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Decentral energy control in a flexible production to balance energy supply and demand

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Abstract

A volatile energy supply sector with fluctuating energy prices poses new challenges to sustainable and cost efficient manufacturing. To ensure a stable and cost efficient energy supply in the industrial energy system, energy supply as well as the demand for manufacturing has to be balanced. The goal is to use energy when it is cheap and provide energy or use less energy during periods of high energy prices. Achieving this goal is strongly limited by ensuring the production performance especially the delivery time and the output and depends on the flexibility of the production. While smart grids provide solutions for balancing supply and demand for regional and higher structured energy networks, solutions in an industrial energy environment are missing. This paper presents the ongoing research concerned with the development of a decentral system including methods and control units to autonomous control an industrial energy system with fluctuating prices. The system will ensure production performance while decreasing energy cost through balancing energy demand and supply. For this purpose, the control units will measure the energy available inside the system. This information has to be balanced with the actual production order situation of each single machine. Based on this comparison, the control units will decide autonomously, considering different production relative parameters, to produce or to wait for more, cheaper energy in the network.

Keywords: volatile energy supply; smart grid; energy demand control

1. Introduction and Motivation

Due to a growing proportion of renewable energy sources as well as a decentralization of energy production, the energy system faces major changes and challenges [1]. The role of the consumer is in particular focus, since e.g. the increasing penetration of wind and solar power is necessitating a more active role for energy management in homes, buildings, and industries [2]. Industrial facilities are high energy consumers which are responsible to lead the change on the consumer side. The intermittency and unpredictability of renewable power generation is in sharp contrast to traditional power generation. With power coming entirely or almost entirely from the latter assets, system operators have been able to keep the grid balanced by adjusting generation in real-time in response to demand variation [3]. With unpredictability now extending to generation, imbalances in the grid may cause grid reliability issues or energy price fluctuations. Therefore, industrial facilities tend to transform its infrastructure more and more from a consumer only to an energy prosumer system. On-site energy production, consumption and storage on the one hand as well as an increasingly complex interface to the energy system on the other hand require an advanced on-site grid and energy focused production management.

2. State of the Art

2.1. Demand Side Management

Historically the energy system is dominated by large power plants, which produce the required energy quantities and balance demand and supply at any time. Due to a growing

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fluctuation and decentralization on the production side, balancing supply and demand is getting more and more complex and dynamic. A more active involvement of the consumer side is not an entirely new approach. However, falling costs of communication infrastructure and embedded systems enable a "smart" and controllable consumption [4].

In the early 1980s the concept of Demand Side Management (DSM) was developed in the US and is increasingly used in Germany since the Energiewende. DSM is based on the assumption that it is more cost-effective to intelligent influence a load than to build or install new power plants or energy storage [5]. DSM includes the planning, implementation and monitoring of efficiency and flexibility measures on the consumer side to change the load profile of the consumer. [6]

The foundation of DSM are measures to increase energy efficiency. These include all permanent system optimization to increase energy productivity. Measures for flexible adaptation of the energy consumption to signals from the energy market can be described as a function of time and grid interaction and are divided into two areas (Fig. 1).

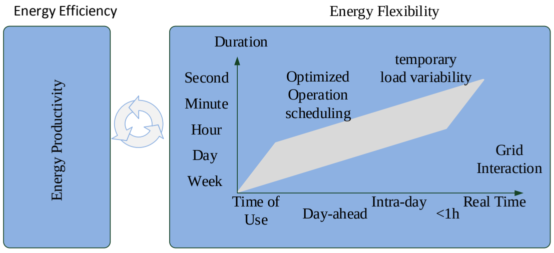

Fig. 1 Levels of DSM

An energy optimized operation scheduling adjusts the load curve of a production system with regard to the avoidance of peak loads and the relocation of energy-intensive processes in times of favorable energy prices [3].

A temporary load variability describes a temporary measure to reduce or increase the power used [7,8]. Based on the load change signals from the power system (for example, price or control signals), which are triggered by unplanned, irregular or extreme energy economic events, this is referred to as demand response [9].

Energy optimized operation scheduling as well as temporary load variability do not primarily reduce energy consumption, but optimize the load profile based on the available energy flexibility.

2.2. Energy Flexibility

Flexibility refers to the ability to adapt to changing conditions. Due to an increasing complexity of production tasks and a continuous increase in product variants, production systems are in an environment that is characterized by a great uncertainty. [10] This uncertainty provides manufacturing companies with major challenges and risks. To be able to adapt to such uncertainty, companies need to have sufficient flexibility [11].

With uncertainty now extending to the energy supply, energy flexibility enables the energy consumer to adapt to changing energy prices. Different approaches to flexibility can be identified in the literature [11,12]. In this study only the approaches with a direct relevance to the developed model are considered.

Volume flexibility refers to the ability of a production system to economically adjust its production volume to socioeconomic constraints [13,14].

Route flexibility refers to the possibility of a production system to produce a specific product through alternative routes or production order [11,15].

Product flexibility is defined as a company's ability to be able to produce different products with a short setup time [15]. Due to a growing individualization of customer requirements and an increasing complexity of products forms, product flexibility is a big step to an increasing competitiveness.

Machine flexibility describes the possibility of individual machines to perform various manufacturing operations with minimal setup effort. The machine flexibility may also increase the flexibility of other approaches such as the route and product flexibility. [11,15]

Based on this general approaches to flexibility, approaches to energy flexibility can be classified.

Interruption of production describes the interruption of processes when the energy price is high. By temporarily stopping the processes, the power consumption of a production station is reduced in large measure [7]. This approach is especially critical in terms of delivery dates. The limiting factors for the interruption of production are defined through the volume flexibility as well as the delivery dates.

Adjustment of Stock describes the strategy to use store capacity depending on the energy prices. During periods of high energy prices processes can be stopped or slowed down while upstream process run on stock capacity. The limiting factors are defined through the volume flexibility, product flexibility as well as the storage capacity.

Adjustment of process parameters can change the energy consumption of a process e.g. changing the temperature in a batch reactor. The adaptation of processing parameters describes the regulation of the process parameter according to the change of the electricity price [8]. The limiting factors are defined by the available machine flexibility.

Adjustment of maintenance and set-up time to periods of low energy prices, describes a time and energy sensitiv strategy of maintenance and set-up time in order to reduce the energy costs of production [7].The limiting factor are defined through volume- and route flexibility of the production system.

2.3. Implementation of Energy Flexibility

To successfully implement energy flexibility in production systems, it is necessary to include production costs, quality and time in the optimization. Energy optimization can be implemented on different levels, which can be described based on grid interactions (Fig. 1). Most approaches which implement energy as a factor in the production planning process, e.g. Enterprise-Resource-Planning or Manufacturing Execution System, do it on a low grid interaction level [8,16,17]. These approaches match the energy optimized operation scheduling. On the other end automated demand response demands a high grid interaction on level of temporary load variability [3]. So far these approaches do not take planning results on machine- and production system level into account.

3. Problem Statement and Approach

After examining the approaches on energy flexibility implementation discussed in 2.3, this paper presents an approach on

How to autonomously control an industrial energy system in the context of fluctuating prices with respect to the production planning

To address this problem, a manufacturing process chain is simulated, while tracking the energy consumption and the production volume.

In a case study of a plastics manufacturer, the simulation model determines an optimized energy consumption for a planned production volume.

4.1. Modeling the Production System

A two process production system is modeled to analyses the effect of an energy flexible production control (Fig. 2). The following essential premises are formulated for the developed model:

- *Constant sequence of order*
- *At the end of each day all the orders have to be processed*

The working hours are described in a predefined shift schedule. Material buffers are modeled as single-mode sinks. On process level the available flexibility is restricted by:

- *Minimal continuous processing time*
- *Minimal time to change between operational modes*
- *Energy consumption to change between operational modes*
- *Process time variability*

On production system level the available flexibility is significantly influenced by the number of orders, which can dramatically change the production volume, the duration it takes for each order to be finished and the required set-up time between each order.

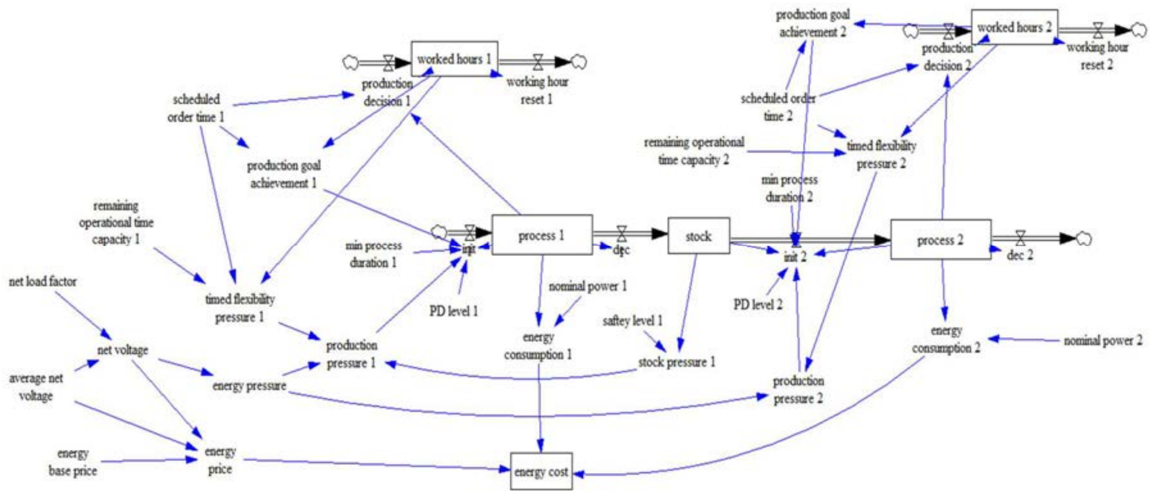

Fig. 2 Energy flexibility Effect Analysis

4. Methodology

A system dynamics simulation-based method was chosen to analyze the production system behavior on energy flexibility and production volume. First, a model of a production environment is created. Then the energy supply is varied in a series of experiments, followed by an analysis of the production volume.

4.2. Modeling an autonomous production energy control

To model an autonomous production energy control, it is assumed that a production management system provides each process with the orders and the associated start and mandatory end time of each order (Fig. 3). Furthermore, the processes as well as the storage systems are able to communicate with each other. Every process is able to assess the energy supply situation. Based on these information it is possible to energetically optimize each process and the production system itself.

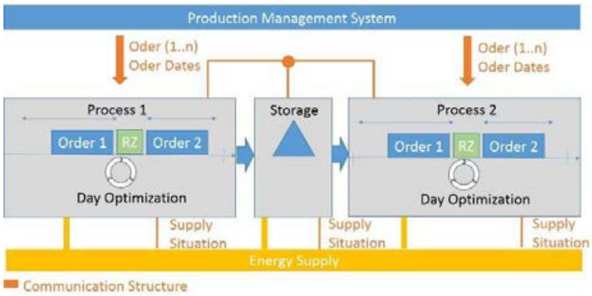

Fig. 3 Communication Structure of the Energy Control

For each process the flexibility potential for one day can be calculated based on the operational time capacity for each day,

Fig. 4 Communication Structure of the Energy Control

the working time of each order and the required setup time (Eq.1).

$$flexibility\ potential = \frac{otc}{\sum(order\ working\ time + setup\ time)} \quad (1)$$

otc = operational time capacity, describes the maximum working hours per day including the setup time.[hours]

To calculate the potential flexibility of each process at any time the remaining work time is required (Eq.2).

$$RWT = \sum_{n=1}^{remaining\ orders}(WT_{order,\,n} + ST_n) \quad (2)$$

RWT = Remaining Work Time [hours]
WT = Working Time [hours]
ST = Setup Time [hours]

Based on the remaining work time and the remaining operational time for each order the flexibility pressure can be derived (Eq.3).

$$FP = C_{fp}\frac{remaining\ work\ time}{remaining\ operational\ time\ capacity} \quad (3)$$

FP = Flexibility Pressure
Cfp = Constant

The flexibility pressure is a dimensionless factor describing the ratio of the remaining work time and remaining operational time capacity. For example, for a machine which is able to produces a 100 parts per hour with a typical order of 200 parts, no setup time and operational time capacity of 22 hours, the flexibility potential is calculated as:

$$flexibility\ potential = \frac{22\ hours}{2\ houres + 0\ hours} = 11$$

The remaining work time for a day with six scheduled orders at the beginning of the day calculates as:

$$RWT = \sum_{1}^{6} 2\ hours + 0\ hours = 12\ hours$$

The flexibility pressure at the beginning of the day with the constant cp set to one then calculated as:

$$FP = 1 * \frac{12\ hours}{(22\ \ hours - 0hours)} = 2$$

Additional to a logistic component described by flexibility pressure an energy component must be established. This component describes whether high or low energy prices (little or much energy) are available for the production system.

It is necessary to distinguish between two cases of application. On the one hand, production sites that operate its own isolated energy grid. Balancing loads and supplies is essential, especially when fluctuating energy sources are part of the supply infrastructure. In this case the available energy is described by the net voltage (Ep.4). The more energy is available in the system, the higher is the net voltage.

$$EP = C_{EP}\frac{actual\ net\ volatage - minimal\ net\ voltage}{maximum\ net\ voltage - minimal\ net\ voltage} \quad (4)$$

EP = Energy Pressure
C_{EP} = Constant

On the other hand, production sites that are connected to a supply grid, where the energy costs depend directly on the energy market price. In this case the energy component is described by the energy market price (Ep.5)

$$EP = C_{EP} * EMP \quad (5)$$

EP = Energy Pressure
CEP = Constant [$\frac{1}{€}$]
EMP = Energy Market Price [€]

The energy pressure is a dimensionless factor describing the energy availability to the system. Additional to a logistic and an energy component a stock component is established. Stock capacity can dramatically enhance the flexibility of a process by storing the output of the process. In this context, only stock which follows after the process to store the output and decouple the process from the following process is considered. The stock component is then describe by actual the stock level at a given time and the safety stock level (Eq. 6).

$$QP = C_{QP}\frac{safety\ stock\ level\ after\ process}{actual\ stock\ level\ after\ process} \quad (6)$$

QP = Quantity Pressure
CQP = Constant

The quantity pressure is a dimensionless factor describing stock level directly after the process. For each process an autonomous production energy control can be modelled based on the logistic component, the energy component and the stock component (Eq.7).

$$Production\ Pressure = FP + EP + QP \quad (7)$$

For each process a threshold value must be established (Eq.8).

$$if\ production\ pressure > S \ \rightarrow \text{then produce} \quad (8)$$

S = Threshold Value, depends on the

- Machine flexibility (high flexibility → large threshold)

- Volume flexibility
- Costs to change between production modes
- Energy intensity of the machining
- production based personnel utilization degree

Implemented in the two process production system (4.1) the production pressure is computed for each process over a period of 24 hours. To test the model for robustness and sensitivity the net voltage is randomly varied while the sequence of order remains constant.

Based on the production pressure, production decisions of process 1 as well as process 2 happen during periods of high voltage (Fig. 4).

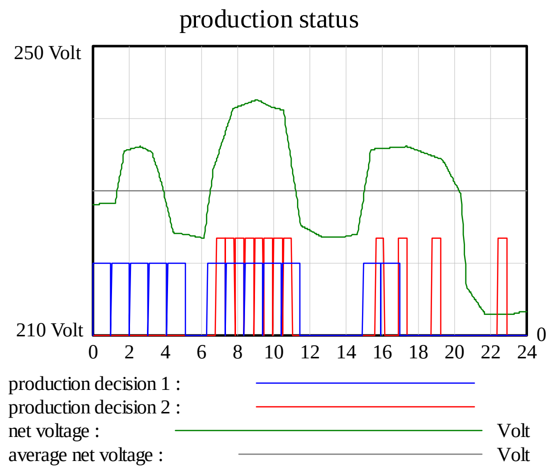

Fig. 4 Production decisions as a function of the net voltage and time

The function of the energy pressure of process 1 displace the random voltage change. The flexibility pressure decreases in relation to time and produced volume. The stock pressure however fluctuates dependent on the time delay of process 1 and process 2. (Fig. 5)

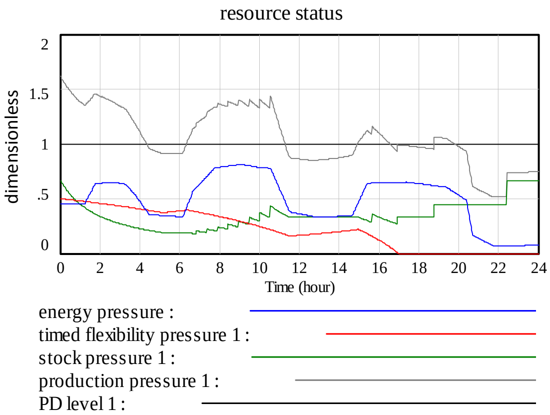

Fig. 5 Production Pressure for Process 1 as a Function of Time

5. Case Study

A plastics part manufacturing system with two injection molding machines and a clear coat paint shop under controlled conditions was selected (Fig. 6).

5.1. Hybrid Simulation

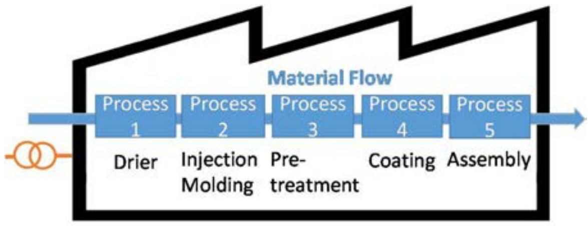

Fig. 6 Case Study production flow chart

On the one hand a logistic simulation of the production chain was set up in the software Plant Simulation. All on-site collected data were imported into the model and a production planning system was programmed. The model is thus able to track logistic and energy parameters e.g. production volume, energy consumption on machine level or stock level.

On the other hand the energy supply system and the energy consumers of the production system were recreated on model scale. Every process and storage system was equipped with a machine control as a hardware in the loop sub-system. Furthermore, every process was equipped with a voltage meter and a communication platform was implemented. This allows to vary the energy supply situation of the production system and to track the supply system behavior for energy flexibility approaches (2.2).

To enable data exchange and to track feedback effects both models were connected via the communication platform.

5.2. Production Pressure Calculation and Hypothesis

Using the case study specific processing time, set-up time, and production volumes, the production pressure was calculated in accordance with the approach in 4.2 for each process. Based on the ability of each process and stock system to communicate with each other the team expected to see a complete system optimization and therefore a lower energy consumption and a cost reduction dependent on the price for the consumed energy and number orders.

5.3. Results

The optimization was run over a period of four weeks. The energy prices were imported every 15 minutes from the German energy market. In total the energy costs were reduced by 10 % (Fig. 7).

The storage capacity as well as the human resources were not changed. For each day all orders were processed. Results of the simulation at the plastics manufacturer support the assumption that energy flexibility can significantly reduce energy costs.

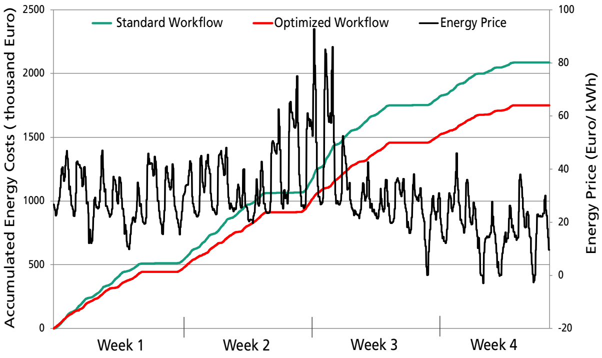

Fig. 7 Cumulated energy costs with and without optimization

Every production system has a flexibility potential, which is not a constant but rather a dynamic function depending on e.g. order situation. The introduced model provides the potential to dynamically and automatically adapt to a changing flexibility potential of a production system. Besides of the technical aspects a variation of the production based personnel utilization degree can have huge economic impacts. The results of the plastics manufacturer show a use case where the personnel utilization degree does not change. Typically process with a high degree of automation show the highest degree of freedom in terms of energy flexibility. However, energy efficiency can be affected by the optimization depended on the process flexibility. The effects on energy efficiency will be investigated in detail in further simulations.

6. Outlook

The simulation results indicate a trade-off for manufacturers not only between economy and flexibility, but also between efficiency and flexibility. Even with a low energy price, energy flexibility is a promising approach in a rapidly and randomly changing supply environment. Further factors influencing the industrial energy consumer, such as energy storage, on-site energy production and production sequences are currently being investigated in the context of energy flexibility and energy efficiency, with the goal to further enhance energy productivity and lower energy costs.

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