking into account the number of LU that are located on the considered conveyor at the respective time points, the following observations can be formulated: Within the intervals in which the number of LU remains constant, the electrical power varies only slightly. Higher oscillations are suppressed by the constant mass of the conveyor. It can be concluded that modeling these intervals with a constant power value is possible if the number of LU on the conveyor is considered. Detailed measurements with a chain conveyor confirm the influence of the LU weight and affirm the significant impact of conveyor speed [5, 6]. Accordingly, the relevant influencing factors for the identification of states are:

- conveyor speed
- LU weight, and thus especially the number of LU on the conveyor

Fig. 5 shows a diagram with the main influencing factors for the example shown in Fig. 4. The nomenclature expresses the states’ dependency on the conveyor speed: standby (st), constant speed (v), acceleration (a), delay (b). There are additional indices for the information regarding the number of LU: Lower indices are the number of LU on the segment and the top indices describe whether a LU enters the segment (+) or leaves (-) it. For example, the state v^1+, corresponds to one LU on the conveyor (1), constant conveyor speed (v) and a transitional process of a second LU (+).
Introducing these states sets the basis for the determination during the discrete event simulation. The modeling for the state-dependent power value will be described in the next section.

### 3.4 Modeling of State-Dependent Electrical Power

For each state identified in the previous step, a value or function of electrical power is assigned. However, the weights of the LUs located on the conveyor segment can differ significantly and therefore must be taken into account when determining the power value. There are two possibilities: First, to determine the electrical power value using analytical formulas, e.g. as presented in [14]; second, to assign measurement values to the states. Determining the electrical power requires knowledge about the design parameters of the conveyor, such as the efficiency characteristic map of the drives, for example. A determination of the electrical power for the individual states requires sufficient existing measurements covering different LU weights. Thus, assigning a state and conveying mass to an electrical power value is required. Depending on the available information, one of the two approaches can be chosen.

### 3.5 Development of a Modeling Approach to Identify the States within an Discrete Event Material Flow Simulation

The concept is based on the state-dependent modeling of the electrical power and state durations. In Section 3.3, the main influencing factors that cause a state change and allow an exact delimitation of individual states were determined. Depending on the level of detail required, the definition of conditions can be adjusted. Since the electrical power of a state depends on variable factors, such as the LU weight, a determination based on the frequency of the execution of individual operations is not sufficient. It is necessary to determine the electrical power required for each state considering the duration. The sequence of the different modes of operation can be described based on state machine diagrams. Moreover, the other information required for the implementation in the flow simulation model can be obtained. Fig. 6 shows the state machine diagram for the batch building process and the “conveying 2-Batch” process.

**Fig. 5. Description of States Based on the Main Influencing Factors**

**Fig. 6. State Machine Diagram of Different Modes of Operation**
available when using standard modules of commonly used discrete event simulation software. This concept is utilized to identify the states and the state durations. Combined with the state-dependent power, the energy consumption within an observation period can be quantified using the following equation.

\[ E = \sum_{i=1}^{n} t_i \cdot P_i \]  

(1)

The entire process is illustrated in the following sequence diagram (Fig. 7). The model consists of two functions as well as one table. The "assess_energyConsumption" function obtains the identification of the states and the determination of energy needs and writes these data into the "Tab_energyConsumption" table. The "assess_power" function assesses the state-specific power. Within the "Tab_energyConsumption" table, any identified state has one line with the following parameters:

- Datetime: starting time
- Datetime: end time
- String: state
- Time: state duration
- Real: electrical power
- Real: energy consumption

Once a change in one of the main influencing factors is detected, the current state ends and a new state begins. Every time such a change is identified, the "assess_energyConsumption" function is called, initializing the calculation of the energy consumption. The duration of the previous state and its electrical power value are calculated by the "assess_power" function. The state duration and electrical power value are then multiplied in order to obtain the energy consumption. Finally, the new state’s starting time is documented in a new row in the "Tab_energyConsumption" table.

The proposed concept offers the possibility to determine the total energy consumption during an observation period. In addition, an extension to identify the maximum power of a material handling system is possible without necessitating extra effort. For this purpose, the "assess_power" function can be adapted in order to store the current maximum value.

4 Exemplary Application & Simulation Study

The model presented in Section 3 will be applied by way of example. The aim is to show that the model can be included in a discrete event simulation and that an exact determination of the energy consumption can be made by the model.

A widely used simulation tool for simulating conveyor technology is the discrete event simulation environment Plant Simulation by Siemens PLM. Plant Simulation is used here for the exemplary implementation of the model. Thereby, we implemented the functionality for identifying the states as follows:

- We implemented a conveyor system using the standard Conveyor module offered by Plant Simulation.
- To identify the start and end of a transitional or disposal LU process, we use sensors, which call a function upon detecting a LU.
- To identify the “reaching the target speed” event, Plant Simulation offers a default function. Transitions to the states v or st can easily be identified using this function.
- To identify the acceleration and deceleration processes, we use the default observer functionality. It calls a function every time the observed variable changes, in this case the conveyor speed.

By means of these functions, all state changes are detected and assigned processes for the energy consumption assessment are started (see Fig. 7). The electrical power is modeled by the input of the values of the electrical power based on a measurement. The considered LU have the same LU weights, whereby this

![Fig. 7. Sequence Diagram for Model Description](image-url)
procedure is useful because no major variations in the LU weights occur in the example. The values of electrical power for the chain conveyor are shown in Table 1.

Table 1. Values of Electrical Power per State

<table>
<thead>
<tr>
<th>state</th>
<th>st_0</th>
<th>a_0</th>
<th>v_0</th>
<th>v_0+</th>
<th>b_0</th>
<th>st_1</th>
<th>a_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrical power (W)</td>
<td>0</td>
<td>130</td>
<td>380</td>
<td>380</td>
<td>370</td>
<td>0</td>
<td>350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>state</th>
<th>v_1</th>
<th>v_1+</th>
<th>v_1-</th>
<th>b_1</th>
<th>st_2</th>
<th>a_2</th>
<th>v_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrical power (W)</td>
<td>450</td>
<td>460</td>
<td>400</td>
<td>0</td>
<td>300</td>
<td>400</td>
<td>510</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>state</th>
<th>v_3-</th>
<th>b_3</th>
<th>st_4</th>
<th>a_4</th>
<th>v_4</th>
<th>v_4-</th>
<th>b_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrical power (W)</td>
<td>400</td>
<td>400</td>
<td>0</td>
<td>450</td>
<td>610</td>
<td>440</td>
<td>410</td>
</tr>
</tbody>
</table>

In the first step of the simulation study, a validation of the model is carried out based on the measurement shown in Fig. 4. We simulate a conveyor line of 46.55 meters, which consists of seven 4-buffer segments 6.65 m in length and has a conveyor speed of 0.3 m/s. The LU has a dimension of 0.8 m x 1.2 m (0.8 m in conveyor direction), which are typical values for pallet conveyor systems. Validation is based on the second conveyor segment after the source. Fig. 8 shows the simulated profile of the electrical power. The energy requirement in the measurement is 4.28 Wh. The value of the simulation results is 4.29 Wh. The deviation is therefore less than one percent. Thus, the model is sufficient for performing a simulation study. With the validated model, an exemplary simulation study is then performed in order to demonstrate the benefits.

Within the simulation study, the operating strategy of the conveyor segments is varied. One experiment contains a batch building with four LU without timeout criterion. The other experiments include a timeout criterion of 10-40 s. For the LU arrival sequence, a negative exponential distribution is assumed with a beta value of 30 s. For each set of experiments, ten observations are carried out. Every observation includes 100 LU transported from source to sink. Fig. 9 shows the results of the experiments. It is apparent that the choice of operating strategy has a significant impact on energy consumption. A batch building of 100 % (= no timeout) results in a difference of 70% as compared to batch building with a timeout of 10 s. Due to the low timeout value, only a small number of 4-Batches and 3-Batches is formed. The majority of LU are fed in single or in 2-Batches through the system. This leads to longer activation times of the motor and to significantly increased energy consumption. The results show that the batch building strategy has a major influence on energy consumption. The huge deviation between the identified energy consumptions can be traced back to the influence of the negative exponential distribution of the source.

By applying it to an exemplary chain conveyor, it could be shown that an implementation of the model is possible and that it can be used to study different operating strategies. The model shows a good match between results and measurement values (see Figs. 4 and 8) and is thus suitable for the execution of simulation studies. Overall, the model is a powerful approach to expanding existing material flow simulation models to include the determination of the energy consumption, or to create new models with the functionality.

5 Conclusion

This paper introduces a model and an approach to allow the determination of energy consumption in existing material flow simulations. The developed model is based on state-dependent modeling of the electrical power and the state durations. We applied our model for the purpose of validation and studying the influence of batch building on energy consumption. We were able to quantify the influence of different conveyors and different modes of operation on energy consumption within a monitoring period.

By determining the energy consumption within a longer period, a statement can be made about the overall cost effectiveness of energy efficiency activities (e.g. using energy-efficient drives). In addition, a determination of the maximum power of the system is also possible. Moreover, the model can not only determine the energy consumption, but other performance indicators as well, e.g. the number of acceleration processes. The next step
of research is to use the model for extensive simulation studies. The effect of different conveyors and operation strategies can thus be investigated systematically. Furthermore, the concept is utilized for the detailed investigation of various commonly used pallet conveyor systems, those used in the area in front of high rack warehouses.

References