Jahresbericht 2005, November 2005

Modeling and Optimization of Energy Consumption in Multipurpose Batch Plants

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BFE-Nummern	Projekt: 100536; Verfügung: 150659
Dauer des Projekts	Vom 01.03.04 bis 31.08.07

Zusammenfassung

Im Hinblick auf die Erstellung eines Modells, das zur Vorhersage und zur Optimierung des Energieverbrauchs in chemischen Batch-Betrieben eingesetzt werden kann, wurden im laufenden Jahr erhebliche Fortschritte gemacht. In erster Linie wurde das Modellierungstool für den Bottom-Up Ansatz auf eine neue technische Grundlage gestellt (Matlab® statt Excel®) und die Verwaltung der verschiedenen Daten sowie die Dateneingabe verbessert. In diesem Zusammenhang wurde ein Tool entwickelt, mit dem automatisch elektronisch abgelegte Produktionsdaten in das Modellierungsprogramm eingelesen werden können. Desweiteren wurde ein weiterer Modellierungsansatz entwickelt und getestet, bei dem mittels multivariater Statistik versucht wird aus den Mengen der produzierten Chemikalien und dem Gesamtverbrauch eines Energieträgers in verschiedenen Monaten den spezifischen Verbrauch pro Produkt abzuleiten. Für die durchgeführten Untersuchungen führte dieser Ansatz nicht zu befriedigenden Ergebnissen. Mittels Messungen wurden alle Rührer im untersuchten Gebäude charakterisiert. Die Messungen des Stromverbrauch verschiedener Apparate die zum Grundverbrauch beitragen steht kurz vor dem Abschluss. Bei den Dampfmessungen ergaben sich technische Probleme und daraus Verzögerungen. Ab Januar 2006 kann aber das geplante Messprogramm durchgeführt werden.

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1 Goals of the project in year 2005

The project goals in year 2005 follow-up the achieved goals from previous year, when the basic Top-Down and preliminary Bottom-Up modeling were carried out. The main focus was given to further development of the modeling tools that can be used in the second phase of the project when the investigation will be concentrated on the optimization of the energy utilities consumption. The basic relations and outcomes of the particular steps are depicted in the Fig. 1. The focus in 2005 is represented by the Phase 1, i.e. further development of the model (testing different approaches of the modeling in the case study plant), measurement of the utilities consumption (fitting the empirical parameters for the Bottom-Up model) and development of the software modeling tools (increase the efficiency of the data-handling and calculation). The performed work and achieved results are discussed further in the report.

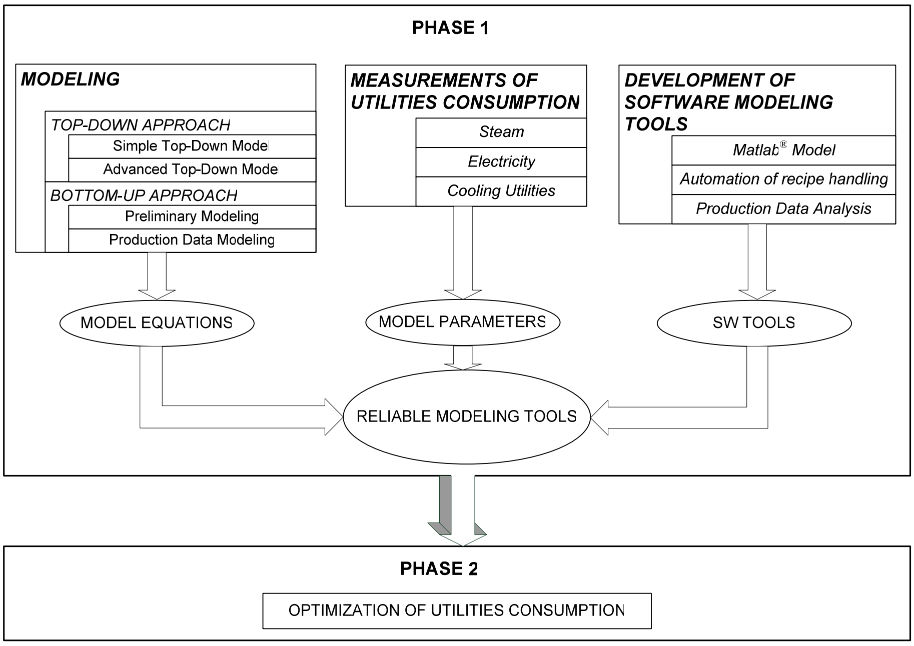

Figure 1 Project goals overview

2 Performed work and achieved results

2.1 ADVANCED TOP-DOWN MODELING OF THE UTILITY CONSUMPTION

As shown in the previous research [1], the simple top-down approach, correlating the consumption of a particular energy utility with the overall production output, as shown in Eq.(1), could not be applied in the case study plant due to the large variance in the production procedures of particular chemicals resulting in considerably different specific energy consumptions.

$$TUC_{period} = BUC.nm_{period} + P_{overall}.SC_{overall} \quad (1)$$

Thus the approach failed to predict the consumption of steam, electricity and cooling energy for specified product portfolio using the correlation coefficients fitted for historical data.

However the prediction of the overall energy demand for the planned future production is an important parameter for the decision makers in the plant management, so additional effort was dedicated to solve this problem using more sophisticated methods. The new approach using the concept of individual specific consumptions for each product and their multiple linear regression fitting was investigated. If we consider the modeling of the utility consumption during a specified period on monthly basis, one can express the total utility consumption as follows:

$$TUC_{period} = BUC.nm_{period} + \begin{pmatrix} P_{11} & \cdots & P_{1j} \\ \vdots & \ddots & \vdots \\ P_{i1} & \cdots & P_{ij} \end{pmatrix} \begin{pmatrix} SC_1 \\ \vdots \\ SC_i \end{pmatrix} \quad (2)$$

where TUC_{period} [energy units/period] represents the total utility consumption during the modeled period, BUC [energy units / month] represents the monthly base utility consumption, $nm_{mperiod}$ stands for the number of months in the period, P_{ij} [t] is the matrix with the production amounts of product i in the month j and SC_i [energy units / t] represents the specific consumption of the utility for product i. The input parameters for this model are the total utility consumption, the number of days in the period and the matrix of product amounts. The output is base consumption and the SC_i which are fitted to the model using a least square method and genetic algorithm (this allows us to use the heuristics and empirical values to influence the range of SC_i see also Chapter Advanced Top-Down modeling – Conclusions)

2.1.1 Advanced Top-Down modeling of the steam consumption

The steam represents the heating energy utility used for production purposes and the space heating in the case study plant as well. In order to incorporate the fluctuation of the ambient temperature, the heating degree days concept was applied. Thus the equation (2) extended for heating can be written as:

$$TUC_{period} = h.HDD_{period} + BUC.nm_{period} + \begin{pmatrix} P_{11} & \cdots & P_{1j} \\ \vdots & \ddots & \vdots \\ P_{i1} & \cdots & P_{ij} \end{pmatrix} \begin{pmatrix} SC_1 \\ \vdots \\ SC_i \end{pmatrix} \quad (3)$$

where h is the amount of the steam needed for heating of 1 degree-day [energy untis / Kday]. To determine the HDD, the ambient temperature from the meteorological station close to the case study plant was used. The definition of the HDD is taken from Swiss standard [1]:

$$HDD_{period}(T_{room}, T_{th}) = m_k \sum_{k=1}^{n} (T_{room} - T_{ambient}) \quad (4)$$

m_k = 1 day if $T_{ambient,k} \le T_{th}$, m_k = 0 day if $T_{ambient,k} > T_{th}$. In Eq. (4), T_{th} denotes the threshold temperature for heating set to 12°C and k stands for particular day of the modeled period.

Production data P_{ij} for a period of 30 months were used in equation (3) in order to get the correlation coefficients (h, BUC, SC_i). During this period 42 products were produced which gives the P matrix of size 30×42.

As can be seen in Fig.2, the modeled steam consumption during the training period fits particularly well with the measured consumption. However, the fitted parameters, mainly the specific utility consumption for particular products, seem to be unrealistic (discussed with plant chemist, some products compared with the Bottom-Up model). This can be caused by changes of the recipes and resulting different energy requirements during the modeled period for the same product. The variations of the recipe can not be incorporated into the Top-down type of model, so the resulting SC_i is an averaged value for the modeled period, but in real production varies as a function of recipe.

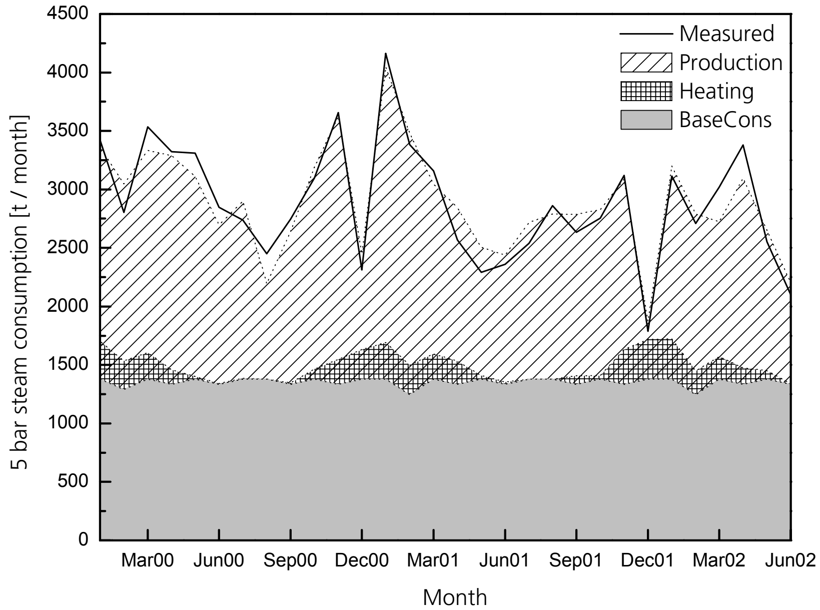

Figure 2 Comparison of the modeled and measured steam consumption for the training set in the period of 30 months

Another problem of the model becomes obvious when investigating the steam consumption in December 2001. Here the steam consumption for production is doubtable. The overall production in December 2001 was 94 t (42% of the average monthly production during 30 months period) however the modeled production dependent steam consumption is only 152 t (11% of the average monthly steam consumption). The reason might be a partial shut-down of the infrastructural and comfort heating devices because of lower production (e.g. scrubbers which use steam during desorption cycle). Nonetheless the base consumption and space heating is set to a constant value in the model and the SC_i of the products produced in December 2001 are fitted to artificially low values.

Mentioned inaccuracies will influence the reliability of the energy utility consumption prediction as seen in Fig. 3. For the prediction of the steam consumption, the period of 23 months was selected. During this period 34 products were produced as a subset of the products produced during the training period.

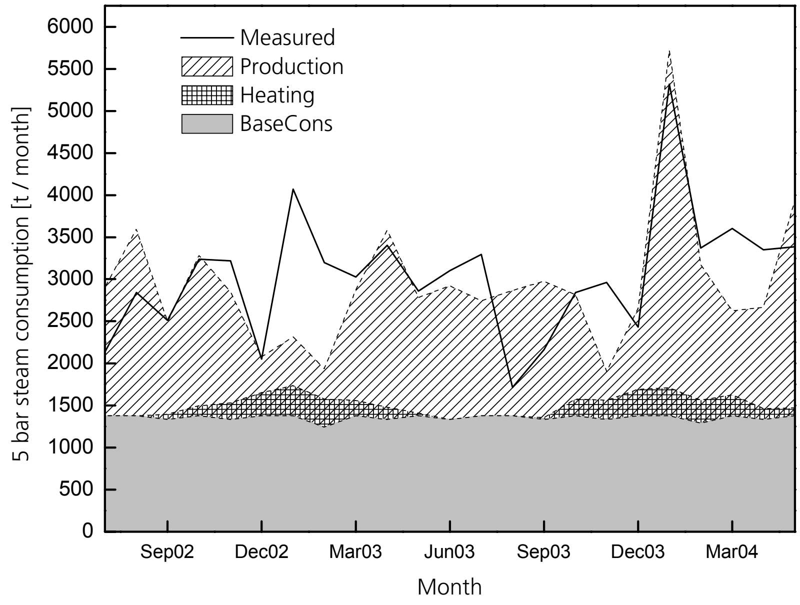

Figure 3 Comparison of the modeled and measured steam consumption for the prediction period of 23 months

2.1.2 Advanced Top-Down modeling of the electricity consumption

The modeling of the electricity consumption was carried out for the same training and prediction period as the steam consumption modeling. The Eq. (2) was used because electricity is not used for space heating.

In the Fig. 4 it is obvious, that the modeling of the electricity consumption even on the training set is much less accurate compared to steam consumption modeling.

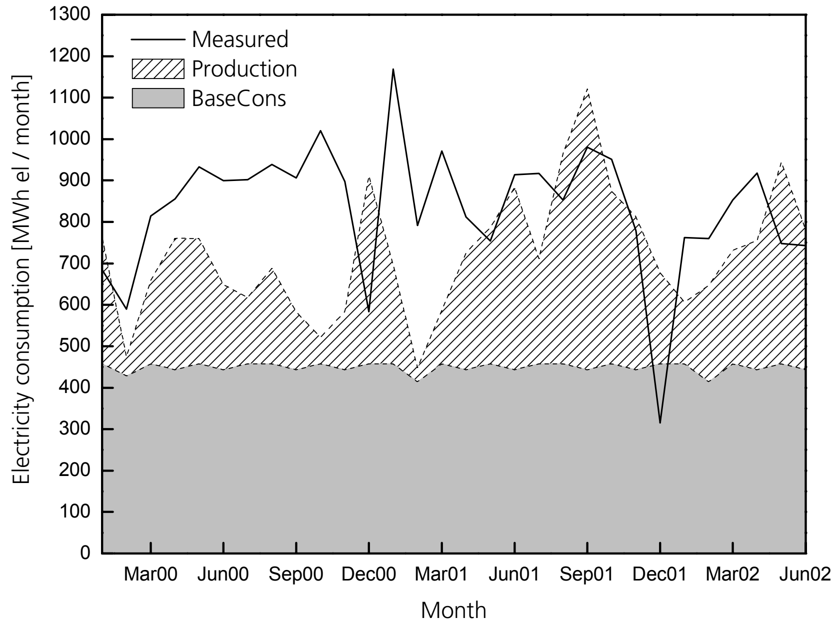

Figure 4 Comparison of the modeled and measured electricity consumption for the training set in the period of 30 months

The reason is a much higher dependence of the electricity consumption on the recipe and process variations (e.g. variations of operation times of the stirrers for different batches of the same product) and for manual operations the human interface influences the variations of the electricity consumption (e.g. when the operator lets the stirrer run different time for different batches).

The issue of "December 01 production" mentioned for the steam consumption appears as well considering the electricity consumption. Here the measured consumption is only 42% of the measured consumption and is even lower than the base consumption itself.

One problem might be the value of the calculated base consumption which seems to be overestimated. Another point is the shut-down of the infrastructural equipment (ventilation system) which has tremendous power consumption.

The model of the prediction period shown in Fig. 5 shows relatively poor correlation with the measured consumption as well. The main drawback is the opposite prediction in Dec03 and Jan04. This example shows sensitivity of the calculated specific consumptions to the product portfolio in the training period.

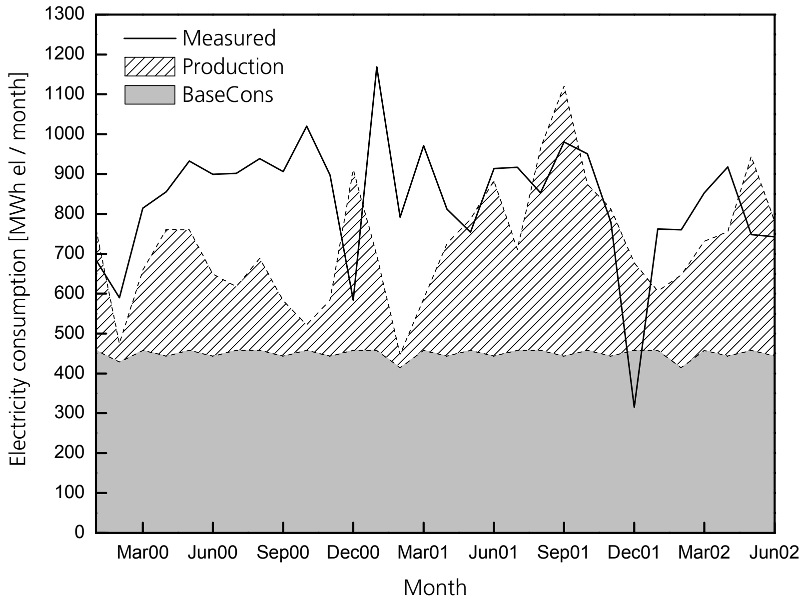

Figure 5 Comparison of the modeled and measured electricity consumption for the prediction period of 23 months

2.1.3 Advanced Top-Down modeling – Conclusions

The advanced Top-Down modeling was performed on the set of 42 products, which represent a system with enormous complexity and similarly the period of modeling 30 + 23 months introduces numerous variations in recipes and technologies, which cannot be included into the Top-down based model.

Although the model cannot be used for highly precise prediction of the utility (see Tab 1) consumption, it can give some basic overview of the energy-usage and base consumption of the investigated production building.

Table 1 Correlation between the model and measurements

Modeled utility consumption	***Correlation coefficient***
Steam consumption 30 months	0.951
Steam consumption prediction 23 months	0.566
Electricity consumption 30 months	0.693
Electricity consumption prediction 23 months	0.545

In order to get more precise output data from the model, heuristics can be used. For the fitting of the parameters used in the models in the previous chapters basic heuristics were used (see Tab. 2).

Table 2 Model parameters constraints

Parameter	***Condition***
BUC	>0
SC_i	≥0

In the future more advanced heuristic rules or partial results from bottom-up modeling can be used:

- specific consumption of product A is higher than the one of B $SC_A > SC_B$ (estimation from process step procedure, information from plant chemist)
- SC_i of some products is set to zero (e.g. no steam consumption)
- SC_i is directly calculated from Bottom-up model and supplementary parameters are fitted

The advantages and weaknesses of the mentioned modeling approach are summarized in Tab.3.

Table 3 Summary of the advanced Top-Down modeling

Advantages	***Weaknesses***
- easy applicability of the model in the industry with minimal engineering effort - modeling of energy consumption for specified product portfolio - estimation of base consumption for the specific energy utility - possibility of applying the heuristics, empirical data and Bottom-up modeling results	- inaccurate or unrealistic values of specific utility consumptions (SUCs) for some products - dependence on the product-portfolio of the training period - impossibility to include the recipe or technological changes which result in different SUC during modeled period - only analytical function, no application for optimization of energy consumption

2.2 ELECTRICITY MEASUREMENTS

Electricity consumption of the stirrers is calculated as a product of nominal power, coefficient gamma (part of nominal power consumed by the stirrer) and the time of operation of the equipment. The coefficient gamma is specific for each stirrer, but at the moment for modeling of the electricity consumption of all stirrers in the chemical plant an average value for the typical set of stirrers is taken. However the model allows defining different coefficients for individual stirrers or group of stirrers. The groups of stirrers will be defined based on evaluation of additional measurements that were already carried out.

The electricity consumption measurements in selected vessels were carried out in order to get adjusted values of gamma coefficient for the case study plant. As can be seen in the Table 4, this parameter varies significantly for the different stirrer types and the average value 0.44 for the measured set of stirrers differs from the gamma value from the chemical batch plant presented by Bieler et al. (average gamma = 0.28).

Table 4 Summary of the electricity measurements of the stirrer motors

#	Vessel	Stirrer type	Volume	Nominal power	Actual power	γ
			m^3	[kW]	[kW]	
1	N41	EKATO / Viscoprop	6.3	22	8.08	0.37
2	N80	Inter-MIG	10	22	1.41	0.06
3	R12	MIG	25	19	9.5	0.50
4	R21	MIG 1st stage	25	19	18.23	0.96
5	R21	MIG 2nd stage	25	27	21.1	0.78
6	R23	Inter-MIG	25	30	2.85	0.10
7	R36	Impeller	6.3	15	8.55	0.57
8	R56	Anker	10	55	10.64	0.19
						0.44

2.3 DEVELOPMENT OF THE MODELING TOOLS

Efficient modeling tools are crucial for detailed Bottom-up energy utilities consumption modeling because a large amount of data have to be handled. The tool was developed in order to use the data in electronic format available from the case study plant. This issue is connected with development of plant-specific tools which can be applied only in the plants with the same data-management systems (e.g. storage of the production data, apparatus specification), but the gained efficiency is needed in order to model systems of high complexity with reasonable accuracy and feasible time with minimal engineering effort. In the plants with different data storing format, the input data handling tools can be adjusted or the data can be handled manually and the modeling can be then performed with existing modeling tool.

In Fig. 6 is shown the flow chart of the developed Bottom-Up modeling tool. The input data are mostly in the electronic format (e.g. data from some older equipments have to be collected manually) and are processed in ideal case automatically and for specific products and conditions with additional effort (e.g. for incomplete specifications the data has to added manually or some default values can be taken). All the information for the specified modeling period is summarized in the input file for the model, which than is processed by the Matlab® Model (calculation engine) which generates the results and exports them to ASCII files or directly Excel® where they can be visualized and communicated to the industry.

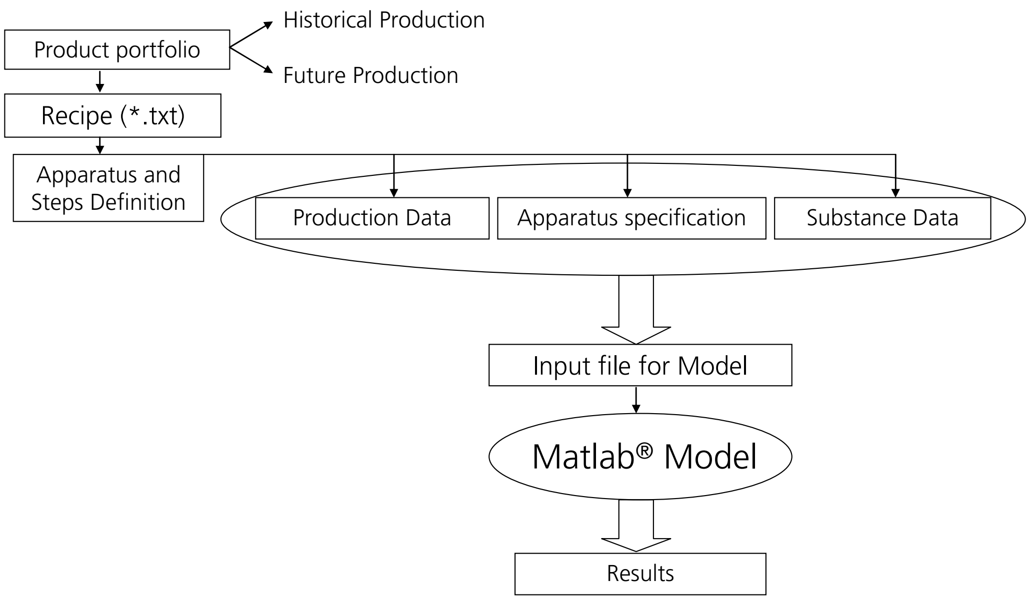

Figure 6 Basic scheme of the Bottom-Up modeling based on electronic data

3 Evaluation 2005

During the year 2005 further development of the modeling tools was carried out which gives additional information about the modeled system (advanced Top-Down modeling), improves the efficiency in the detailed level (modeling tools for Bottom-Up modeling) and adjusts the model parameters to the case study plant.

Summary of the achieved goals:

- advanced Top-Down modeling which provides additional information about the case study plant
- development of the model and the software modeling tools – efficient handling of large amounts of the data
- electricity measurements – adjustment of the parameters in the model

Compared to the planned goals form the previous year, the activity was shifted more to the development of the software modeling tools instead of measurements (namely steam measurements). This was caused by some problems with steam measurement device, which was solved by the end of the year 2005. The delay against the planned schedule can be caught-up by shifting the activity in the beginning of year 2006 to measurements.

4 Outlook 2006

The main goal for the first half of 2006 is to finish the modeling stage of the project and to shift the research activities to the energy optimization field.

To reach this goal, following partial goals have to be fulfilled:

- finishing of the measurements of the steam consumption for selected devices
- completing the electricity consumption measurements for the infrastructure devices
- implementing the new parameters to the Bottom-Up model
- testing the updated model for the specified period and product portfolio

The comprehensive model is the key element to the energy optimization, which is planned to be started in the second half of 2006. The optimization-stage can be divided into following steps:

- identification of the possible energy – saving improvements
- choosing the most promising set of improvements (discussions about applicability with the industry)
- implementing the chosen improvements into the modeling tool
- evaluation of the improvements (overall consumption of the utility, economical benefits, environmental improvements)

References

[1] SIA Standard 381/3: Heating degree-days in Switzerland, Swiss Association of Engineers and Architects (in German), Zurich, Switzerland, 1982.

[2] Szíjjarto, A. (2004), BfE Annual Report 'Modeling and Optimization of Energy Consumption in Multipurpose Batch Plants'– December 2004