ESL-IC-06-11-172

Application of Inverse Models for Long-Term-Energy-Monitoring in the German Enbau: Monitor Project

Christian Neumann, Sebastian Herkel
Fraunhofer Institute for Solar Energy Systems
Freiburg Germany

Günter Löhnert
so°li°dar planungswerkstatt
Berlin, Germany

Karsten Voss
University Wuppertal, Faculty for Architecture
Germany

Andreas Wagner
University Karlsruhe, Faculty for Architecture
Germany

Abstract: in order to pave the way for energy savings and utilizing solar energy in non residential buildings, the german federal ministry of economics and technology (bmwi) has established an energy research program called "energy optimized building" that supports the planning and evaluation of demonstration projects.

enbau:monitor, as the related accompanying project, documents and analyzes these projects on a common platform. in the framework of enbau:monitor, two different monitoring phases were defined. a detailed monitoring takes place during the first two years of operation. after this period a long-term energy monitoring was established in order to evaluate the sustainability of the innovative designs and systems.

fraunhofer ise defined enhanced guidelines for the long-term-energy-monitoring and developed a system for prescription of the placement of meters. furthermore the application of inverse models for automated control of the energy use connected to heating, cooling and electricity is envisaged. the paper presents the new concept as well as the most important findings of the enbau:monitor project.

ENBAU:MONITOR

In the Framework of the EnBau:MONITOR program 23 demonstration projects were build and analyzed during the last 10 years. The program is still ongoing until 2009. shows the location of the demonstration buildings.

In advance of the 2002 EU energy performance directive EBPD a limited primary energy coefficient of 100 kWh/m^{2}a was postulated as a goal for the complete building services technology (HVAC + lighting) for all demonstration buildings to be supported. Further condition was that active cooling has to be avoided. Techniques like natural or mechanical night ventilation or heat removal by slap cooling with bore hole heat exchangers were applied as well as earth-to-air heat exchangers in the ventilation system.

Tab. **1**, DVZ Barnim

Fig.and Fig. gives an overview over the demonstration buildings, their supply systems and the primary energy consumption. More information about the different projects is available at www.enbau-monitor.de.

Fig. 1 Location of demonstration projects in Germany

ESL-IC-06-11-172

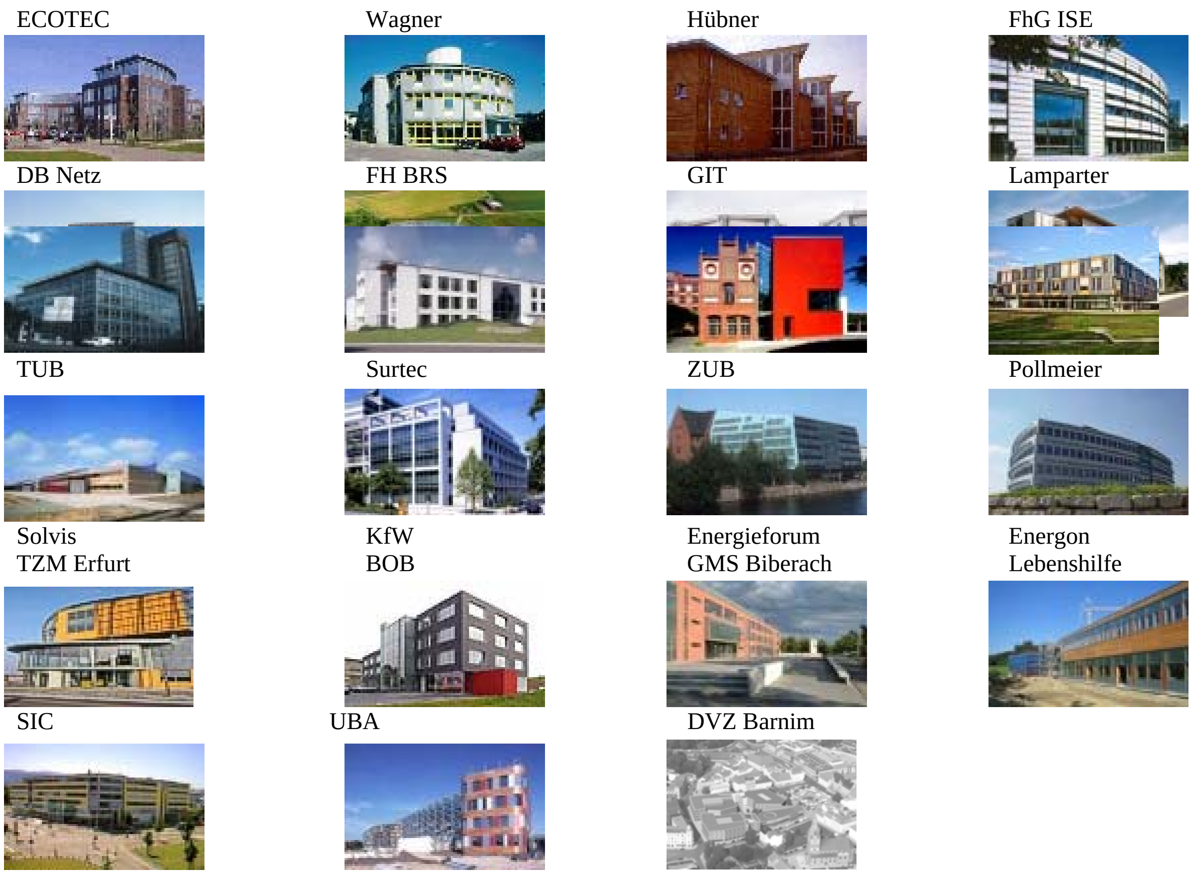


Fig.2 Demonstration buildings in the EnBau:Monitor program, www.enbau-monitor.de

Tab. 1 Overview of supply technologies for the EnBau-projects , Neumann (2005)

			Heat							Electricity			Cold			
Project	Net heated area [m²]	Mean U-value of building envelope [W/m²]	Gas- Boiler	Wood Boiler	District Heating	Combined Heat & Power	Heat Pump	Exhaust Air Heat Pump	Thermal Solar Plant	Grid	Combined Heat & Power	Photovoltaic	Compression Chiller	Absorption Chiller	Reversible Heat Pump	Passive Cooling
ECOTEC	2,941	0.54			■			■	■	■		■			■	
Wagner	1,948	0.21				■			■	■	■					■
Hübner	2,122	0.32			■				■	■						■
FhG ISE	13.150	0.43	■			■			■	■	■	■	■	■		■
DB Netz	5,974	0.57	■							■			■			■
Fh BRS	26,987	0.42	■			■				■	■	■				■
GIT	3,243	0.36	■					■		■		■				■
Lamparter	1,000	0.30	■						■	■		■				■
TUB	8,570	0.63			■					■			■			■
SurTec	4,423	0.27	■							■						■
ZUB	1,732	0.32			■					■						■
Pollmeier	3,510	0.29			■			■		■		■	■			■
Solvis	8,215	0.61	■			■		■	■	■	■	■				■
KfW	8,585	0.54	■	■					■	■			■			■
EnergieForum	20,693	0.69			■		■	■	■	■		■				■
Energon	6,911	-			■					■		■	■			■
TZM Erfurt	8,976	-			■		■		■	■		■			■	■
BOB	2,072	0.48					■			■						■
GMS Biberach	10,650	0.43		■			■			■						■
Lebenshilfe	4,623	0.38		■			■		■	■						■
UBA	32.384	-			■				■	■		■	■	■		■
SIC	13,833	0.74			■				■	■		■	■			■
DVZ Barnim	-	-					■			■					■	■

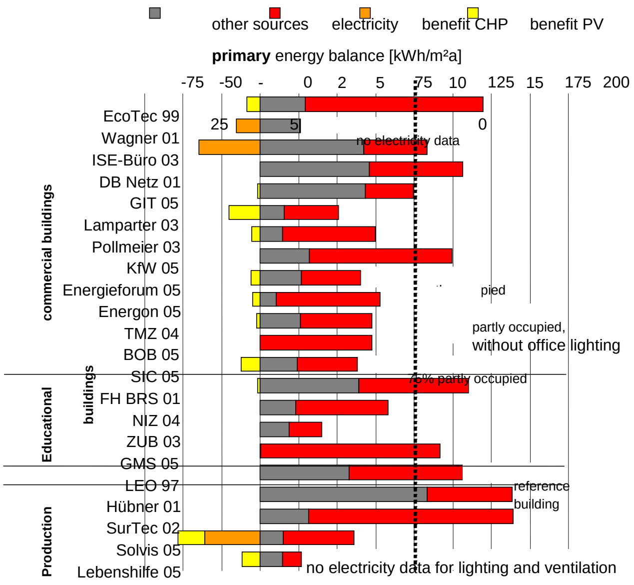


Fig.3 Measured primary energy coefficients

All data refer to the heated net floor area. The primary energy factors and electricity credits are based on German DIN 4701 (DIN 4710, 2001): Electricity 3, fossil fuels 1.1, biomass 0.2. To simplify the balancing procedure, photovoltaic electricity (PV) was evaluated with the same electricity credit as for combined heat and power plants (CHP). The consumption values refer to HVACL. The numbers following the project titles indicate the year for the measurements. The data source in each case was the university which was responsible for the measurement programme. In the case of the " ISE-Büro" building, a zone of 525 m^2 consisting purely of offices plus the adjoining access areas was selected from the Institute building with a total area of 14,000 m^2. Beside the Hübner building the so called "production " building have a mixed use as office and as workshop or pharmaceutical production.

Results of first 10 years

Since the start of the program in 1995 the results can be summarized like this (Voss et.al.(2006)):

- The prescribed primary-energy demand of 100 kWh/m²a is met by more than 60% of the buildings.
- The construction cost were not higher than for standard buildings without an energy efficient design.
- Simulation has been an essential tool in designing the energy efficient buildings, especially for passive cooling.
- In the mild central European climate, passive cooling is sufficient to provide a comfortable indoor climate, if building and systems are properly designed and coordinated. Due to the complex interactions between the outdoor climate, the building, the technical services and user behavior, the success of a passive cooling concept is jeopardised at many points of the planning, building and commissioning process. Any ''errors'' in planning or commissioning directly worsen the indoor working conditions. Due to the major economic significance of high-quality working conditions, the planning certainty and quality assurance must be further improved.
- Significant deviations of the energy consumption from the intended design occurred mainly due to faulty operation.
- The detailed monitoring was used for optimization of the building operation almost in all cases. In fact, many faults in the operation would have stayed undiscovered without the monitoring.
- The building automation system is a necessary part of the monitoring but often not sufficient.

Long Term Monitoring

Besides the detailed monitoring phase during the first two years of operation, a long-term energy monitoring was established in order to evaluate the sustainability of the innovative designs and systems.

During the past years the long-term-energy-monitoring was based on manual weekly meter-readings of the most important energy flows in the buildings. In deviation to the detailed monitoring phase, in most cases only the overall energy consumption was recorded, i.e. including the also electricity for appliances and all other consumers.

The data was evaluated in form of time-series plots and energy signature-plots which are displayed on the project web site (www.enbau-monitor.de). Furthermore the specific energy consumption was calculated and compared to the benchmarks of the programme. Despite the relatively simple evaluation this kind of monitoring already was appreciated as a valuable backup by the different project teams.

However, the manual approach that was purposely kept simple and low cost, showed the following drawbacks:

- Inspection of the data
  As the inspection of the data is a manual approach, fault detection or identification of energy saving potentials are highly depending on the analyst and on his personal inspection interval.
- Comparability of the projects
  As the choice of the meters to be included in the long term monitoring was done by the different project teams, it was not possible to apply a standardized analysis. Thus, the comparability of the results of the long term monitoring is limited.
- Continuity of data collection
  The intention of the long term monitoring was to collect data from the demonstration projects over a period that exceeds 2 years significantly. The manual approach of meter readings by the operation stuff of the building was found to be inadequate for this task.

ENHANCEMENT OF LONG-TERM MONITORING

In order to overcome these drawbacks Fraunhofer ISE defined an enhancement of the guidelines for the long term monitoring which comprises the following:

- Automated data collection
- Standardized scheme for representation of supply system and placement of meters.
- Automated analysis of data by means of inverse models

This paper will focus on the second and the third point.

<u>Standardized supply scheme</u>

In order to facilitate a prescription of the placement for the meters, a standardized graphical representation of the energy supply system was developed. Fig. shows an example. The scheme follows the subsequent rules:

- End-Energy
  All kinds of end energy are displayed as horizontal lines in the top of the scheme. Dependend on the supply system the following energy sources are to be considered: gas, oil, wood, biofuels, district heating / cooling, electricity.
- “Environmental” Energy and waste heat below the end-energy, sources of environmental energy and waste heat are shown also as horizontal lines (ground, ground water, ambient air, waste heat from the building, insolation).
- Useful energy
  Useful energy is displayed as horizontal lines in the lower part of the scheme. Generally space heating, DHW, cooling and electricity have to be considered. These categories could be further devided (additional lines), e.g. for different parts of the building or different qualities of useful energy (e.g. cold at 6 °C and 15°C).
- Generators
  All generator are displayed by a homogenous symbol in the center of the scheme. Energy (or more generally: input) supplied to the generators is displayed as vertical lines from the end-energy or environmental energy to the generator. Energy output from the generator is displayed as vertical line from the generator to the useful energy. If one generator supplies another one with energy, this is displayed by a horizontal line from the out put of one generator to the input of another. Following this scheme, generators that receive energy from another generator has to be placed “below” and “right” of this generator. Thus a distinct order of generators is created from the top to the bottom of the scheme: 1) Systems for extraction of energy from the environment (e.g. cooling towers, ground heat exchangers, ground water well), 2) Combined heat and power units, 3) heat generators and system which uses are extract waste heat, 4) cold generators.

Storages are neglected as long as their capacity does not exceed the amount of energy which is transferred to and from the storage during one evaluation interval. Using weeks or days as evaluation interval, storages can normally be omitted.

This scheme can be used for the prescription of the placement of meters as well as for the visualisation of energy and/or cost flows and display of COPs of the different generators. It has to be regarded that the scheme is rather an input/output scheme than a representation of the hydraulic coupling.

The rules for the placement of meters are quite easy: Every end-energy as well as every input and output of a generator is measured. If two meters in this scheme would measure the same energy flow, one could be omitted.

Inverse Modeling Tool

Furthermore the aim is to use this scheme as basis for an automated model based analysis of the building operation. Every element in the scheme (i.e. every end-energy, generator or useful, energy) can be represented by a model of arbitrary complexity. The models should be used for fault detection and optimization.

The first step towards this aim is the development of a tool which can identify the parameters of change-point linear inverse models.

Change-point linear models based on monthly or weekly meter readings are well known in the field of measurement and verification of energy saving measures. Kissock (2002), Haberl, Culp (2005).

In the Framework of Enbau:Monitor they should be used to analyze the consumption for heat (space heating and DHW), cooling and electricity and detectabnormal operation on the level of useful energy.

The chosen model resembles a 4 point model. The change-point is typically defined for the ambient temperature. shows examples for a simple model where the ambient temperature is the only independent variable.

A multiple-linear model is chosen for the EnBau program. For one of the independent variables a change-point is defined, which divides the model space in two parts with different Parameters. The general form of the model is as follows:

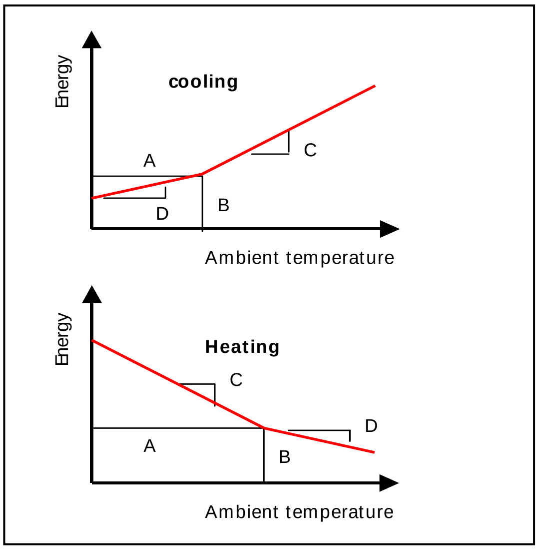


Fig. 2 examples for simple change-point linear models with four parameters

$$Y = b_0 + LTCP\,(b_1 X_{cp} + b_2 X_2 + ... + b_m X_m) + GTCP\,(b_{m+1} X_{cp} + b_{m+2} X_2 + ... + b_{2m} X_m) \qquad (1)$$

Where:

Y dependent variable (consumption for heat, cold, electricity)

X_{cp} variable for which a change-point is defined

$b_0 - b_m$ Parameters of the model

m number of independent variables

The functions LTCP (less than change-point) and GTCP (greater than change-point) are defined as follows:

LTCP equals 1 if X_{cp} is less than the change-point and zero otherwise

GTCP equals 1 if X_{cp} is greater than the change-point and zero otherwise

In order to identify the parameters of the model, in a first step the location of the change point of the variable for which a change-point was defined must be determined. This is done by a two level grid search algorithm as described in Kissock (2003).

In the first step of this approach the minimum and the maximum of X_{cp} are identified and the interval is divided in 20 increments dx. Then the minimum value for X_{cp} is used as change-point for regression of the model in order to find all b_n. The value of the change-point is incremented by dx and the regression is repeated. The CP which delivers the best fit is used for a second iteration with a finer grid of width 2 dx.

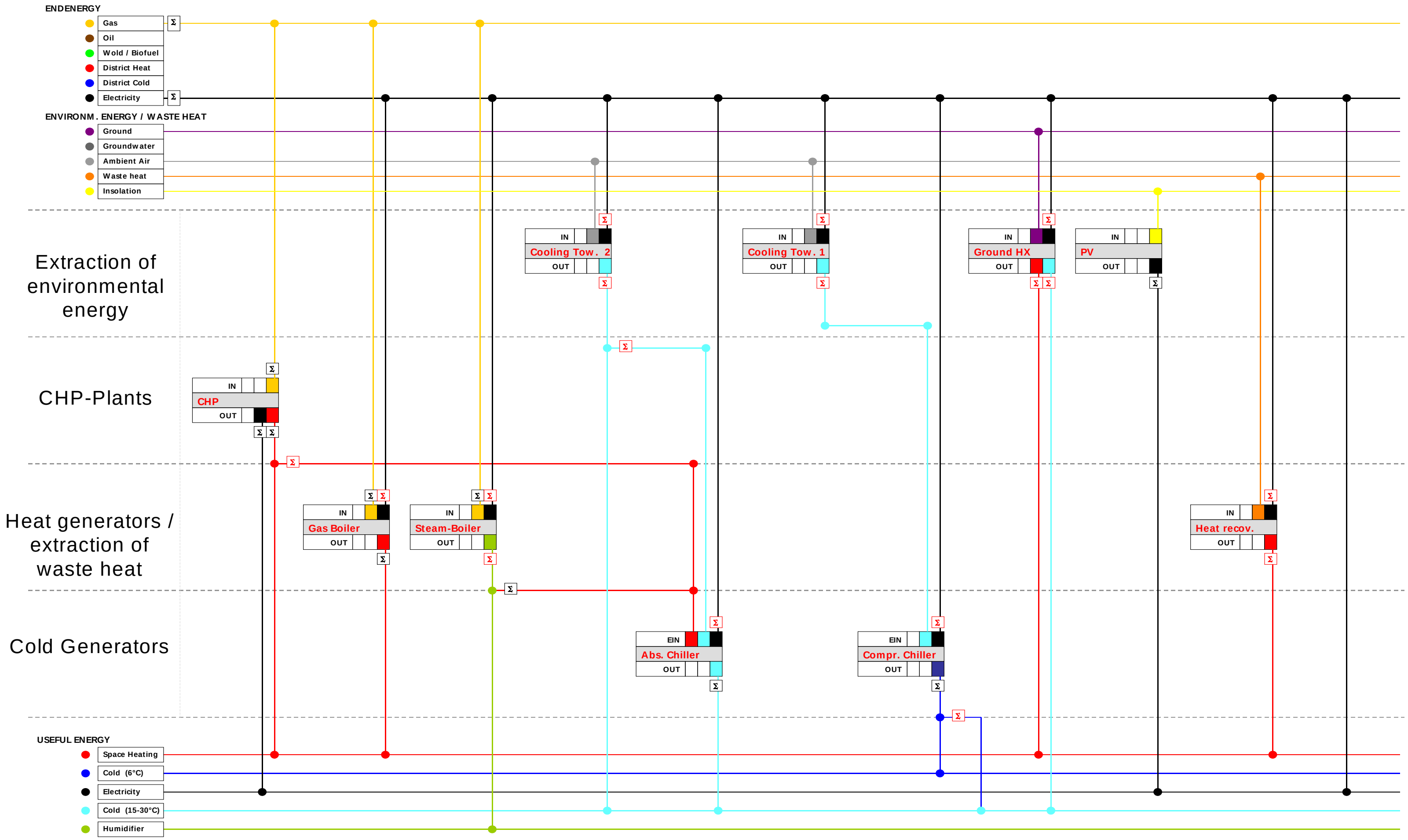


Fig. 5 Example of energy supply scheme (supply system of Fraunhofer ISE).

The type and number of generators is dependent on the system under consideration. The structure of the scheme itself is fixed. The supply system consists of a CHP-Plant which supplies the heating system and an absorption chiller. A steam boiler is also used for supply of the absorption chiller during peak load and for supply of steam for humidification. Besides the absorption chiller, there is a compression chiller. Every chiller is connected to a cooling tower. One of these is also used for direct cooling during winter. The gas boiler only serves the heating system. Furthermore there is a ground heat exchanger for pre-heating and pre-cooling of ambient air, a pv-system and a heat recovery based on an air to water heat exchanger.

As measure of the model fit the coefficient of variance of the root mean square error (CVRMSE) with respect to the median of the dependent variable is used:

$$CVRMSE = \left[\sum (y_i - \hat{y}_i)^2 / (n-p)\right]^{0.5} / y_{MED} \quad (2)$$

where:

y_i dependent variable

$\hat{y}$ regression model's predicted value of y

n number of data points

p number of parameters in the model

y_{MED} median of the dependent variable

The regression itself is a robust linear regression using the Huber M-estimator, which is solved in an iterative re-weighted least square process (IWLS), Huber (1981). For this task the statistical software R (R (2006)) was used.

In order to automate the processing of the data a tool based on the Python language was developed which can handle the following tasks:

- identify change-point according to the method described above
- fit the model by a robust regression
- identify outliers
- output of model parameters
- graphical output in form of energy signatures

Example TUB

The tool was tested with data from the long term monitoring of several demonstration buildings. As an example the results for the IT-center of the Technical University of Braunschweig (TUB) are presented here:

The administrative building has about 10.000 m2 of heated floor area and comprises mainly offices. Space heating of the well insulated building is supplied by district heating and heat recovery from a compression chiller. chillers are used for cooling of IT-areas. The offices are cooled passive by night-ventilation. .

The available data are weekly readings of the following meters and variables:

- heat consumption (district heating + heat recovery)

Fig. shows a picture of the building.

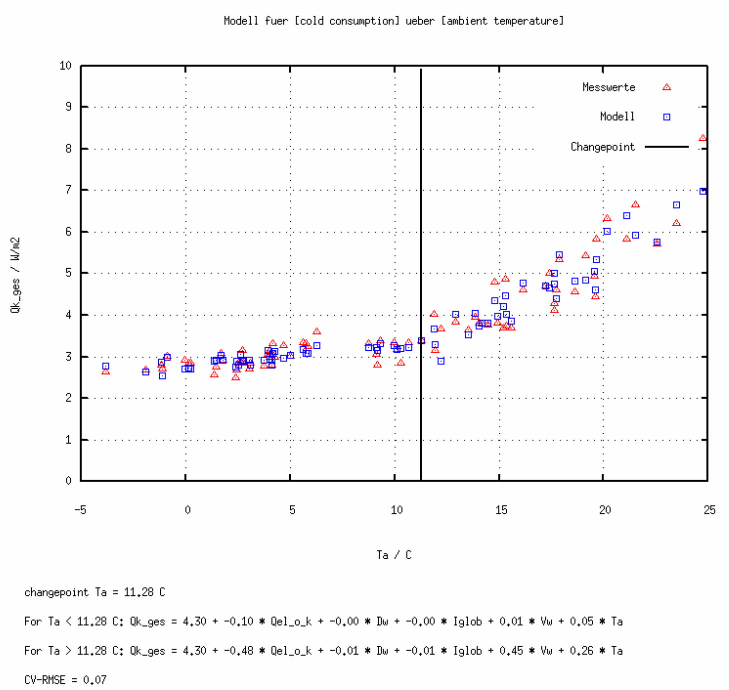
The available data are weekly readings of the following meters and variables:

- heat consumption (district heating + heat recovery)

Fig. 6 IT-Center of the Technical University of Braunschweig

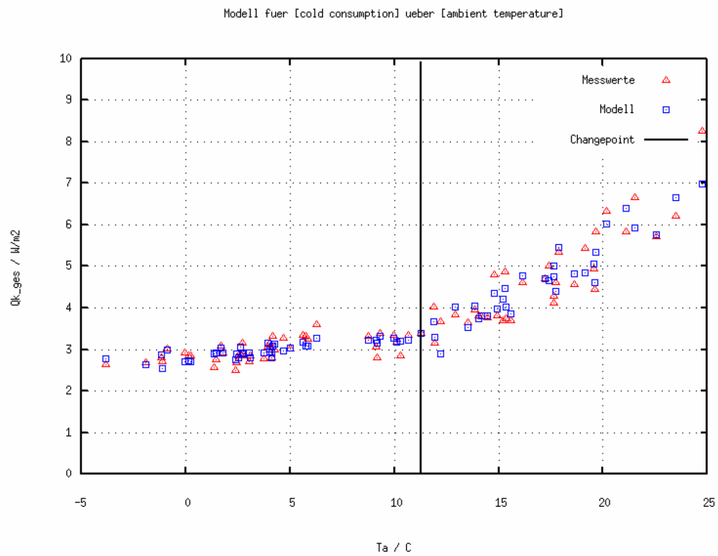
- cold consumption
- overall electricity consumption
- electricity consumption without compression chiller
- Ambient temperature
- Insolation
- Windspeed
- Wind direction

The energy values are converted to weekly average values of specific load with respect to the heated floor area.


Modell fuer [cold consumption] ueber [ambient temperature]
Messwerte
Modell
Changepoint
Qk_ges / W/m2
Ta / C
0
1
2
3
4
5
6
7
8
9
10
-5
0
5
10
15
20
25
changepoint Ta = 11.28 C
For Ta < 11.28 C: Qk_ges = 4.30 + -0.10 * Qel_o_k + -0.00 * Dw + -0.00 * Iglob + 0.01 * Vw + 0.05 * Ta
For Ta > 11.28 C: Qk_ges = 4.30 + -0.48 * Qel_o_k + -0.01 * Dw + -0.01 * Iglob + 0.45 * Vw + 0.26 * Ta
CV-RMSE = 0.07

■ Fig. and

■ Fig. shows the output of the tool for the TUB.



changepoint Ta = 11.28 C

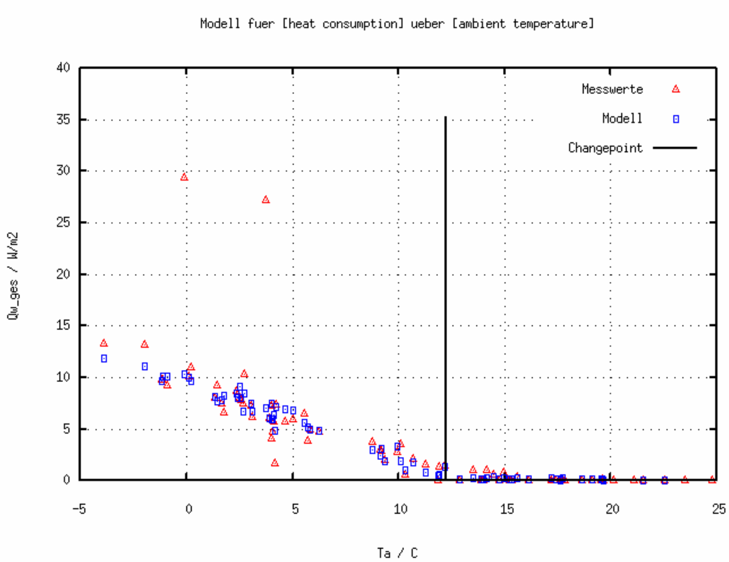
For Ta < 11.28 C: Qk_ges = 4.30 + -0.10 * Qel_o_k + -0.00 * Dw + -0.00 * Iglob + 0.01 * Vw + 0.05 * Ta

For Ta > 11.28 C: Qk_ges = 4.30 + -0.48 * Qel_o_k + -0.01 * Dw + -0.01 * Iglob + 0.45 * Vw + 0.26 * Ta

CV-RMSE = 0.07

Fig. 7 Output of the tool for the model of heat consumption of TUB.

The graphical output displays the energy signature in form of weekly average values for specific heating load. As change-point variable the ambient temperature is defined. Below the graph the model with the respective parameters for the cases below and above the change-point are shown. The change-point is automatically located at 12.24°C. A CVRSME of 0.15 is reached. As can be seen from the plot, outliers (that have been inserted manually) have no major influence on the fit. The outliers are detected by inspecting the weights of the residuals.



changepoint Ta = 12.24 C

For Ta < 12.24 C: Qw_ges = -0.79 + 1.50 * Qel_o_k + -0.00 * Dw + -0.00 * Iglob + 0.32 * Vw + -0.54 * Ta

For Ta > 12.24 C: Qw_ges = -0.79 + 0.21 * Qel_o_k + 0.00 * Dw + -0.00 * Iglob + -0.16 * Vw + -0.00 * Ta

CV-RMSE = 0.15

Fig.8 Output for the tool of the cold consumption of TUB

The output is similar to the heat consumption. For the cold consumption model a CV-RSME of 0,07 is reached.

Testing the tool with different buildings of the EnBau program revealed that the method can be used for automated model fitting. A CVRSME of about 0.10 can be reached for the models of heat and cold consumption. Extreme outliers are detected by automatically inspecting the weights of the IWLS process.

CONCLUSION & OUTLOOK

A scheme has been developed for the graphical representation of supply systems for long-term monitoring of the buildings in the German EnBau program. The scheme should be used for visualization of energy and/or cost flows and COPs of generators.

Furthermore the scheme should be used as basis for a model based analysis of the building performance. The first step towards this aim is the development of a tool which can identify the parameters of change-point linear inverse models for the energy flows on the useful energy level.

For this tool a robust regression method has been applied and tested for the heat and cold consumption of several buildings in the EnBau program. The method provides a simple, robust and automated way to fit the models and to detect outliers.

The further development of the tool will focus on defining models for the other elements in the scheme for analysis of the building or system operation.

ACKNOWLEDGEMENTS

[1] The authors sincerely thank the team members of the demonstration projects for their valuable co-operation and specially the provision of monitoring data. The accompanying research project was funded by the German Federal Ministry for Economics and Technology under reference 033O.

[2] REFERENCES

[3] DIN 4701, part 10 (2001): Energetische Bewertung heiz- und raumlufttechnischer Anlagen, German Institute of Standardization, Berlin, Germany

[4] Neumann, C. (2005) Langzeitmonitoring der Demonstrationsgebäude im Rahmen des Forschungs-programms EnBau:MONITOR, intermediate report

[5] Voss, K., Löhnert, G., Herkel, S., Wagner A., Wambsganß M. (2005): Bürogebäude mit Zukunft, second Ed., Solarpraxis-Verlag, Berlin, Germany, www.solarpraxis.de

[6] Kissock, Haberl, Claridge (2002): Development of a toolkit for calculating linear, change-point-linear and multiple-linear inverse building ernergy analysis models, ASHRAE research project 1050-RP, final report, 2002

[7] Kissock, Haberl, Claridge (2003): Inverse Modeling Toolkit: Numerical Algorithms, ASHREA transactions, Volume 109, Part 2

[8] Haberl (2004), Literature review on uncertainties of analysis methods (inverse modelling toolkit), report to the Texas commission on environmental Quality, Texas A&M University, 2004

[9] Haberl, Culp (2005): Review of methods for measuring an verifying savings from energy conservation retrofits to existing buildings,

[10] Olive (2005): Applied robust statistics, Southern Illinois University, Department of Mathematics, 2005

[11] Huber (1981): robust statistics, Wiley

[12] R (2006): A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2006, www.r-project.org