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Approach for implementing a control and optimization loop for an energy-efficient factory

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Abstract

Information about the energy performance of individual processes in a production system is only insufficiently available. To solve this problem, a holistic approach has been developed enabling operators to continuously monitor a factory's energy consumption. The aim is to keep the manufacturing system in an energy-optimal state. However, examining and optimizing the energy consumption of individual components does not always achieve the desired result. Additional targets, such as 'quality', 'cost', and 'time', must be considered. For this, a metric-based approach has been developed that allows assessing optimization scenarios and taking immediate actions if energy consumption gets too high.

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Keywords: energy efficiency; energy monitoring; continuous analysis; energy optimization

1. Introduction

The awareness is growing that a more economical and intelligent use of energy is needed in both industry and private sector. Rising energy prices as well as an increasing number of political initiatives at national and international level are bringing the energy topic to the forefront of attention. Energy efficiency plays a more and more important role in production technology. Various studies estimate that the potential for energy-savings in industry amounts to 20 to 30 percent [1, 2].

That companies are increasingly aware of the issue of energy efficiency should primarily be seen as a response to external drivers such as the slow but continuous rise of energy prices and climate protection in general.

In addition to cost savings and climate protection, a "sustainable production system" improves the image of a company, since the sustainable use of resources is welcomed by both industry and society.

For these reasons, manufacturing companies finally strive to take energy consumption into account when planning, operating and optimizing their production systems.

In general, more and more manufacturing companies are caught in the production triangle of time, cost and quality [3]. As energy is not regarded as an explicit factor, a new overall understanding of energy as a requirement in manufacturing is needed. Currently, there is a lack of practical methods that allow evaluating production processes while taking a holistic view on both the triangle of production and on energy efficiency.

The following article presents an approach that considers energy consumption in manufacturing over the long term in order to keep a factory in an energy-optimized state of operation. This approach has been developed as part of the research project ECOMATION. The project aims to develop methods that enable energy savings in manufacturing technology through automation. The consumption of a machine is minimized by situation-oriented machinery components. At the factory level, energy waste in plants is identified and improvement measures are taken.

The implementation of the approach is carried out in a simulation-based environment, covering the partial functionalities of energy planning, energy optimization and energy monitoring. To this end, a simulation model of the

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considered production system is used to which the measurement data of the facilities' energy consumption are added. This is the basis for analyzing the energy consumption and for simultaneously reviewing alternative production scenarios for all resources.

2. State of the art

A number of publications address the need to increase energy efficiency through innovative manufacturing processes in various production areas [3, 4, 5]. DIN EN ISO 50001, published in December 2011, provides an internationally accepted and comparable standard for an energy management system. However, the standard defines only general requirements for an energy management system. The specific configuration is subject to the company itself and not necessarily transferable. Müller et al [6], Engelmann [7], Junge [8] and Weinert [9] describe methods that are mainly based on specific processes and not generally valid. Müller addresses the energy-efficient design and operation of factories. By using various methods and a checklist in the planning phase of factories, Müller at al [6] want to achieve an improvement in energy efficiency. At the moment, a holistic approach to energy flows and savings at the factory level does not exist.

Various initiatives in Germany want to unlock the energy saving potential in industry, especially for small and medium-sized companies. The aim of these initiatives is to show that energy efficiency provides a competitive advantage and also supports the decision-making process for future investments. The goal of energy monitoring systems in terms of energy data collection systems is to create transparency over energy consumption. An energy monitoring system can be understood as an information and communication system that plays a central role in an energy management system. Based on Horváth [10], Wohinz et al [11] and Trautmann et al [12] energy monitoring can be defined as "a partial function of corporate energy management, which includes energy planning and control, which allows transparency of energy consumption and supports operational energy management". Based on this definition, energy monitoring fulfills the following functions:

- Information tool: continuous and systematic evaluation of collected energy consumption data; analysis and evaluation of data based on indicators
- Planning tool and control instrument: continuous monitoring of the objectives set out by Energy Planning
- Advice tool: instrument which is used to derive specific solutions or actions based on the information collected, for the continuous reduction of energy consumption and associated costs.

Through the use of such systems, companies can realize energy savings.

3. Basic methodology

To reflect the energy behavior of a factory, it is essential to fully model its energy flows. To find out the product-related values of energy use, the production data must be linked to the energy data. The basis for monitoring energy is provided by collecting and mapping the energy consumption of equipment and plants as well as of appliances that are directly (e.g. compressed air supply, plants for processing cooling lubricants) and indirectly related to the production environment (lighting, social rooms). Within the scope of the project, models for the main processes were developed and connected to status-based energy profiles. For a realistic simulation, the system has to be continuously supplied with energy-related field data. Through bidirectional communication, the energy data of individual machines can be transmitted to the control level (factory level). Likewise, this general communication method can be used for sending messages (commands) from the control level to the machine (e.g. to switch off the machine for 5 minutes). The basics and the implementation of the modeling approach are illustrated in [13]. The real-world data (permanent field data) are transferred to a simulation-based planning system, where the energy performance of the factory is optimized.

Energy efficiency can only be monitored holistically if visibility is provided for both the current production status and for the optimal state, in particular to enable the assessment of production control intervention [6, 14]. Currently, there is no comprehensive monetary assessment of alternative production scenarios that takes into account all resources and peripheral systems. To solve this problem, an indicator system has been developed. Based on the production program data and machine data, it was examined how to include the optimization variable 'energy' while taking account of other target variables. An isolated examination of energy demand in manufacturing may not lead to the desired results. If production is solely focused on achieving an energy minimum, this may negatively affect other target variables. To thoroughly assess the relevant production system, the factors „quality", „costs" and „time" were considered. Accordingly, the manufacturing process is evaluated in terms of four dimensions: energy, quality, costs and time.

The 'time' factor is based on cycle times and on schedule adherence of an order. To determine schedule adherence, it is necessary to capture all data, from receipt of a customer's order to the delivery of the products to the customer. However, given the restrictions of the present model, it is not possible to collect such data. Therefore, schedule adherence is not included in the assessment of time. The achievement of the criterion of time is only verified by the throughput time of a product (equ. 1). In the simulation system, the flow of each product is monitored to calculate its manufacturing throughput time.

$$K_{Time} = \frac{time\ reference\ value}{time\ actual} \quad (1)$$

The quality dimension is based on the indicator OEE (overall equipment effectiveness), which indicates availability, level of quality, and utilization of resources (equ. 2).

$$K_{Quality} = overall\ equipment\ effectiveness \quad (2)$$

Energy consumption is considered by the key figure called 'energy efficiency factor' (equ. 3)

$$K_{Energy} = \frac{energy\ consumption\ reference\ value}{energy\ consumption\ measured} \quad (3)$$

The key figure K_{Energy} shows the difference between the actual energy consumption (energy consumption measured) and the optimal target energy consumption (energy consumption reference value).

The 'cost' factor is based on the manufacturing cost of a product (equ. 4). The manufacturing cost include manufacturing material cost, material overheads, finishing overheads, labor cost, reference energy costs, and overheads. The manufacturing costs are not calculated in the simulation-based planning tool but in a separate tool.

$$K_{Cost} = \frac{manufacturing\ cost\ reference\ value}{amanufacturing\ cost\ actual} \quad (4)$$

The individual key figures (K_i), as presented above, are integrated into a quality function (equ. 5, 6). The indicators may be weighted differently by a variable weighting factor. Each indicator is multiplied by a specific factor (w_i). The sum of all w_i is equal to one. Depending on the intended emphasis, the weighting can be varied individually and adapted to specific tasks. Based on this approach, the optimization of the production scenario from an energy perspective is possible.

$$g = \sum_{I=1}^{n} w_i \times K_i \quad (5)$$

$$g = [(w_{Time} \times K_{Time}) + (w_{Energy} \times K_{Energy}) + (w_{Quality} \times K_{Quality}) + (w_{Cost} \times K_{Cost})] \quad (6)$$

4. Optimization approach

4.1. Strategies for optimization

The optimization of a production scenario will be explained by an example. The simulation can be used to determine optimal machine utilization for a production program and defined equipment. The simulation allows calculating alternative production programs (small / large quantities, different manufacturing order) and different energy levels of the equipment (work, warm-up, wait, block, save, error, off). Before the production design is evaluated, the system will configure the parameters. There are two groups of parameters: non-changeable parameters such as machinery and equipment, and characteristics of products and energy costs. By contrast, parameters, such as different working hour's model, capacity of buffer and the sequence of operations (production program) can vary and the optimal configuration can be determined.

In a first step, an optimal production is planned done. This requires information such as the number of produced units and latest completion date for each job. In addition, an optimization strategy is selected and the individual targets are weighted as outlined in equation (1) to (4). Based on these parameters, the machines are scheduled taking into account the selected priorities. A scheduling algorithm allocates the production orders to the available production resources. The simulation will determine the optimum machine scheduling sequence, taking into account the quality function. The planning proposal is transferred to the manufacturing floor by releasing the initial design alternative. During ongoing production operation, current machine status, operational data, and finished production quantities are reported to the control component of the ECOMATION tools. It compares timing and quantities, or, in other words, the progress of plan fulfillment, and allows to make controlled interventions to correct deviations from plan. In a number of cases, actual production will in part deviate from the previously defined plan, necessitating controlled interventions in the ongoing planning process. Here, two types of faults can be distinguished influencing the manufacturing process. Minor disturbances, such as the deviation of the real predetermined processing time from the nominal processing time, resulting in a shift of job blocks, provided this is allowed for by the planning reserve. If a postponement of the planned orders is not possible or if events occur in the manufacturing environment, which represent a major disturbance, such as a machine failure, re-planning is based on the current state of completion. The control component of the ECOMATION tools will initiate a new planning run.

4.2. Control loop

As part of ECOMATION, a prototype of a closed control loop at factory control level was implemented. This closed control loop serves to control the fulfillment of targets and to derive the necessary measures. By comparing planned values to actual values it provides the data input for future decisions. In general, the monitoring of energy efficiency can be understood as a systematic information processing procedure which allows for an evaluating comparison between two parameters. Figure 1 points out the feedback control system (fig. 1).

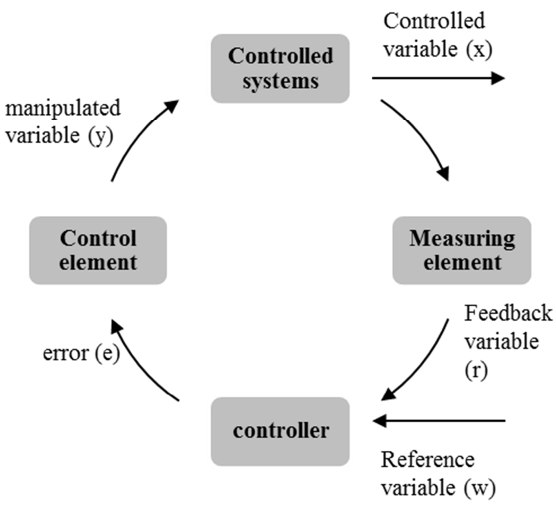

Fig. 1. Feedback control system

The command variable or reference variable w represents the superior target variable, for example the maximum permissible energy consumption. The actual value is represented by the measured indicator of current energy consumption. Comparing target to actual values makes it possible to identify measures. If actual energy consumption is higher than maximum permissible energy consumption, measures can be taken to lower consumption.

The measuring element will then reveal the state of the considered production system with a view to energy consumption.

Essential in setting up such a control loop is to systematically collect and process the energy data. In line with VDI 4661 [15], the steps of data collection and processing are as follows below (fig. 2).

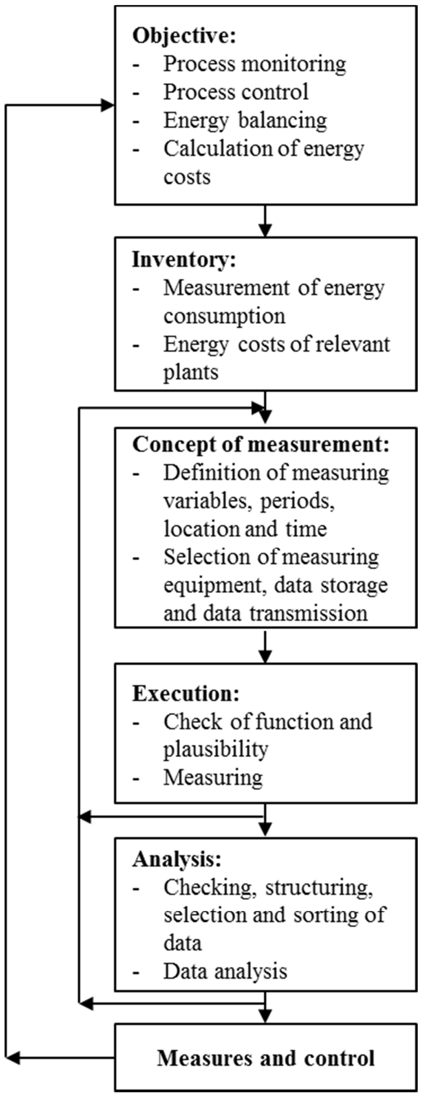

Fig. 2. Acquisition and processing of energy data

4.3. *Cost evaluation*

An analysis of different approaches has shown that the assessment of system performance is not or only partially possible. Most often, approaches are based on a one-time analysis of operating scenarios without subsequent verification. Thus, present approaches are not suitable in terms of permanent system optimization for energy efficiency. Within the project, an approach of extended process costing combined with the calculation of hourly rates for machines was developed.

This approach allows the specification of energy costs (such as gas, electricity, water), which are already included in the hourly rates for machines. The method was extended as follows: The fixed energy costs were turned into variable ones to be able to take into account volatile energy prices and energy consumption. In addition, the control functionality was integrated in an appropriate way in the calculation methodology. The continuous return flow of energy efficiency data for control purposes allows an evaluation of the cost estimate and therefore initiates a learning process for better quality forecasts.

Based on the core functionalities of energy planning, energy optimization and energy monitoring, the result is a methodology that avoids unexpected peaks of energy consumption and identifies potential savings in the current energy consumption. An example is given in figure 3 (fig. 3).

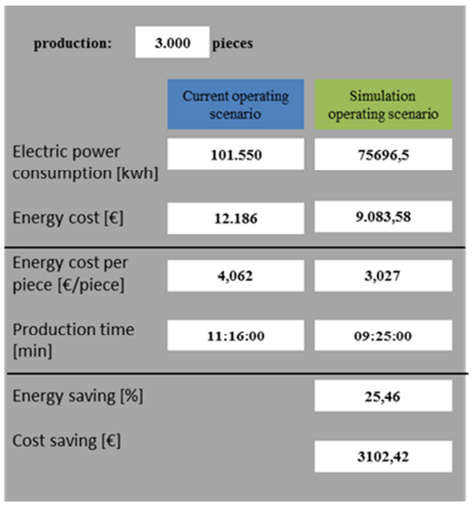

Fig. 3. Comparison of key performance indicators

5. Scenario and benefit

With regard to figure 1, the target scenario of maximum energy consumption means to compare the manipulated variable y (i.e. current energy consumption) with the reference variable w (i.e. the target value). The comparison will produce the error e, representing the deviation from the reference variable. If y is bigger than w, then current energy consumption is bigger than the permissible target value, i.e. the maximum permissible energy consumption. Now the user can opt for re-planning or optimization. The modeling and simulation can be done in a material flow simulation system such as Siemens Plant Simulation. When modeling and simulating manufacturing scenarios by Siemens Plant Simulation, different options for operations scheduling can be displayed.

The simulation aims at re-planning the production sequence, i.e. production orders are re-allocated to the available equipment. The criterion for optimizing the machine schedule is the maximum permissible consumption of energy for processing orders. To this end, energy consumption values were attributed to the resources (machines and the necessary manufacturing peripherals). The energy consumption values are based on real consumption values of each resource. Taking the possible machine production schedules and simulating them in Siemens Plant Simulation allows determining production volume, lead time and energy consumption. Planning can them be evaluated with a view to schedule adherence, lead time, machine utilization, manufacturing cost and energy consumption.

Summary

The objective of the presented work has been to model the energy behavior of a production system to provide a basis for an optimal control of energy consumption. To this end, a control loop at factory level was established which allows for production planning from an energy-saving point of view while taking into account criteria such as 'quality', 'cost' and 'time'. The results of this planning process as well as the current production parameters can be exchanged via bidirectional communication between the individual manufacturing resources and the factory level. This is achieved by linking up the planning processes and thus setting up a connection between machine control, management system and the material flow system including energy information. On the one hand, the planning processes comprise activities concerned with work scheduling (especially work schedule preparation and operations planning), on the other hand they cover activities concerned with production planning and control (PPC). By combining these two planning horizons and linking the corresponding models and their associated assessment methods it was possible to create control loops which are the basis for optimization.

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