Energy-efficient production of safety glass through model-based optimization

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Kurzfassung

In vielen industriellen Produktionsprozessen ist Energie einer der größten Kostenfaktoren. Speziell in energieintensiven Prozessen wie beispielsweise der Stahlproduktion oder bei der Glasveredlung ist die Minimierung des Energieeinsatzes eine der wichtigsten Maßnahmen zur Ressourceneinsparung und Verringerung der Herstellungskosten. Das Forschungsprojekt OptPlanEnergie fokussiert die Herstellung von Sicherheitsglas. Es wird dabei simulationsbasierte Optimierung zur Identifikation und Verringerung von Energieverlusten welche während des Produktionsprozesses auftreten, angewandt. Das Projektziel ist eine Toolchain zur Erstellung hoch performanter Simulationsmodelle der wichtigsten energieintensiven Produktionsschritte, welche dann in das Advanced Planning and Scheduling (APS) Framework importiert werden. Dieses Framework führt die Optimierung der Produktionsabfolge und die Kapazitätsplanung zur Minimierung der Energie aus. In OptPlanEnergie wird prototypisch die Herstellung von Sicherheitsglas optimiert, allerdings ermöglicht es der Einsatz von Functional Mockup Units das Framework auch in anderen energieintensiven Industrien zu verwenden.

Abstract

In many industrial manufacturing processes energy use is one of the most important cost factors. Especially in energy-intensive industries like steel production or glass processing minimizing the required energy is a key measure to save resources and reduce manufacturing costs. The research project OptPlanEnergie concentrates on the production of tempered glass. In this project we apply simulation and optimization techniques to identify and reduce energetic losses that occur during the fabrication process. The aim of the project is to supply a toolchain for creating high-performance simulation models of crucial, energy-intense production steps and integrating these models in an advanced processing and scheduling framework to facilitate the optimization of loading sequences and capacity allocation to reduce energy consumption. In OptPlanEnergie we prototypically study the production of tempered glass, but our approach by importing the process models as Functional Mockup Units (FMU) into the optimisation framework allows a simple adaptation to a wide range of industries.

Introduction

Energetic losses in production processes often result from two main factors (among others), insufficiently calibrated processes with too long standby times and the generation of waste heat.

In the project OptPlanEnergie [1], the production process for the manufacturing of tempered glass is analysed and optimized. The aim of the project is to develop an integrated optimization and scheduling platform that uses simulation models of the production process to calculate the expected energy consumption. Optimization algorithms are employed to determine optimal production sequences. This will minimize the energy-usage per produced unit while maintaining high quality as well as high production output and availability. The optimization and scheduling platform will aid manufacturers in the operative planning of existing processes as well as in the strategic planning of production facilities. The four main subjects in this project are data analysis, model design and simulation, as well as optimization.

Data Analysis

In this chapter a summary of the production process will be given. Furthermore the data collection and analysis will be described in detail.

A. Glass Tempering Process

Tempered glass is produced from standard float glass in an oven where it is heated above the transition temperature to around 640°C without melting for 5 to 10 minutes. After that the glass is rapidly cooled in a cooling chamber by blowing cold outside air onto the surface which creates internal tension in the glass while solidifying. In case it is destroyed, tempered glass breaks into tiny shards instead of lager pieces. Tempered glass is among other fields of application utilized in many office buildings.

In the centre of the project is the tempering process with the oven and the cooling fans. This process requires a lot of heat which is generated from electrical energy by 30 heating coils. The oven has a power consumption of up to 2 megawatts (MW) for heating and up to 750kW for three large fans installed in the cooling chamber. Roughly 80% of the energy is required for heating and the remaining 20% are used for cooling. A tiny fraction compared to heating and cooling is used for auxiliary processes and will be neglected.

B. Data Sources

At the beginning of the project a white box approach was envisaged but due to the lack of detailed physical data from the oven this approach was deemed not feasible. Therefore a black box approached was pursued.

In order to develop a black-box model of the oven and the tempering process a detailed data analysis and a large data pool is required. The only available data source at the start of the project was the ERP (enterprise resource planning) system, which stores job data for every glass pane such as glass type, thickness, dimension, production and job numbers.

An energy monitoring system was not available at the beginning of the project and had to be installed before data acquisition could begin. The energy consumption of oven and fans are recorded with one data set per minute.

A challenge in this project was data analysis because energy and production data are acquired by different systems which makes data merging necessary. Both data sources are exported as Excel files (see Figure 1). Energy data of the oven and fans display typical peaks in power consumption well above standby consumption whenever glass is tempered. Production data contains the aforementioned data sets. The problem however is the manual interaction of employees with the process i.e. the manual scanning procedure of barcodes which takes places before the production process. Time delay between scanning and start of the process is distributed between a couple of seconds up to 1h in case of lunch breaks and other unplanned disruptions. Therefore it is difficult to identify the correct pairs of energy peaks and their corresponding production data set simply because there are too many possible matches.

Aim of the project was to create an automatic data analysis process. The black-box approach for the design of the process model requires statistical data analysis and therefore a large amount of sample data where manual analysis would be not feasible.

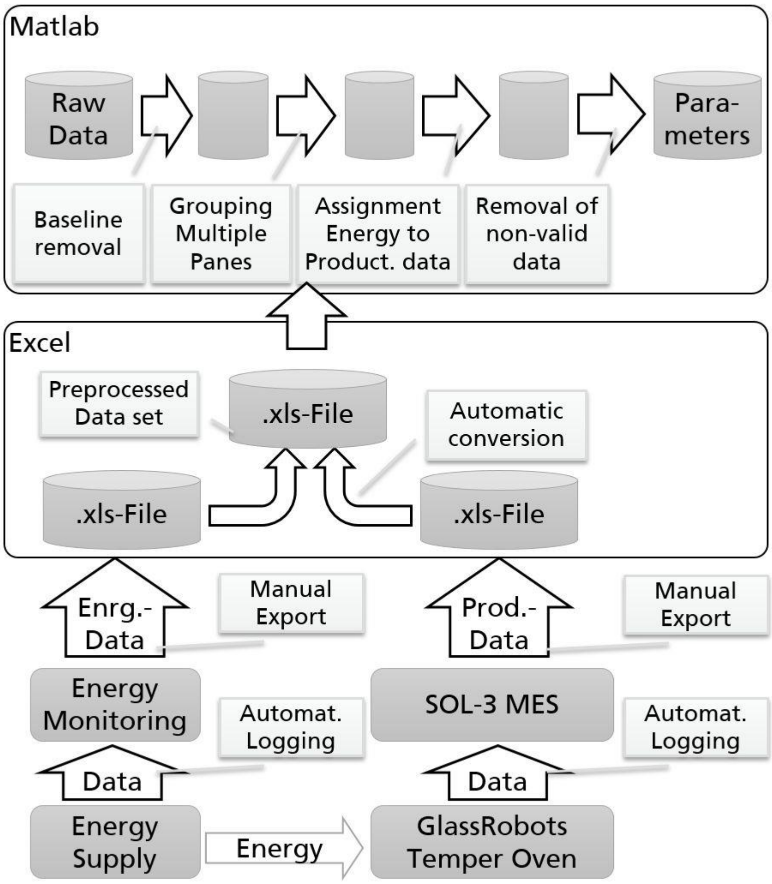

Figure 1 - Data flow for obtaining model parameters during data analysis

The data is processed and analysed as follows:

- Preprocessing the Excel files with Visual Basic
- Import into Matlab
- Deduction of the standby consumption
- Detection of energy peaks
- Find and group a set of glass panes that were produced together in one batch
    - Rules based check against property-, time- and area-constraints
- Matching of energy peaks and set of panes
- Assignment of required energy to each set of panes
    - Energy values are again checked against min and max constraints
- Average energy consumption and heating times are established for each glass type and dimension
- Results are stored in MAT-files

The data flow is shown in Figure 1.

In addition the temperature and energy trends during run up and shutdown the oven were recorded in order to establish the typical amount of energy required for the operation of the oven during standby and heat-up operating modes.

Result of the data analysis are the following parameters:

- Standby electrical power consumption of the oven
- Power consumption per glass volume
- Temperature gradient for a transition between two temperatures for cooling and heating
- Typical heat loss and effectiveness of the oven at different temperature levels.
- Typical tempering on cooling times for different glass types and dimensions

Model Design

A black-box process model is used to simulate the production jobs and calculate the energy consumption and time duration. These values are required for the optimization framework which uses the process model for simulation-based optimization to find the energy-optimal sequence of production jobs. The oven model is going to be an integral part of the framework and thus has to be very fast and should be exchangeable. Model and optimization tool should therefore provide the same standardized interface. To fulfil these requirements the oven model was developed in the simulation language Modelica as exportable Functional MockUp unit with the simulation tool SimulationX [5].

A. Model Structure

As mentioned before w.r.t. the large amount of data that is recorded from the process and to fulfil the need for a fast model it was decided to employ a black-box approach for model design. The developed process model doesn't feature any inputs but several parameters and outputs. Parameters are glass type and dimension, amount of panes, delay times as well as oven temperature at the start. Outputs are different time values (processing, preparation, cooling, standby, etc.), energies (for heating and cooling) and the temperature of the oven at the end of processing.

The model consists of two parts. The first part is a structure of Modelica Function Blocks consisting of look-up tables, integrators and conversion blocks among others. This structure processes and calculates the different parameter and output variables w.r.t. the corresponding operating mode. The look-up tables in turn access the MAT-files in which the oven and glass parameters stored. The second part is a state chart diagram containing the different operating modes of the oven such as standby, ready, heating, cooling, etc. Theses modes or states are activated through time- or temperature depended transitions. According to the current operating mode the heating and cooling powers are used for the calculation of the model variables. The state chart was designed graphically with the SimulationX state chart editor which generates Modelica code from the chart's graphical representation [3] as shown in Figure 2. A preliminary validation of the model was done by comparing simulation results with measured data. In addition the performance of the model was evaluated and found to be fast enough to be used for simulation-based optimization.

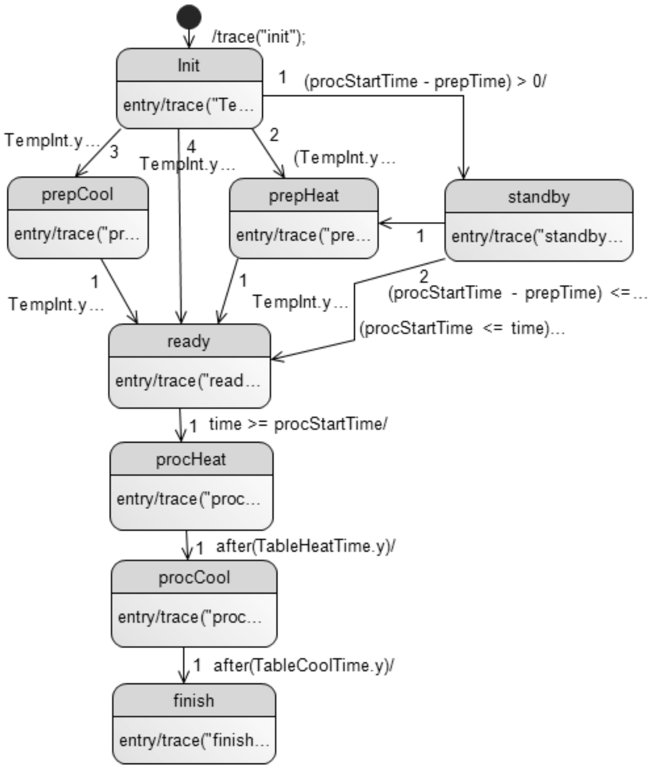

Figure 2 - Statechart of the modelled oven behaviour

B. Model Export as Functional Mock-Up Unit

Another important step is the model export as Functional Mock-Up Unit (FMU). Many Modelica tools can import and export FMUs. FMU models are accessed through the standardised Functional Mock-Up Interface (FMI) [2][4]. Different parts of a larger model can be integrated as FMUs and simulated together. FMU/FMI enables model exchange between different tools, domains and users while the model within the FMU is protected. The process FMU is equal to the original model and yields the same simulation results. In order to use the oven model in the optimization framework the implementation of the FMI was required. With this extension different FMU models from different domains or industries can be utilized by the optimization framework. The optimization toolchain is shown in Figure 3.

IV. OPTIMISATION

The simulation model and the data it provides are required to represent the temper process including heating and cooling completely within the optimisation framework or rather the APS (Advanced Planning and Scheduling) system. Its aim is to plan and optimise the job sequence with regard to the energy consumption but without compromising other requirements of the temper process such as quality and time, throughput and availability.

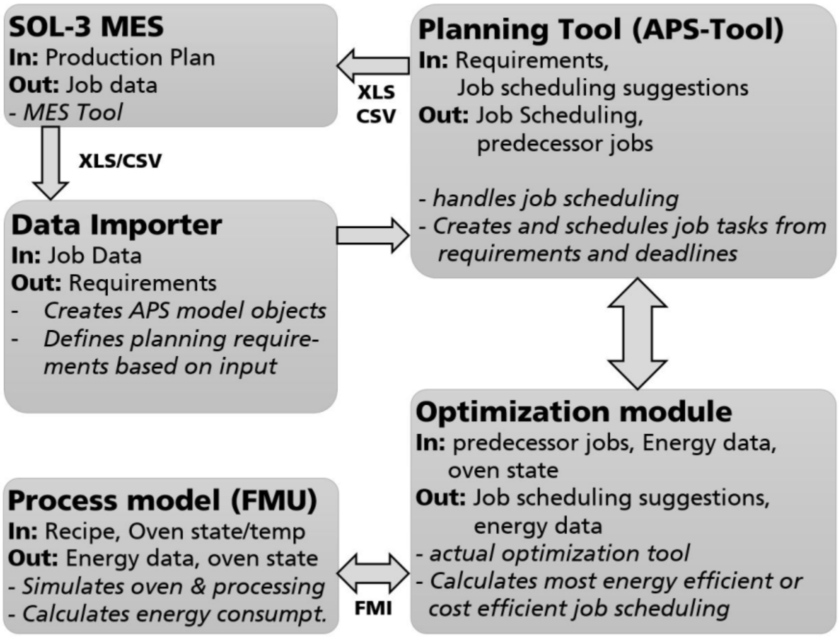

Figure 3 - Toolchain and optimisation framework

The APS system consists of two major modules, a planning tool or scheduler and an optimisation module. The scheduler determines a production schedule based on the required products (glass panes) and their production deadlines as well as available resources and their dependencies. It also provides partial schedules for the optimisation module which uses multi-objective optimisation strategies and an iterative search approach to find the optimal sequence for the scheduled process. The job sequence has a twofold influence on the energy consumption:

1. In case two consecutive jobs require different temperatures the oven has to be cooled or heated between the jobs. It is therefore reasonable to rearrange similar jobs to reduce temperature changes in the oven and thus reduce the energy consumption and increase throughput.
2. Every glass pane has to be manually scanned, placed on the conveyor, aligned and cleaned. In case the preparation takes longer than the actual tempering process the oven has to wait between jobs and is wasting energy.

The APS considers therefore quantity-dependent and non-quantity-dependent setup times, overlapping of production jobs and heating or cooling times that are caused by recipe changes.

In order to store and process parameter data, required energy and the oven state during the calculation and optimisation of the job scheduling, the APS system was extended by non-native model objects which are loaded and saved during the planning and scheduling process. In addition the APS system was extended with an interface that enables communication with specific external modules at certain points during the detailed planning of the job scheduling. Within the tempering process scenario during the detailed planning phase the current oven condition, data of the last production job, and a set of all possible job candidates is transferred to the external optimisation module, which determines the costs for possible job sequences. Required energy and related costs are determined by the oven model FMU which in turn is executed with corresponding job parameters through the FMI.

Depending on the optimisation method a multitude of job sequences has to be simulated. Therefore a short simulation time of the process model is crucial for the applicability of the optimisation framework. The calculated and optimised energy data can be represented as Gantt charts or as tables. This information enables the engineer to recognise load peaks and establish an energy schedule. Thus the introduced extension of the APS system with energy data provides the production engineer with additional information to reduce the required energy.

The toolchain was employed to optimise different sets of historic production data and compare the optimised production sequence with the real one. The optimised sequence is characterised by fewer cooling or reheating breaks which in turn lead to time and standby-energy savings between 6 and 40% and with every saved hour around 80kWh of standby energy are saved. It must be said however that the optimisation potential depends highly on the type and size of production jobs of the glass. Large and uniform jobs have a lower potential for optimisation whereas small and diverse jobs have a higher potential. There are also additional but minor energy savings by avoiding reheating breaks during production.

SUMMARY & OUTLOOK

OptPlanEnergie was finished in February 2018. It is planned to introduce the APS optimisation framework in the production process and use optimised production sequences on site at the glass factory where the system is going to be an integral part of the energy aware production planning process. Reducing the energy is however not the sole objective of the APS system. Throughput and availability are the other main optimisation objectives. Depending on the desired focus a balance has to be found between energy cost savings, increased throughput and availability.

In future projects the APS framework is going to be adapted and applied at different energy intense production processes for different industries where energy saving potentials will be different.

ACKNOWLEDGEMENT

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