Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

**Bundesamt für Energie BFE**
**F&E Programm Verfahrenstechnische Prozesse VTP**

# MODELING AND OPTIMIZATION OF ENERGY CONSUMPTION IN MULTIPURPOSE BATCH PLANTS

## Jahresbericht 2006


| | |
|---|---|
| Autor und Koautoren | Andrej Szijjarto |
| beauftragte Institution | Gruppe für Umwelt- und Sicherheitstechnologie; ETH Zürich |
| Adresse | ETH Hönggerberg HCI G 138; 8093 Zürich |
| Telefon, E-mail, Internetadresse | 044 / 632 56 66, andrej.szijjarto@chem.ethz.ch, http://www.sust-chem.ethz.ch |
| BFE Projekt-/Vertrag-Nummer | 100536 |
| BFE-Projektbegleiter | Martin Stettler |
| Dauer des Projekts (von – bis) | Vom 01.03.04 bis 31.08.07 |
| Datum | 06.12.2006 |


Summary

The modeling part of the project reached the final stage where reliable models and software modeling tools were developed. The tools are based on the Matlab® software and Bottom-up model presented in the previous reports are powerful and robust enough to treat the significant amount of the process data in reasonable time with minimized interaction of the human interface. The model was tested for modeling the energy utility consumption in the case study plant during the period of two months. Up to 30 batches of 9 different products were produced in this period and using the model the highest energy utility consumers were identified. The resolution of the model allows exploring the energy demand of each particular step, which is very useful for identification of the steps with highest energy consumption. These steps are the parts of the process, where the main energy-saving potential is allocated and the energy saving effort should be focused on. The results show also the variability of the batches during modeled period, which indicates substantial variations in the process. These results help us to identify the batches with minimal energy consumption and explore the process conditions under which they were produced.

Based on these results, one product was chosen, which will be investigated in the final stage of the project in order to optimize the energy consumption of the case study plant. The developed methodology and software tools can be applied later for other products or chemical batch plants with similar data management to the case study plant.

## Project Goals

The main goal of the project is to develop reliable tools for **optimizing the energy consumption** in the multipurpose batch plants. From the know-how gained during the development and application of the tools in the case study plant, the **application methodology** and **general guidelines** can be compiled in order to systematize and ease the usage of the tools in other chemical facilities with similar production data structure (data describing the process in general and process data).

Previous work showed inapplicability of the top-down models for the case study plant with broad product portfolio, therefore only the **bottom-up approach** was chosen for further investigated. The detailed process data form the case study plant appeared to be the key element to reliable energy modeling with help of computer programs. The reproducibility of the concepts is tested through the **measurements** of energy utility consumption (electricity, steam) of particular **unit operation**. After finished electricity measurements, the focus has moved to steam measurements. Based on the results of the preliminary modeling and equipment properties (e.g. lining material, volume) of the particular apparatus, the detailed measurement plan was established in order to get the results for a broad spectrum of the unit operations so the data can be transferable to the plants with comparable equipment pool.

With the reliable results of the modeling part, the project can move to the last part – **energy consumption optimization** where concrete energy-saving steps based on the analysis of the modeled results will be proposed.

The overall workflow of this project is depicted in Fig. 1.

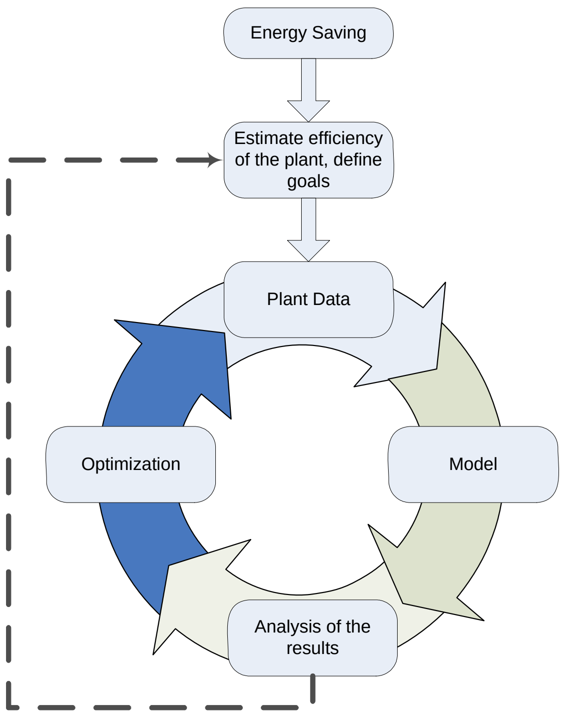


Fig. 1: Energy saving process scheme

## Realized work and results

In this chapter the results obtained during the project realization are presented. In the first subchapter the summary of results presented in previous reports are shortly mentioned (for detailed information refer to particular report). In the second subchapter the results from the previous year are described.

### SUMMARY OF THE PREVIOUS RESULTS

#### *Top Down modeling*

Principle of the Top-Down modeling was to correlate the total utility consumption of the building with the investigated building with the overall production. The top-down approach does not provide the reliable information about the energy utility consumption (e.g. steam, see Figure 1) and therefore the next goal was to get more detailed information about particular unit operations using the Bottom-Up approach. For detailed information refer to [1].

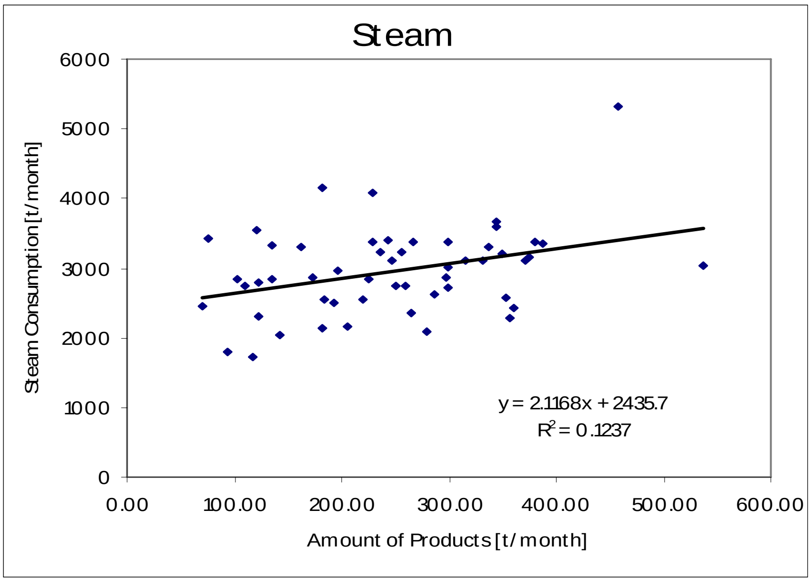


Fig. 2: Top-Down modeling of the 5-bar steam consumption in the case study plant

#### *Preliminary Bottom-Up modeling of the steam consumption*

The preliminary Bottom-Up modeling was carried out in order to test the approach in the case study plant and identify the highest steam consumers (see [2]). Based on these results, the steam measurement plan which covers all important consumers was created.

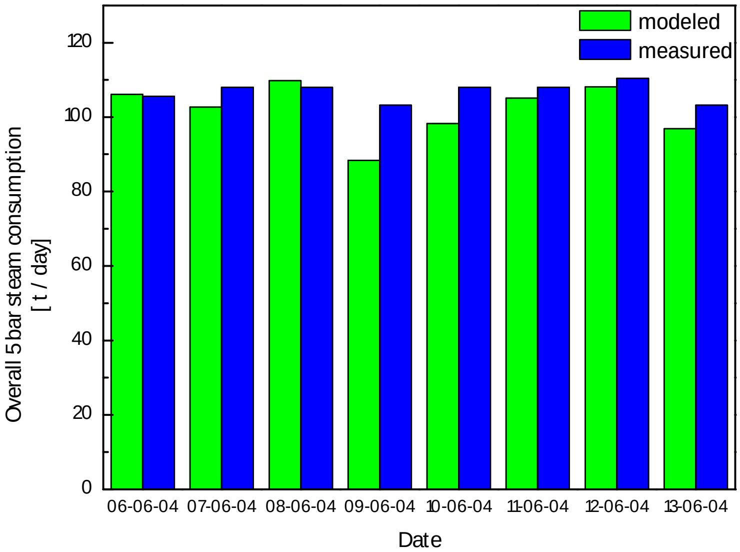


Fig. 2: Comparison of the measured and modeled daily steam consumptions

In t Fig. 2

***Base consumption***

Base consumption of the particular energy utilities (electricity, heating, cooling) in the case study plant is an important parameter that was determined during the shut-down period [3]. The shut-down period due to the maintenance in the observed plant was carried out in the middle of March 2005 and valuable results were extracted from the utility consumption measurements for the whole building. This production independent utility consumption represents an important feature of the specific plant and can give a basic overview of the infrastructure energy efficiency (for electricity base consumption measurement see Fig. 3). The base consumption can be subsequently used as an offset value for the overall energy consumption model of the plant.

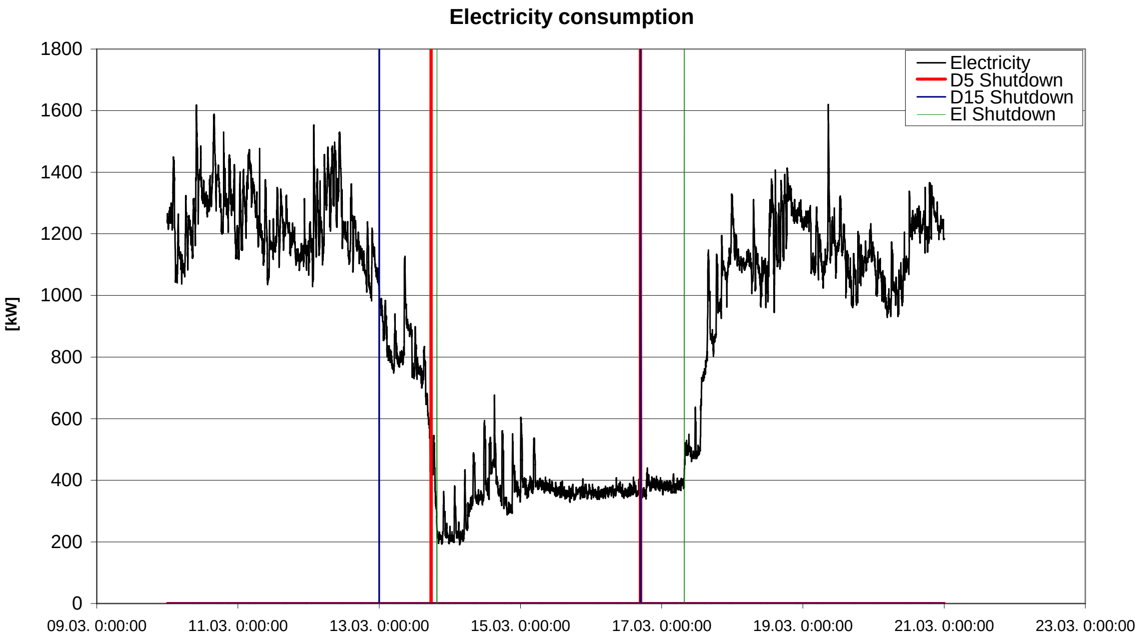


Fig. 3: Electricity base consumption measurement

## RESULTS 2006

### *Process data based modeling*

As a basic modeling approach, the Bottom-up modeling was chosen as the Top-Down approach failed to describe the energy consumption of the case study plant, as described above. The Bottom-up approach uses the process data of particular unit operations and delivers highly detailed results, which can identify the energy consumption hot-spots.

The process data in the chemical batch plants represent an extensive source of information describing the production parameters of particular batch which can be used for modeling purposes. Based on this data, the mass and heat balance of each unit operation can be built.

In Fig. 4 the data flow is described. Data acquisition layer represent the data-mining in the case study plant (either electronically or physically). Following data sources were used:

- process data (PI) – these data are gained from the **process sensors** for each apparatus (inside temperature, pressure, mass of reaction mass) and are stored in specific time sampling interval, which is always connected to particular batch number and step number of the batch
- process step procedure data (BVO) – in these documents the **basic process description** is stored and main output from this document is the mass balance of the process (description of the standard conditions); in the risk analysis part of the BVO, the **physicochemical properties** of the substance involved in the reaction are listed
- recipe – represents the **detailed description** of the process in form of the ASCII file, where each step of a batch in particular apparatus is described; from this data, the link between process data (PI) and concrete step can be extracted
- internal database – from this data source the **apparatus data** can be obtained, which represent the apparatus characteristics and geometrical dimensions, which can be used for the further calculations in the Bottom-up model

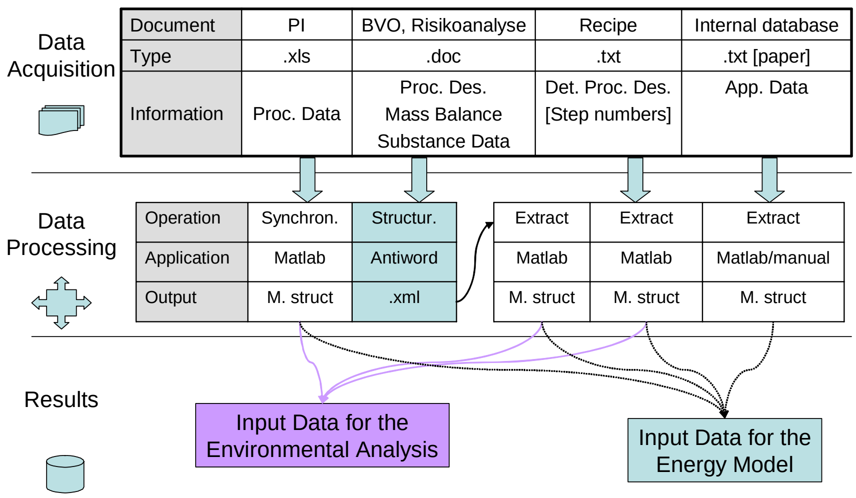


Fig.4: Data management scheme

Mentioned data are acquired from the case study plant in form of Microsoft Office® documents (numerical data as Excel®, textual data as Word®) or as a plain text (recipe).

The BVO and recipe data represent the description (metadata) of the process and the process and apparatus data are fitted to this mask for every modeled batch.

The main modeling is carried out in the Matlab® software, which very efficiently substitutes previously used Excel® which showed to be very inefficient (CPU time) for extensive data sets (couple of hundreds of MB of raw data).

Between the Microsoft Office® and Matlab® model layer, the data processing is necessary in order to transform the acquired data into useful Matlab® structures. Result of the data processing is input data file, which can be used further in the modeling procedure described in Fig. 6.

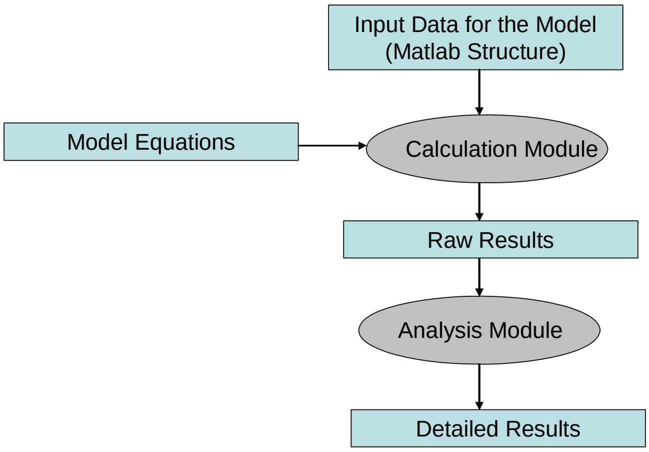


Fig. 6: Calculation and analysis organizational chart

The model equations used in the calculation phase are the ones based on the Bottom-up mentioned in the previous works ([1], [2]). As a result of the calculation module, the raw results of particular utility consumption are generated. These results represent the utility consumption during the time interval of the grid, in which the input data were processed. The data are stored in form of long vectors and have to be summed in following way, in order to get the useful data which can be analyzed and produce the detailed results.

Following summation of the raw data can be done:

raw data are obtained in following resolution

$$E_{[P,A,S\#,\mathbf{TI}]UB\#} = f(\text{Recipe, T, m, Losses, Time Interval})$$

*step-wise summation:*

$$E_{[P,A,\mathbf{Step\#}]U,B\#} = \sum_{TI(S\#)} E_{[P,A,S\#,TI]U,B\#}$$

*apparatus-wise summation:*

$$E_{[P\,\mathbf{Apparatus}]U,B\#} = \sum_{S\#(A)} E_{[P,A,S\#]U,B\#}$$

*product-wise summation:*

$$E_{[\mathbf{Product}]U,B\#} = \sum_{A(B\#)} E_{[P,A]U,B\#}$$

*utility-wise summation:*

$$E_{\mathbf{Utility}} = \sum_{P(U)} E_{U,P}$$

where:

P – Product, A – Apparatus, S# - Step number, TI – Time Interval, U – Utility, B# - Batch#

***Variability of the batches***

In the following section the product-wise summation is presented. In this case, the results are showing the energy utility consumption for production of the particular product in different batches.

Following energy utility consumptions were investigated:

- electricity:
  - M80 – motor for stirring – stage 1
  - M81 – motor for stirring – stage 2
  - M20 - motor for pumping – stage 1
  - M21 motor for pumping – stage 2
  - Mx1,Mx2 – other motors

- heating:
    - o dD5 – direct 5 bar steam
    - o iD5 – indirect 5 bar steam
    - o dD15 - direct 15 bar steam
    - o iD15 - indirect 15 bar steam
    - o HT – heating oil (Marlotherm)
- cooling:
    - o WF – fabric water
    - o WBE – chilled water
    - o WBI – industrial water
    - o Sole - brine
    - o Eis - ice

The results of the model (see Fig. 7) are showing broad variability of the energy utility consumption for different batches (different color in the figure depicts different batch). This result can be used for:

- identification of the batches with minimal and maximal energy utility consumption (batch optimization potential)
- connection to production data – analysis of the process data for interesting batches

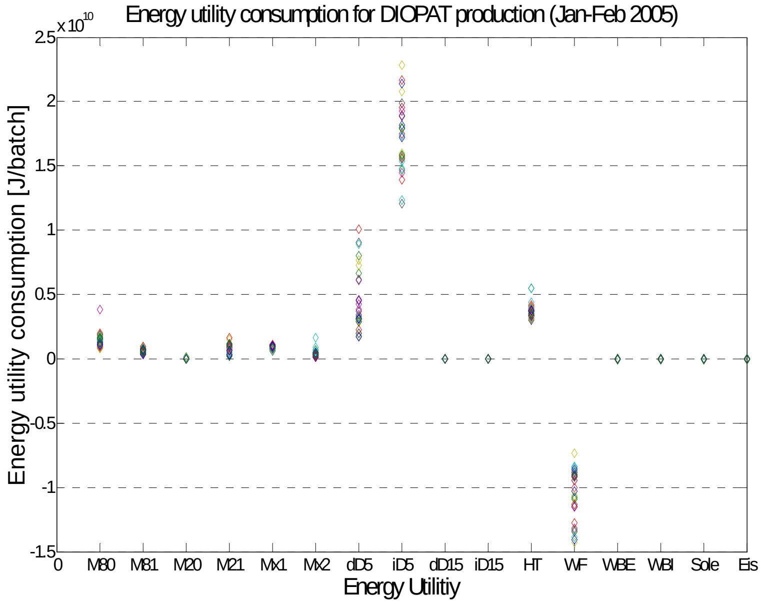


Fig.7: Variability of energy utility consumptions for different batches

In Fig. 8, only one utility consumption is displayed (M80 - electricity used for stirring with the motors in stage 1), showing the variation of the utility consumption for different apparatus. The results can be used in the following analysis steps:

- choosing the apparatus with the highest energy utility consumption (most promising apparatus for optimization)
- estimating the range of possible energy savings

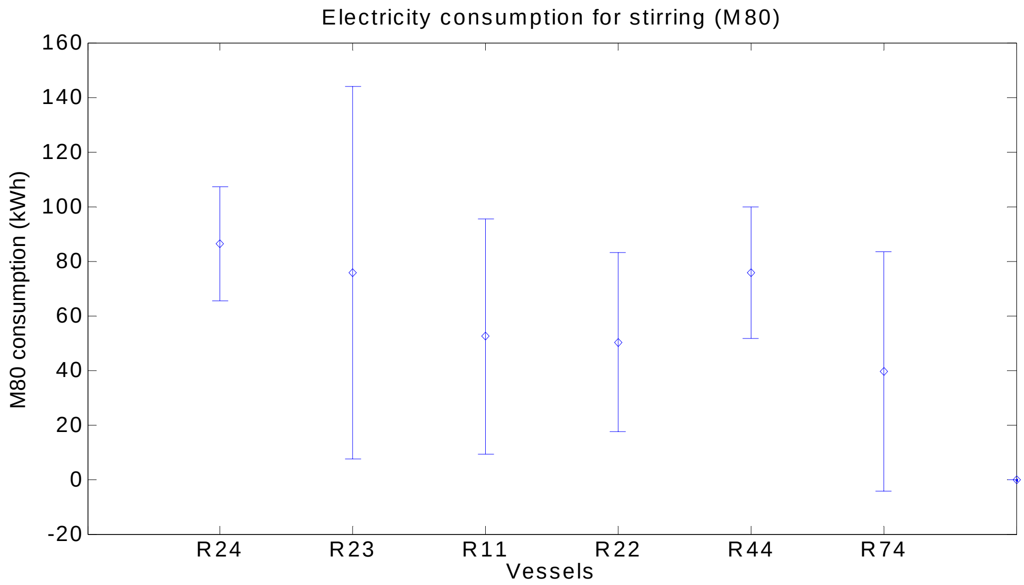


Fig.8 Variability of electricity consumption used for stirring in different vessels

***Steam consumption measurements***

In Table 1 the priority list of the steam consumption measurement in different reactors is depicted. The portfolio of the reactors was chosen in order to cover wide range of the volumes, lining material and type of heating-cooling system.

Table1: priority list and measured reactors

| No. | D5 Consumer | D5 consumption [t D5 / 8 days] | Material | Heating | Volume [$m^3$] | Priority | Measured |
|---|---|---|---|---|---|---|---|
| 1 | R75 | 27.75 | Stnr | indirect | 40 | 1 | |
| 2 | R61 | 24.54 | St-gepl | direct | 40 | 1 | x |
| 3 | R22 | 18.58 | Stnr | indirect | 40 | 1 | x |
| 4 | R32 | 14.16 | Stgum | direct | 40 | 1 | |
| 5 | R62 | 6.74 | Stbor | direct | 40 | 1 | |
| 6 | R33 | 3.63 | Stgum_HBK | direct | 40 | 1 | |
| 7 | R76 | 21.15 | Stnr | indirect | 25 | 2 | |
| 8 | R13 | 12.59 | Stnr | indirect | 40 | 2 | |
| 9 | R53 | 11.57 | Stnr | indirect | 40 | 2 | |
| 10 | R23 | 8.62 | Stnr | indirect | 25 | 2 | x |
| 11 | R44 | 7.44 | Stgum_HBK | direct | 25 | 2 | |
| 12 | R51 | 6.38 | Stgum_HBK | direct | 25 | 2 | |
| 13 | R52 | 17.87 | Stem | direct | 10 | 3 | |
| 14 | R46 | 17.02 | Stem | indirect | 16 | 3 | |
| 15 | R85 | 15.95 | Stnr | indirect | 16 | 3 | |
| 16 | R41 | 15.03 | Stnr | indirect | 16 | 3 | |
| 17 | R86 | 7.31 | Stnr | indirect | 16 | 3 | |
| 18 | R65 | 0.70 | Stgum_HBK | direct | 25 | 3 | |

The results of the measurement are shown in Fig. 9. In this case the heating is used for distillation (between 450 and 950 min) and heating of the reaction mixture (1050 – 1800 min).

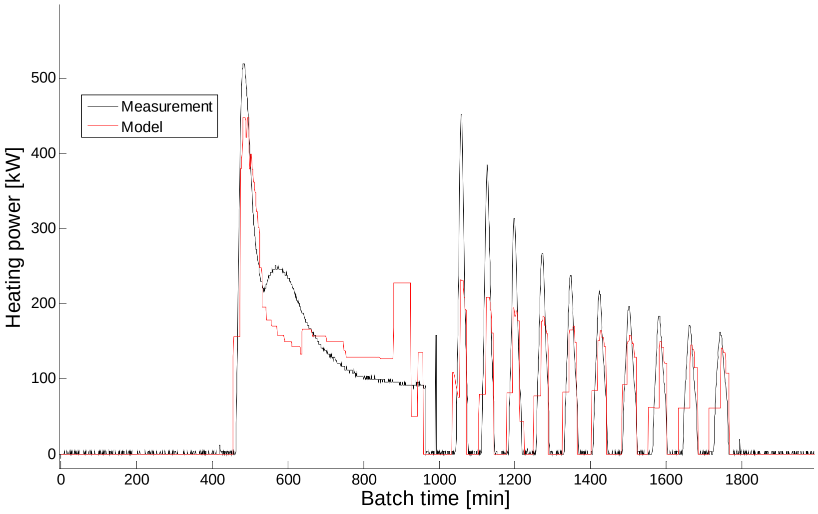


Fig. 9: Comparison of the steam consumption model and measurement for the reactor with double jacket heating

The modeled steam consumption is calculated according to the equation:

$$E_{Utility,prod\_i,equip\_j} = Theoretical\_Consumption + a \times (Theoretical\_Consumption)^{b}$$

where the theoretical consumption is calculated from the classical Bottom-up approach (energy balance of the process)and represents the thermodynamically needed energy to heat-up or evaporate desired amount of reaction mixture, as defined in the production data.

For this particular reactor:

a = 22.9, b = 0.36

Based on the following equation, following Table 2 was calculated, which shows the dependence of the losses on the theoretical steam consumption. The relative losses are significantly lower at higher nominal consumption, because at higher steam consumption rates the relative amount of the steam used for heating-up the apparatus is considerable lower. The heating strategy represents an important optimization element and will be investigated in further research.

Table 2: Losses for different levels of the theoretical steam consumption

| Thoery [kW] | Loss [kW] | Total [kW] | Loss [%] |
|---|---|---|---|
| 10.00 | 50.38 | 60.38 | 83 |
| 50.00 | 90.25 | 140.25 | 64 |
| 100.00 | 116.01 | 216.01 | 54 |
| 500.00 | 207.84 | 707.84 | 29 |
| 1000.00 | 267.17 | 1267.17 | 21 |

## Evaluation 2006 and Outlook 2007

In the year 2006 the **final stage** of the **model-development** phase was reached. The model is providing comprehensive results, which can be used for in the optimization phase. The software tools are efficiently using the plant data with minimized human interaction and therefore broad process simulation can be done in reasonable time. The **variation** of the energy utility consumption is showing big improvement potential, which can be estimated from the analysis of the model results and further investigated in the optimization phase. Due to the technical problems, the steam measurements were not completely finished according to the plan in 2006. The time plan of the measurements was postponed (see outlook for 2007). The flexibility of the model tools allows us to update the results with the new steam measurement results promptly, so the optimization part can start without any restrictions.

***Outlook***

The crucial element of the project remains the **steam measurement**, where the final stage will be finished in the beginning of 2007. Parallel to this, the **optimization part** will run, where the main focus will be dedicated to optimization of the energy utility consumption of one product which was chosen based on the results achieved in the modeling phase. The optimization will be carried out in close cooperation with industrial partner and proposed improvements will be implemented in the model, in order to quantify the overall savings. The modeling and optimization of the energy utility consumption will be compiled into a general methodology, which can be applicable in order to optimize the energy consumption in other batch plants.

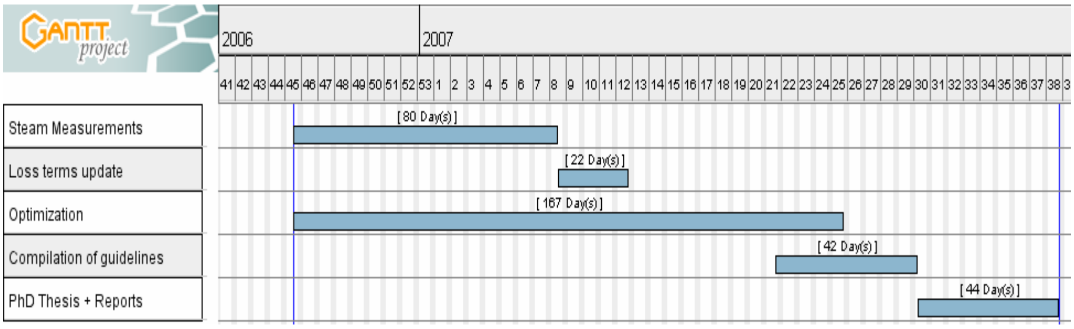

Fig. 10: Time plan 2007

## Reference


[1] A. Szijjarto: ***Modeling and optimization of Energy Consumption in Multipurpose Batch Plants***, Status Report August 2004, 2004

[2] A. Szijjarto: ***Modeling and optimization of Energy Consumption in Multipurpose Batch Plants***, Jahresberich 2004, 2004

[3] A. Szijjarto: ***Modeling and optimization of Energy Consumption in Multipurpose Batch Plants***, Status Report June 2005, 2005

[4] A. Szijjarto: ***Modeling and optimization of Energy Consumption in Multipurpose Batch Plants***, Jahresberich 2005, 2005