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Evaluation of the energy flexible operation of machine tool components

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With the recent increase in the use of renewable energies, such as photovoltaic and wind energy, both companies and energy providers are confronted with an increasingly volatile energy supply, caused by alternating weather conditions. In the case of on-site generation of electric power by wind and solar resources, it can be beneficial to adjust the company-wide power consumption to these fluctuations. This paper presents a real-time control approach for adapting the use-time of energy-flexible components under the constraints imposed by a fluctuating supply from renewables, the requirements on machine tools and indeed, the manufacturing process itself. Based on a hypothetical medium-sized manufacturing company, this paper evaluates different scenarios with regard to varying weather conditions. For the real-time control, no weather forecasts are necessary and the machine tools' productivity is maintained using select machine components.

It can be observed that, given a certain fluctuation within the power supply, rescheduling the use-time of energy-flexible machine tool components leads to a higher utilization degree of the own supplied energy by renewables. This paper depicts a scenario that provides the preconditions for an economic operation of the proposed strategy.

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1. Introduction

To cope with raising energy costs, a self-sufficient energy supply is a possibility worth considering for manufacturing companies. Resulting from the rapid evolution of the energy market, the investment costs for systems that generate renewable energy have decreased in recent years, especially for solar power [1]. In order to increase the economic efficiency of on-site generation, the degree of use of the energy generated from renewables needs to be maximized – a difficult task particularly with regard to the volatile characteristic of solar or wind power. Thus, the energy flexibility of the industrial companies and their production machines is a necessary element to achieve the integration of the renewable sources.

Two important determining factors are the process quality and the throughput of the machines which the energy flexible components are part of. Both factors must basically be ensured during any energy flexibility measure. Focusing on the manufacturing process and the corresponding machine tools, there are limited possibilities to spontaneously adjust power

consumption according to prevalent weather conditions and therefore, solar power supply. However, a number of selected machine tool components, such as the spindle cooling unit or the coolant lifting pump, are characterized by a high degree of technical energy flexibility [2]. In the current design, their use time is typically determined by a two-point control. A more intelligent scheduling algorithm is usually not provided. By a purposeful operation of the energy flexibility, the effective power demand of the factory is intended to be adapted, to the furthest possible extent, to the availability of the on-site-generated electric power. Remaining residual loads must be balanced with the main power supply.

This paper examines to what extent energy flexible machine tool components can reduce the energy demand of the supply grid and therefore, the energy costs. This is done by observing the energy flexible operation of an exemplary model factory. An important prerequisite is that the energy price is higher than the reward for feeding-in electric energy from renewable sources. In Germany, this economically logic situation does currently not exist due to the Renewable Energy Law (EEG).

2. Energy flexibility of production machines

2.1. Definition of energy flexibility

A common definition of the energy flexibility of production systems is *the capability to react quickly and cost-efficiently to alternating energy availability* [3]. Consequently, energy flexibility does not explicitly aim at simply reducing energy demand. However, energy efficiency can also be a by-product of energy flexibility measures.

Among various approaches within the process industry [e.g. 4, 5, 6], certain procedures for manufacturing also exist. The energy flexibility of production systems and machines can be separated into two main approaches: targeting the technical (also known as the *real-time energy flexibility*) and the organizational (*planned*) flexibility [7, 8].

Measures of organizational energy flexibility represent the production planning's ability to schedule manufacturing processes with respect to their energy characteristics. In this way, avoiding operations of high-energy processes at times of low energy availability is possible [9, 10, 11]. During time spans of high energy availability, it is possible for an intended parallel operation to benefit from low energy prices. Measures of organizational energy flexibility typically require a lead time dependent upon, for example, the frozen time interval of the production plan. For adapting the energy demand to changing weather conditions, accurate forecasts are necessary for an economic usage.

Technical energy flexibility measures focus on real-time adaption of the energy demand according to prevailing energy availability, and can be performed on the machine and the subordinated components level. On the machine level, current activities use approaches to short-time reconfigure the production schedule [8, 12, 13, 14]. Inside of production machines on the component level, the energy demand is adapted within the productive state of the machine. Therefore, a machine with a higher utilization ratio has longer periods that are suitable for adapting the energy demand to external circumstances. The more the machine is in operation, the more application time is available. Examples of such measures are a short-time adaption of the components' operating time [2, 15] or changing the process parameters [16].

2.2. Related research in the evaluation and modeling of energy flexibility in manufacturing

Several approaches for modeling energy flexibility exist within the literature. In the field of manufacturing, universal as well as more specific methods and strategies have been developed to estimate the potential of the energy flexibility. Besides sole technical evaluations, economic indicators have also been derived, essentially for energy intensive use-cases.

A state-based approach for quantifying the potential of energy flexibility is presented in [3]. By performing measures, like the adaption of process starts or machine scheduling, the energy demand can be slightly synchronized to external circumstances. An evaluation of the energy flexibility of production systems with quantified values of flexible energy is

not possible. A use-case of this approach and the cost-saving potential under a special electricity tariff is presented in [17].

A mathematical procedure for estimating the energy flexibility potential of a production system is indicated by [18]. Within the context of production theory, they define the energy flexibility on the basis of the energy demand function. This interpretation allows the resulting throughput of the production system to be assessed in the case of a short-time power adaption. Action alternatives can therefore be balanced by their energy demand. The theoretical approach is based on the assumption of a one-product production system. A practical application has not been described yet.

A real-time energy flexibility control method for aligning interlinked manufacturing systems to an energy supply by renewables has been proposed in [8]. For this execution control, no forecasts of energy availability are necessary in order to adapt the operation times of production machines. Although the target is to maintain the throughput time, the described scenarios allow for a lower productivity and a higher inventory in order to achieve energy flexibility aims. Different performance indicators were derived in order to present the method's potential. A full cost model, taking the mentioned disadvantages into account, was not considered. This flexibility approach is similar to [12], who proposed a real-time strategy using disruption management.

Only a few authors have already performed monetary evaluations of the energy flexibility in manufacturing. A method for identifying a compromise solution using the weighted sum of production scheduling performance and electricity demand has been suggested in [19]. Time-dependent energy costs are used to calculate economic benefits within the parallel machine scheduling as well as flexible job shop scheduling problems [20].

Another energy flexibility approach for decreasing energy related costs has been presented by [21]. Reducing electricity consumption during peak periods saves investment costs for power delivery infrastructure and, therefore, the network charge for the company. Energy flexibility is improved by the inclusion of additional buffers within the production system. This approach identifies the minimal overall costs, including enlarged throughput times and saved energy expenses.

The research activities presented within this section focus on methods for evaluating the energy flexibility of production systems on the machine level. How a production machine can adapt its energy demand via the energy flexibility operation on the component level without compromising its throughput has been considered by [7, 15]. By these approaches, the machine components' energy flexibility potential can be estimated, which is an important basis for the research presented within this paper, particularly for the economic evaluation of the energy flexible machine tools.

2.3. Throughput and quality preserving operation

Negative influences on productivity and product quality during the energy flexible operation of a machine tool can be avoided if the real-time control is limited to components of a

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