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Flexibilization of Energy Supply Using the Example of Industrial Hall Climatization and Cold Production

Flexibilisierung der Energieversorgung am Beispiel der industriellen Hallenklimatisierung und Kälteerzeugung

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Abstract: Industrial companies need to measure, evaluate and predict their energy demand to use this knowledge to improve plant control and achieve further energy efficiency. Within the framework of the contribution, two model cases from the food and plastic sector are described, which implement the concepts of a "smart consumer" with the focus on demand-side management and smart control approaches. Simulations show how improved operation of the technical building infrastructure saves energy by using the example of a hall climate control and refrigeration. In addition, the specific energy-saving measures are described and the future realization potential is discussed.

1 Introduction and Problem Definition

Because of the intensified expansion of renewable energies in the course of the German "Energiewende", the energy supply structure is faced with decisive changes and new challenges (BMWi 2015).

Based on an increasingly decentralized, volatile, renewable energy supply, the load on the lower grid levels is increasing, resulting in bi-directional energy flows along the vertical grid structure (Scholz et al. 2012). In order to stabilize the grid, industrial energy consumers increasingly appear as intelligent energy consumers and producers, without losing the goal of increasing primary energy efficiency.

Companies act as intelligent consumers and producers, so-called smart industrial consumers, in a smart grid. They are an important keystone for the success of the energy transition. The advances in technological development are also leading to an ever-increasing role for the conversion and implementation of energy-efficient, grid-based energy supply infrastructures in the industrial environment. For this transformation process automation, energy data collection and digital networking is required.

The preconditions for the development of a Smart industrial Consumer consist in the continuous knowledge of all relevant energy flows, their evaluation, as well as their prediction depending on production programs and ambient conditions (e. g. weather) as well as in the option of intervention by superior control technology.

2 State of Research

Mathematical, simulation based optimization algorithms targeting an improved building climatization including air conditioning units are described in several ways. An example is given by the publication of He et al. (2014) which is minimizing the energy demand of climatized rooms using “particle-swarm-optimization”. Wang et al. (2011) consider besides the energy efficiency also the comfort field and Tejeda (2012) as well as Oldewurtel et al. (2012) are using model predictive controls (MPC). However, previous work regarding the topic of optimized operation through superior controls often just refer to single units or in composited units to simulative studies without a direct practical implementation in the industrial environment. In combination with a complex energy monitoring system, the implementation of modern air conditioning techniques and an optimized and combined unit control system does not exist in this dimension and complexity. Models for the simulation of industrial halls and thermal loads (Schäfer et al. 2012) as well as the probabilistic construction of production schedules (Dunkelberg et al. 2017) are available.

Scientific explorations regarding the issue of grid stability by demand-side management and reaction of market price signals by smart consumers are given for example in Schultz et al. (2016) and Krzikalla et al. (2013).

3 Approach

In order to make changes in the operating mode of plants, by using new technologies or the conversion of the energy supply, predictive and physical models (models for buildings, refrigeration plants, injection moulding machines, ventilation and air conditioning systems) are built. Real measuring results such as internal loads, weather data (radiation and ambient temperature), as well as real production plans are integrated into these models to provide practical information about the modification, operating mode changes and energetic interaction under varying conditions. The complexity of the non-stationary energetic and dynamic technical connections requires the application of a simulation tool, which fulfils the requirements in a high quality. The simulation software MATLAB® / SIMULINK® fits this purpose.

The aim of the simulations is to adapt the calculated, improved operating modes to the real systems via a suitable IT infrastructure (like sFTP server, OPC interface) in the future. Furthermore, efforts are being made to replace the simulation results successively and automatically with real measurement data using the principle of self-learning characteristics or fields from the energy monitoring system.

4 Model Description

Two existing companies with all relevant plants and energy data are available for the investigation. For both cases the air-condition-units were built based on the Mollier-h-x-diagram, the building models consists of a layer model of linked ordinary differential equations (Wagner et al. 2014; Schäfer et al. 2012) and the energy supply models use characteristic diagrams. All of the used simulation models were validated by real measurements on a laboratory scale or by measurements in the companies.

4.1 Case 1: The Food Company

Companies in the field of food processing set high demands on hygiene and adherence to given ambient conditions. Due to process-specific requirements, the considered confectionery manufacturer places particularly strict requirements on air conditioning. In particular, the packaging area of chocolate bars is a sensitive area in which air conditioning is needed. The prevailing air temperatures of the direct product air conditioning system must never exceed 18 °C to rule out deformations of the chocolate. Additionally, the relative humidity must always be kept below 50 % to avoid condensation effects on the chilled chocolate surface. (Wagner et al. 2014)
Compliance with the requirements is achieved by a novel displacement ventilation successfully tested in the laboratory where the product is guided through a local "lake" of conditioned air. This variant's functionality has further been confirmed by extensive computational fluid dynamic simulations (CFD). Therefore the air conditioning of the other production hall can be adapted to the needs of employees. As a result, the temperature and moisture content values can be extended within the comfort range from 16 to 24 °C as well as relative humidity between 35 % and 65 %, enabling high energy savings of up to almost 50 %. (Heidrich 2016; Schirmer et al. 2016; Wagner et al. 2014).
The air conditioning is carried out in the model case via two air-conditioning units, which are supplied with cold water by compression cooling machines and steam by a steam generator for humidification. As shown in Figure 1, a HVAC system ensures the air conditioning of the conveyor belt cooling while the other conditions of the remaining production hall.

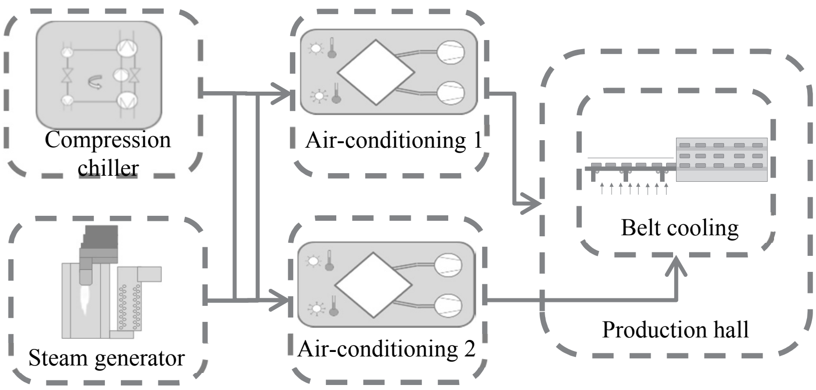

Figure 1: *Schematic model of the food company*

Due to the described conversion to an extended temperature and humidity range within the comfort field in the production hall the control offers a greater scope of the air-conditioning's operation mode. This enables a grid friendly system operation and the use of fluctuating electricity prices. Furthermore, energy can additionally be saved via an adapted, production-schedule-dependent start-up logic of the air-conditioning system, which ensures the required air conditions in the hall at the start of production. For example, previously scheduled, rigid switch-on times of the HVAC system, in this case 8 hours before production start, can be replaced by variable switch-on times depending on the boundary conditions.

4.2 Case 2: The Plastic Fabricator

The plastic company considered produces injection moulded parts for the food sector. High hygiene requirements are applied to the production hall as well.

The injection moulding machines are cooled continuously. Two different cooling circuits are installed. On the one hand the mould cooling circuit at a temperature level of about 14 °C and a machine cooling at about 30 °C. The refrigeration of the mould circuit is carried out by means of EER-optimized compression chiller machines and a dry cooler which is also used for winter relief. The cooling for the machines is provided by cooling towers. The plant scheme is shown in figure 2.

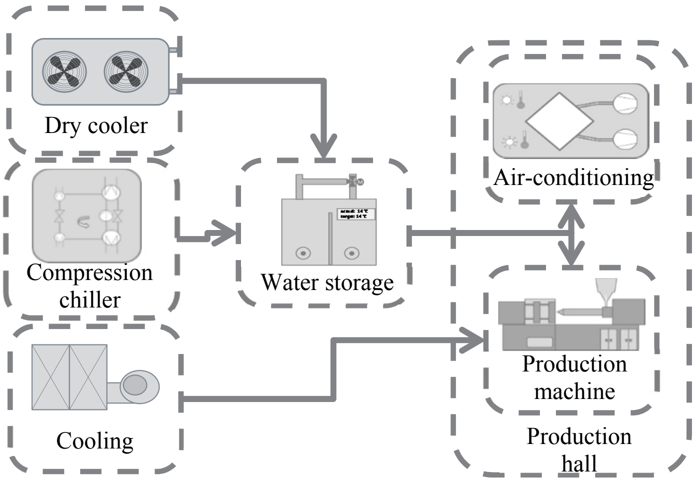

Figure 2: *Schematic model of the plastic fabricator*

Due to high internal loads, an intensified cooling of the production hall especially in summer is necessary to avoid machine failures and to maintain an acceptable temperature level for the plant operators. Often a simple mixed- or window ventilation is used. For these requirements, a ventilation with temperature conditioning is necessary in model operation. A controlled layer ventilation system is used to save energy.

The air is tempered in the need of cooling by the inlet of the refrigeration of the mould cooling circuit. In the case of heating, the return of the machine cooling is used to heat up the air. At the same time the cooling towers are relieved.

Cooling circuits are recirculated via the air-conditioning system. At the same time, there is a direct dependency between the air-conditioning system and the respective refrigeration circuits. This leads to an increase in the degree of complexity, especially since the control of the air conditioning is directly dependent on the production, i.e. the input of loads into the environment as well as into the cold system.

4.3 Scenario Description

For the investigations, an initial scenario and three study scenarios are considered for each model case.

Reference scenario: Displays the control output status without simulation-based, improved operating modes and provides information on the initial energy situation.

Scenario I: Investigates the effects of an optimized start-up behaviour on the energy demand.

Rigid start-up times of the HVAC system are replaced by calculated, optimized and the starting conditions (indoor temperature, outdoor temperature) adapted switch-on times. Figure 3 shows the calculated, physically necessary start-up times for the model case of the food company with a target temperature of 18 °C at the start of production in order to achieve the required hall temperature under different conditions. For the simulation, a safety margin of 15 min. is also calculated to the start-up time in order to be able to react to fluctuating boundary conditions.

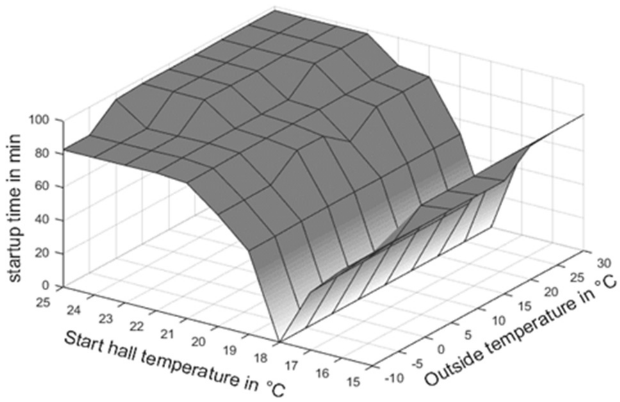

Figure 3: *Simulated start-up times at a hall temperature of 18 °C depending on the indoor and outdoor temperature for the food processor*

Scenario II: Investigates the effects on the energy requirement, the energy consumption costs, as well as the grid behaviour by setting a temperature range in the cold water systems.

For the plastic fabricator, this means the implementation of a sliding set-point change of the refrigerant circuits within a temperature range. For the cooling of the mould, nominal temperatures between 12-15 °C and for machine cooling 25-30 °C are possible. In addition, a dew point control is implemented which limits a drop in the flow temperature. In the case of the food company, a variable flow temperature control in the cold water system for the supply of the air-conditioning system -

within the limits of the Mollier diagram - replaces a rigid cold water temperature setting of -1 °C.

In order to establish variable set-points within the respective temperature limits under ecological aspects, a method for the evaluation of variable current prices has been developed. This includes the fact that the Day-Ahead hour contracts from 2006 to 2016 are approached by a standard normal distribution. The integral of this function is also used as an allocation function for the predetermined temperature limits.

In order to evaluate the current electricity price, its deviation from the daily mean value is formed and inserted into the normalized distribution function from Figure 4.

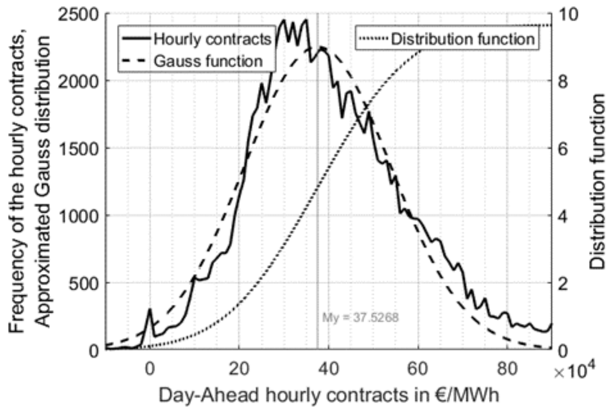

Figure 4: *Distribution of Day-Ahead hour contract from 2006 to 2016 with the approximated Gaussian distribution and the associated distribution function*

Negative values indicate favourable, positive values accordingly for expensive electricity prices. This evaluation normalized to the interval [-1; 1] is applied to the temperature limits and a set-point temperature dependent on the current price is set.

Since the re-cooling units only have different power values when the nominal temperature is changed, the normalized current price evaluation is delayed by an integral.

Scenario III: Shows the effects of changing the nominal air temperature in the production area to the energy requirement, the energy reference costs as well as the electric grid behaviour. Extension of the comfort field control to the consideration of the current grid situation.

5 Presentation of Results

Scenario I: Optimized start-up time

Compared to the reference scenario the optimized start-up time of the air conditioning system allows the unit to start several hours later. This difference is shown clearly by looking at the total power consumption in Figure 5. The areas between the graphs point out the potentials of energy savings.

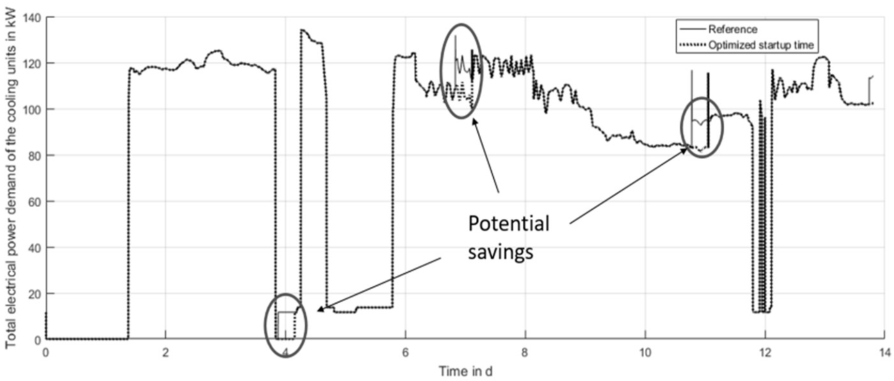

Figure 5: *Total electrical power consumption of the air conditioning system in the reference scenario compared to the optimized start-up time scenario in winter for the food production plant*

The specific energetic saving potential over two reference weeks in different seasons is displayed in table 1.

Table 1: Comparison of the energy consumption over two weeks with and without optimized start-up time of the air conditioning unit for the food production plant

	Reference in MWh	Optimized start-up time in MWh	Energy savings in MWh
Summer	32.51	31.79	0.71
Transition period	28.17	27.81	0.36
Winter	28.63	28.37	0.25

Since the heat supply of the HVAC unit in the second model case is depending on the machine cooling circuit and cooling is only needed if machines are running, the HVAC unit starts with the production and an optimized start-up time can only be implemented after modifying the machine constellation.

Scenario II: Variable set point temperature of the cooling water circuit

Figure 6 shows on the example of the manufacturer of plastics processing plant the difference between the total power consumption of the chillers including the affiliated pumping systems in the electricity-price-adapted scenario in comparison to the reference scenario in dependency of the current electricity price.

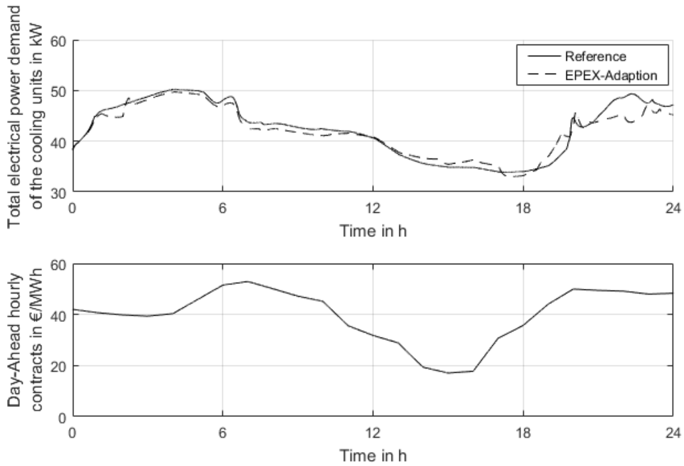

Figure 6: *Comparison of the total power consumption of the chilling units in the reference scenario and the electricity price driven control*

Thus, up to 5 % of the chilling power consumption can be shifted to benefit from cheap electricity prices and to in- or decrease the load of the power grid respectively. Since in this model a dry cooling unit is used the flow temperature in some cases, especially at warm outside temperatures, cannot be set to the lower limit without causing a significantly higher energy demand by the compression chiller unit. Thereby the flexibility in winter is higher than in summer.

A variable cold water flow temperature for the supply of the air conditioning unit of the food manufacturer is saving energy in the lower one-digit percent region. Due to the higher EER of the compression chiller unit at higher flow temperatures the electricity demand can be

Scenario III: Variable hall temperature

There is the possibility to vary the hall temperature and thus using the production hall itself as a thermal storage system as well. In the case of the plastic manufacturer the required heat for the air conditioning system is provided by the return of the hydraulics cooling circuit, decreasing the load of the cooling towers. Respectively a lower hall temperature increases the load of the compression chiller units in case of cooling the air. An electricity price dependent hall temperature causes in these cases a temporarily shift of the cooling power demand, but simultaneously causes a significantly higher energy demand which affects the overall balance negatively.

In the case of the food manufacturer the heating and cooling power is directly related to heating- and cooling units, so the effect shown by the plastic processing company does not occur in this case. However, in both cases the production hall provides such a low thermal storage potential that the impacts on the cooling systems are marginal. To provide additional flexibility the deployment of thermal water storages should be analysed.

Overall this analysis shows energy saving potential through the implementation of optimized start-up time by little effort and without affecting the production.

Furthermore, cooling circuits can be used as thermal storages by varying the flow temperature to in- or decrease the grid load and possibly benefit of low electricity prices. However, the potential of savings and realization of the operating optimizations depend greatly on the existing unit and production constellations, as shown in table 2 for the two example scenarios.

Table 2: Assessment of the suitability of the optimization approaches (+: high, o: average, -: low)

Evaluation target	Plastic processing plant	Food manufacturing plant
Start-up time	o	+
Variable cooling water flow temperature	+	+
EPEX energy price depen ding hall temperature	o	o

6 Conclusion and Future Outlook

The results of the simulative analysis show an energetic saving potential for the companies which is theoretically feasible through optimized controls. Furthermore, the plants can switch to a grid-driven control of the units in the future by operating cooling and climatization units at variable temperatures. Since there can be shifted up to 5 % of the cooling power demand in the case of the plastic processing plant, fluctuations in the grid due to volatile electricity feed of renewable energies can be compensated by the intelligent operation of the units and by that contributing to the reduction of greenhouse gases. Since fluctuations in the electricity grid are related to the electricity price, there are additionally financial saving potential for companies.

Expanded with self-learning characteristic curves and predictive controls which is based on forecasted energy demands, weather and electricity prices a flexible unit operation will be implemented in practice. Through the installed energy monitoring system in both plants real time values about the energetic situation and the production schedule will be processed in the simulation. Combined with weather and electricity price predictions the optimal operating states can be determined.

A possible dynamic renewable energy levy (EEG levy), which significantly extends the peaks of the electricity price (Agora 2014), increases the financial incentive for companies to invest in flexible techniques.

Acknowledgment

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