# Enhancing the Energy-Efficient Production of Tempered Glass by Using Simulation-based Optimisation


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***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 energy use 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 production steps and integrating these models in scheduling frameworks 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 allows a simple adaptation to a wide range of industries.**



***Keywords—Simulation, Optimisation, Production Planning, Energy Efficiency***


## I. Introduction

One of the main cost factors in many industrial processes is energy consumption. Minimizing energetic losses is therefore a key challenge faced by energy-intensive industries, such as glass and steel production or chemical industries. Energetic losses often result from two main factors, insufficiently calibrated production processes with waiting times and the generation of waste heat.

In the project OptPlanEnergie [1], the production process for the manufacturing of tempered glass is analyzed and optimized. The aim of the project is to develop an integrated optimization and scheduling platform that uses simulation models of the tempering process to calculate the expected energy consumption. Optimization algorithms are employed to determine optimal production sequences. This will allow the minimization of 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 three main subjects in this project are data analysis, model design and simulation, as well as optimization.

## II. Data Analysis

In this chapter we will summarize the production process and describe the data collection and analysis in detail.

### *A. Glass Tempering Process*

Tempered or toughened glass is produced from standard float glass in an oven where it is heated above the transition temperature to around 640°C. Afterwards the glass is rapidly cooled by blowing cold outside air onto the surface which creates internal tension in the glass. In case the glass is destroyed, it breaks into tiny shards which are mandatory in safety applications. Toughened glass is among other fields of application utilized in the glass fronts of 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 usually generated from electrical energy. The oven has a power consumption of up to 2 megawatts (MW) for heating and up to 750kW for three large fans that are used to cool the glass. Roughly 80% of the energy is required for the heating of the glass 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*

In order to develop a 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 of tempered glass such as glass type, thickness, dimension, size, 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. This energy monitoring system records the energy consumption of the oven with its main components heating, fan 1, 2, and 3, storing one data set per minute.

Data from both the ERP and the energy monitoring system are combined and imported into Matlab, which is then employed for an in-depth data analysis. Multiple steps are executed to obtain characteristic indicators and parameters which are utilized afterwards in the black-box models that are able to simulate the total energy consumption of a scheduling sequence.

A challenge in this project was data analysis and the subsequent model design because data from production and energy consumption are collected separately. 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 breaks. Therefore it is difficult to find matches between energy peaks and their corresponding production data set.

Aim of the project was to create an automatic data analysis process. A manual identification of energy peaks and production data would be feasible for data of up to a few hours production time. However, in order to analyse data from weeks or even months of production, an automatic analysis is inevitable. The black-box approach we chose to design the oven model requires statistical data analysis and therefore a large amount of sample data.

Result of the data analysis are the following parameters:

- Stand-by electrical power consumption of the oven (heating and fans). This depends on the standby temperature.
- Power consumption per glass volume. This depends on glass thickness, dimensions, type, surface coatings, surface prints etc.
- Trend and typical durations for a transition between two temperatures for cooling and heating and for a change of the operating mode (off, standby and ready).
- Typical heat loss and effectiveness of the oven at different temperature levels.
- Typical tempering times for different glass types and dimensions. These can be obtained from the parameter set associated with each end-product.

During data analysis the Excel files are first combined, converted and pre-processed with Visual Basic. The resulting Excel file is then imported into Matlab where an in-depth data analysis takes places. First the standby power consumption is deducted from the power data. Then the energy peaks are identified. After that the production data is analysed and because of the aforementioned time deviations a set of rules is applied to find and match glass panes that have been processed together. These rules are mostly based on property-, time- and area-restraints. Energy and production data are matched thereafter so that an energy value is assigned to each glass pane. These combinations of energy and production data are then analysed to obtain the energy consumption values which are in turn validated against a set of rules such as minimal and maximal power consumption, theoretical and practical oven efficiency and a few more. The results are stored in .mat files which can be accessed by the oven model. The data flow of the data analysis is shown in Figure 1.

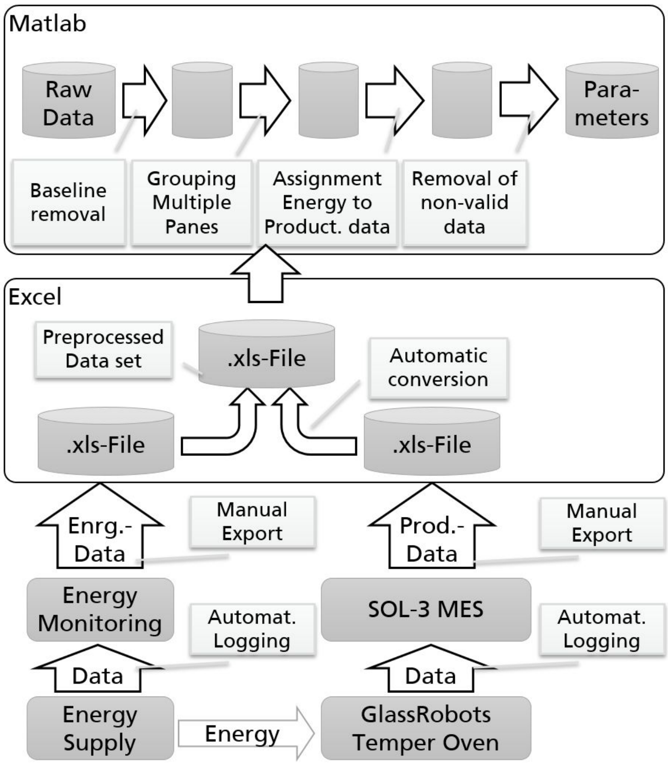


**Figure 1 - Overview of the Data Analysis Data Flow**

In addition the temperature and power trends during power-up and shutting-down the oven were recorded in order to establish the typical amount of power required for the operation of the oven during stand-by and while not processing glass.

## III. MODEL DESIGN

The simulation model of the process is required to simulate a production job and calculate the energy consumption and duration. These values are required for the optimization framework which uses 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. In addition the model 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 with the simulation tool SimulationX [5].

### A. *Model Structure*

The process model can be developed by using different paradigms. It was decided w.r.t. the large amount of data that is recorded from the process and to fulfil the need for a fast model to employ a black-box paradigm 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 and oven state 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 Modelica Function Block structure with interconnected blocks that represent 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 files in which the parameters obtained by the Matlab data analysis are 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. W.r.t to the current operating mode the heating and cooling powers are used for the parameterization of the model variables. The state chart was designed graphically within a state chart editor for Modelica 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 that is not part of the parameter files for the model. In addition the performance of the model was evaluated and found to be fast enough to be used for simulation-based optimization.

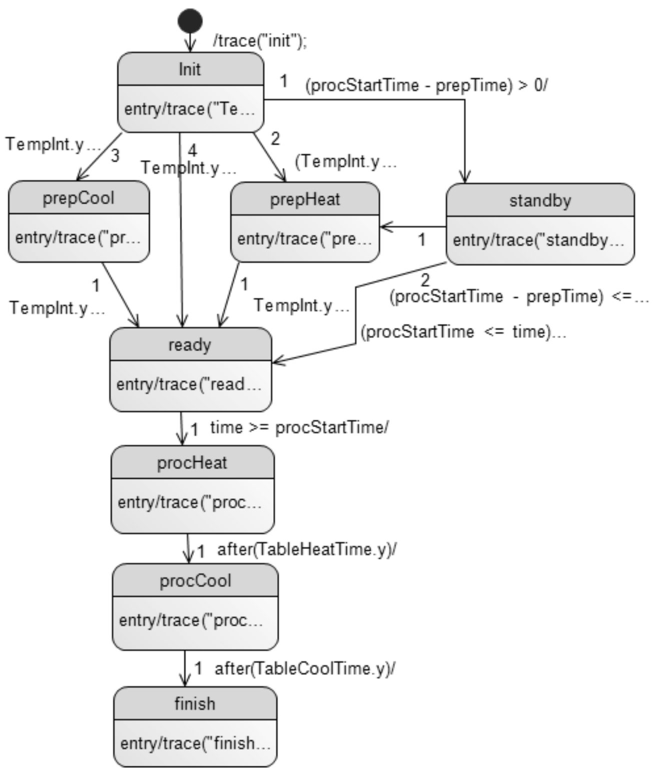


**Figure 2 - Statechart of the modelled oven behavior**

### B. *Model Export as Functional Mock-Up Unit*

Another important step for model creation is the export of the model as Functional Mock-Up Unit (FMU). Many Modelica tools can import and export FMU. FMU models are accessed through the Functional Mock-Up Interface (FMI) [2][4] which is standardized as well as the FMU itself. 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 and cannot be opened if necessary. The process FMU model is equal to the original model and yields the same simulation results. In order use the oven model in the optimization framework the implementation of the FMI was required. With this extension different FMU models from different domains can be utilized by the optimization framework which can be used for optimization purposes in different industries. The oven model has no internal memory for storing the temperature and state of the oven between simulation runs. This is however not required because the model is initialized by the framework before every simulation run. Initial values are provided by the optimization module which stores data for each job with oven state and start temperature. The optimization toolchain is shown in Figure 3 and Figure 4.

## IV. Optimisation

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

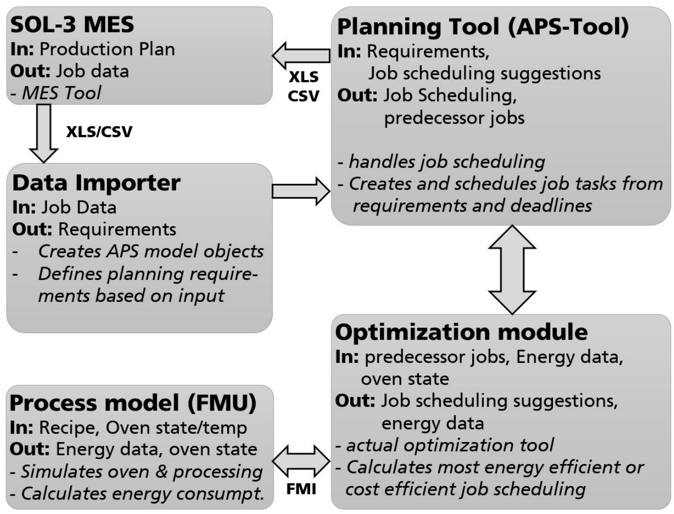


**Figure 3 Overall Toolchain**

The APS system consists of two major modules, a scheduler and an optimisation module. The scheduler determines a production schedule based on the required products (glass sheets) and their production deadlines as well as available resources and their dependencies. It also provides partial schedules for the optimisation module which uses multiobjective optimisation strategies and an iterative search approach to find optimal parameters or a different partial 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 up. 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 placed on the conveyor, aligned and cleaned if necessary. After that a barcode is scanned into the ERP system. Thereafter the oven recipe is loaded into the oven control computer. These preparation steps take place while another set of glass panes is tempered in the oven. In case this takes longer than the actual tempering process the oven has to wait between jobs thus wasting energy.

The APS model of the tempering process 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.

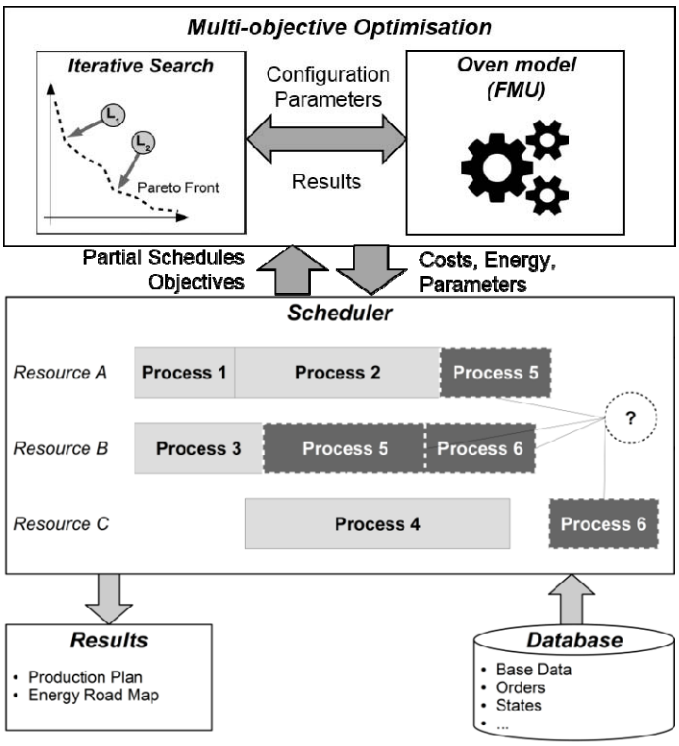


**Figure 4 Scheduler and Optimization Module**

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 saved and loaded during the planning and scheduling process. In addition the APS system was extended with another interface that allows communication with specific external modules at certain points during the detailed planning of the job scheduling. Within this tempering process scenario during detailed planning the current oven condition, data of the last production job, and a set of all possible job candidates is transferred to an external optimisation module as shown in Figure 4. The optimisation module determines the costs for possible job sequences while the required energy and related costs are determined by the oven model 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 response time of the process model is crucial for the practicality of the optimisation framework. The calculated and optimised energy data can be represented as 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 consumption data provides the production engineer with information to reduce the energy consumption. An overview of the toolchain is shown in Figure 3.

## OUTLOOK

Currently the associated project is still being developed and data that would confirm energy savings from applying the energy efficient APS system is not yet available. Cautious estimates number the cost savings from reduced energy consumption at up to 10%. Once the APS toolchain is operable it is planned to use historical production and energy data from a defined production period and optimize the energy requirements as a first benchmark. Thereafter the APS system should become an integral part of the tempering 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.

## ACKONWLEDGEMENT

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