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Evaluation Tool and Retrofit Matrix for Office Buildings

Gregor Hillebrand, Gesine Arends, Rita Streblow
Reinhard Madlener, Dirk Müller

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1 Executive summary

This report describes the methodology and calculation methods of two tools developed to evaluate the energy efficiency potential of buildings.

The first tool provides a detailed analysis of retrofit options for the building envelope and its supply system. Different simplification measures accelerate the data acquisition process for building stock owners and offer data handling in line with the existing building information. Office building structures can be prompted to design typical building constructions. An automated calculation of the most common refurbishment measures allows a comparison of up to 64 combinations of measures and the illustration of energy and $CO_2$ savings as well as an economic evaluation. The economic evaluation takes into account the time value of money, the uncertainty of future energy prices, and the possibility of delaying an investment. To this end, a net present value analysis has been implemented which allows to compare retrofit alternatives with different initial and future cash flows both for buildings used by the investor and for rented buildings. Energy price scenarios as well as a Monte Carlo simulation account for the uncertainty in energy price trends. Furthermore, a real options analysis may be performed which determines the optimal investment time. Standard values and guidelines help the user with selecting the parameters for the economic analysis.

The second tool enables to store relevant operation data out of building management systems to the universal data file format HDF 5. With the help of a graphical user interface the tool prints and evaluates the building’s energy performance. Several data mining routines are implemented to assess the data quality and completeness. The yearly heat and electricity consumption, incorrect or improvable control settings, comfort evaluations as well as the heat generation and distribution can be visualized and evaluated. Possible energy saving potentials through optimizations are calculated and illustrated.

The evaluation tools developed have been applied to two buildings within RWTH Aachen University. Results show high energy-saving potentials both for the optimization of the building operation and optimal retrofit paths. However, none of the energy-saving paths is economically advisable since energy costs saved in the sample buildings supplied with district heat are too low to offset the investment costs. Economic benefit can only be generated when switching to a gas boiler in the sample cases. These results point to the importance of a more detailed analysis of both relative and absolute energy price trends as well as underline the capabilities of the tool in selecting combinations of retrofit measures with both energy-saving and economic benefits.
2 Introduction

As a consequence of the Kyoto Protocol and the required reduction in CO$_2$ emissions, huge efforts must be made in the future to conserve high quality energy resources. Besides the discussion about the type of energy production preferred, the efficient use of energy in all economic areas is key (see Nitsch et al. [2010]). This is also reflected in the climate policy plans of the European Union. By 2020, a reduction of the greenhouse gases emissions of around 20%, a rise in the renewable energy share to 20% as well as an increase in the energy efficiency of 20% is planned (see Directive 2009/28/EC [2009]). Especially in the building stock there is still considerable energy-saving potential. With a portion of 37% in the German CO$_2$ emissions (see Diefenbach [2008]), and a similar portion in the primary and final energy consumption (see Hirschberg [2008]), it becomes clear that the energy efficiency of buildings is highly relevant. The fact that more than 80% of all buildings are older than 25 years and were not retrofitted to a large part yet underlines this claim (Mauch and Schönhoff [2008]). But also regarding buildings of younger construction dates considerable efficiency increases are possible. Research has shown that up to 20% energy savings are feasible only by management changes (BINE [2010]). Most studies focus on the heat energy consumption of residential buildings. This study focuses on office buildings because these buildings need approximately 10% of the final energy used in Germany. As economic efficiency is probably the most important decision criterion besides actual energy and CO$_2$ savings, the tool also comprises an evaluation of the financial consequences of each retrofit alternative.

2.1 Goals of the project

The main goal of the project was to organize and guide the retrofit process for private and public office stock holders. Therefore, two simple system-independent software tools were developed to enhance building energy efficiency.

First, the project includes a detailed analysis of different retrofit options for the building envelope and its supply system. A matrix of retrofit measures was derived to indicate possible pathways enhancing the building's energy efficiency. The matrix includes all measures, potential energy and CO$_2$ savings, cost estimates and additional information, including special user requirements and internal building ratings.

In addition to the above, the tool will allow a reliable estimate of the economic impact of each investment alternative. To this end, not only the investment itself, but future payments arising
from each retrofit measure are taken into account. The most important of these are payments for energy or rental income (depending on whether the investor is the user or the landlord of the building), financing, and operation and maintenance. Investments with different initial and future payments will be made comparable by employing a dynamic evaluation method, i.e. considering the time value of money, where prior art mostly uses static methods. Furthermore, the problem of uncertainty regarding energy price development, which is the most influential parameter, will be addressed in two ways: (1) The simultaneous evaluation of different scenarios and (2) Monte Carlo simulation to determine possible outcomes based on historical price developments. Based on the latter, the user may then choose to analyze the value of waiting with the investment. A further element of the projected tool will be a set of standard values as well as guidelines for choosing the values for the various parameters governing the outcome of the investment evaluation. This allows the user to both tailor the analysis to each specific case and to react to changing boundary conditions.

Second, the project provides an interface for the most common data file format to convert all energy and building stock data to the universal data file format HDF 5. Based on this file format an evaluation tool programmed in the open script language Python prints and evaluates the building energy performance. Advanced data mining routines give a fast check on basic energy-saving potentials.

Both tools provide guidance for building stock owners to find the best option for a budget-constrained retrofit process. These are tested with the data from two buildings of RWTH Aachen University.

2.2 State-of-the-art

An overview of the most important EU directives, laws, regulations and standards concerning energy efficiency is given in Figure 2.1. For the energetic evaluation of buildings the European Union has created the Directive EPBD [2010]. This EU Directive was implemented at the national level in Germany with a set of preliminary standards defined in DIN V 18599 (“Energy efficiency of buildings - Calculation of the energy needs, delivered energy and primary energy for heating, cooling, ventilation, domestic hot water and lighting”). This standard allows the calculation of the total energy efficiency and also considers energetic refurbishment potentials. Since the introduction of the regulation EnEV [2007] (energy saving ordinance) the calculation methodology is prescribed after this standard and was also expanded on residential buildings with the EnEV [2009] ordinance. However, the technical norm DIN V 18599 describes a far-reaching and complicated approach to assess the building’s envelope and facility management technology, which leads to high temporal and monetary expenditures. Several studies examined the time needed for the so-called "requirement certificate", which evaluates the energy demand of a building and shows retrofit possibilities. It became apparent that the average time exposure ranges from 78 (Erhorn et al. [2005]) and
Introduction

80 hours (Lichtmeß [2010]) up to 240 hours (Römmling [2008]), depending on the building size. Besides the vast amount of time it was shown that often the required data, e.g. on construction materials and surfaces, were either not available or did not exist.

Based on these outcomes, future energy evaluation or retrofit tools need to focus on simplification measures that can help to accelerate the assessment process and to adapt the analysis to the available data stock. The realization of this challenge with the integration of the latest research in this field will be outlined in chapter 3.1 below.

Various decision aid tools were developed to support and advise building stock owners with respect to retrofitting options. An early example is the TOBUS software (Flourentzou et al. [2002]), which implements the results of a European research project on building diagnosis and selecting upgrading solutions (Caccavelli and Gugerli [2002]). Jakob et al. [2006] perform a comprehensive evaluation of costs and benefits of energy efficiency measures in the Swiss service sector, based on reference building types and building simulation. They deplore the lack of “computer-based tools which identify the relevant cost-benefit-relations and allow optimization in the first place” (Jakob et al. [2006], p.235). Similarly, a review of tools for the residential sector performed by Mills [2004] finds that only few tools offer substantial decision-support content.

Figure 2.1: EU directives, laws, regulations and standards concerning the energy efficiency.
Introduction

One such methodological attempt was made in a Greek study by Doukas et al. [2009], who rely on building energy management system data for their decision support model. More recently, a screening methodology for implementing cost-effective energy retrofit measures in Canadian office buildings was presented in Chidiac et al. [2011]. Like the study by Jakob et al. [2006], it uses building archetypes and energy simulation software. The problem of multiple objectives influencing retrofit decisions was addressed by Diakaki et al. [2008], whose model allows the user to evaluate alternatives according to criteria influenced by user preferences.

In addition, while some of the above-mentioned models offer a fairly complex treatment of technical and energy aspects, economic evaluations are considerably less comprehensive. Flourentzou et al. [2002] as well as Diakaki et al. [2008] use investment cost only, thus neglecting future cash flows. This is unsuitable for comparing retrofit investment alternatives, since these generate costs and benefits, such as maintenance and energy costs savings, far into the future. A static approach, such as the computation of the payback period based on first-year costs (Meyer [2010]), disregards both cost changes and the different value of present and future payments. Even if the time value of money is accounted for by using net present values (Doukas et al. [2009]) or a discounted payback period (Chidiac et al. [2011]), relevant cost factors, such as maintenance costs, are neglected (Chidiac et al. [2011]). Furthermore, all of these tools employ fixed assumptions for energy prices, ignoring the uncertainty inherent in this most relevant economic factor. Historical data for energy prices show fluctuations and trend reversals, indicating that a linear development is merely a rough approximation (Milanowski [2011]). Verbruggen et al. [2011], in a recent paper, argue for a dynamic model of decision-making in energy retrofit investments. Since many retrofit decisions are highly irrevocable and/or preclude later changes, in their opinion a “wait and learn” approach with sequential decisions may give better advice.

Thus, an economic evaluation tool accounting for the relevant cost factors, inclusion of the time value of money and the uncertainty in energy price trends, is still lacking, and a sequential decision-making framework would be a valuable advancement.

In the last couple of years the continuous commissioning of the building operation moved into the focus of several studies. In national and transnational research projects some tools and methods were developed which allow to store and evaluate the measured data and ensure an optimal building operation. Nevertheless, further developments and improvements are necessary and reasonable. In BINE [2010], the "Energie-Navigator" is presented, which follows a holistic approach and links planning, construction and controlling on an Internet-based working platform. Details of the electric equipment, instrumentation and control engineering can be deposited at the server and compared with the actually measured data. In Eicker et al. [2009], an approach for online monitoring operations is introduced where optimized control strategies are supposed to be ensured through continual online simulations. Both approaches presuppose detailed information on the building and are primarily intended for new buildings. Other tools and examinations, like Jensch et al. [2008] and Jacob and Neumann [2010], follow a different path and attach more impor-
tance to existing buildings. In both tools, a graphic user interface in combination with an offline data storage was used to store the data of own measurements, or such retrieved from building management systems, for evaluation. These evaluations are mainly focused on simple set point comparisons and operating time visualizations. The need for a more technical assessment and the comparison of measured data with benchmarks and standard values are not considered adequately in the mentioned sources. These areas require closer examinations which are treated in chapter 3.3 below. The evaluation tool described in this report covers primarily the rapid detection of incorrect and suboptimal settings and neglects long-term continuous commissioning.

2.3 Positioning of the project within the E.ON ERC strategy

The project fits into the overall strategy of the E.ON Energy Research Center regarding the research in the field of energy concepts for buildings and communities. It relieves the complex data recording and analysis and enables a fast technological, economic and ecological evaluation and optimization. The developed tools are used in various further research projects at the E.ON Energy Research Center.

Within the framework of the project "Quartierskonzept energieeffizientes Rinsheim" (Grant Nos.: 0327400G and 03ET1105A) an analysis of different refurbishment possibilities has been performed with the help of detailed simulations. An extensive capturing of measurement data was carried out and all monitored data have been stored in and assessed with the developed evaluation tool.

In the interdisciplinary research project "EASE - Energetische Aufrüstung und Stadtentwicklung" (Leibniz Gemeinschaft) investment decisions adopted by public or private property owners are examined, regarding retrofit options as well as impacts of possible state interventions promoting an energy-efficient urban redevelopment. For the structural, technical and economic evaluation of the energetic refurbishment of buildings the retrofit tool is currently used and under further development.

Furthermore, a link from the retrofit tool to the simulation environment Modelica was developed and is used in two other projects concerning the energy efficiency of urban districts. The monitoring of energy systems that provide heating and cooling energy at the neighborhood level as well as electric power is an appropriate approach to identify superior connections between buildings, district-heating networks and the system technology. "2DSM - Dual Demand Side Management" (E.ON ERC gGmbH) and "EnEff: Campus" (Grant No.: 03ET1004A) are two projects that examine these subjects. For a fast data recording of existing buildings, and the representation of the building layout in the simulation environment Modelica, the retrofit tool offers an important and easy-to-handle program.
3 Results

The project was divided into 5 work packages, which are described in the following 5 sections. Section 3.1 comprises the development and design of a retrofit matrix for a detailed evaluation of different retrofit options. Potential energy and CO₂ savings as well as cost estimates are considered. Based on the retrofit matrix, Section 3.2 describes an economic evaluation method to find a cost-optimized retrofit path. An automated evaluation procedure is provided, which defines a best-practice retrofit assembly. The second evaluation tool is addressed in chapter 3.3. The storage of measured data out of a building management system as well as the evaluation of these stored datasets is explained. Chapter 3.4 describes the available building and measurement data of two buildings of RWTH Aachen University, which were aggregated for further evaluations. In chapter 3.5 the developed methods and tools are applied to evaluate the two buildings described in chapter 3.4.
Results

3.1 Development and design of a retrofit matrix

The overall objective of the retrofit matrix is the energetic analysis of existing non-residential buildings. To do that, energetic qualities and weaknesses of the building envelope and the system technology need to be assessed and identified. For that reason, the energy demand of the current building state and refurbished states need to be determined. To do that, a software program was developed which is explained in the following.

The functional principle of the program realization explained in this chapter is illustrated in Figure 3.1. It shows that the program consists of two parts. The first part is the program core which is not visually accessible and includes the computation core with the implemented algorithms and several default values. It is described in more detail in section 3.1.1. The second part represents the user level which enables inputs and selections as well as visualizations of the calculated results (see section 3.5.2).

![Figure 3.1: Program structure of the retrofit tool.](image)

3.1.1 Program core

To evaluate the energetic performance of a building, the energy demand needs to be calculated. The energy demand in this context is the calculated annual energy consumption for heating, cooling, ventilation, lighting and domestic hot water, using standardized boundary conditions. Figure 3.2 schematically shows the calculation methodology used to ascertain the sufficient energy demand for a building. Energy losses through ventilation and transmission as well as energy profits through solar irradiation and waste heat of persons or technical equipment are balanced. The energy for conditioning the building on a specific, standardized level under consideration of these profits and losses, as well as the system technology, are referred to as the energy demand for a building.
To perform an energetic balance, detailed information about the building must be available. Data about the size and the building shell characteristics, details about the functional areas, and information on the installed technical equipment are needed. Furthermore, a calculation methodology is necessary which merges the building data and performs an energetic balance. Once the actual energetic state of the building is determined, building details can be varied to calculate refurbishment potentials. For instance, an insulation layer can be added to the construction elements of an outer wall to reduce the transmission losses. Therefore, refurbishment costs for the economic evaluation are essential.

In practice, the parameters for the energy balance need to be extracted out of floor plans, views and detailed drawings. As highlighted in chapter 2.2 this procedure is very time-consuming and precise information for existing buildings is commonly not available. Therefore, a method will be introduced in the following which focuses on two possibilities for a fast refurbishment examination:

- Simplification measures for fast data acquisition.
• Data stock adaption due to incomplete building information.

The starting point for this method is not the complete, detailed building data, but standardized building types. In a first step, and with a minimal set of data, enveloping surface areas, functional areas etc. are estimated. The characteristic thermal behavior of this building type can be shown and typical, common refurbishment possibilities can be calculated. If more detailed information is available, it can be used to calculate the building's characteristics in a more accurate way. Figure 3.3 shows the procedure schematically. On the basis of very limited data, first estimations can be made and a small amount of time is needed. Depending on the time and available data, a smooth transition according to the depth of detail of the data acquired can be made.

The following discussion outlines the different levels of detail which are implemented in the program and explains the methodology and the scientific foundation in terms of five sub-criteria:

• Computation core
• Facility technology
• Zoning and enveloping surfaces
• Construction and materials
• Costs

Computation core

The computation core is the basis for the calculation of the net final and net primary energy demand for heating, cooling, ventilation, lighting, and domestic hot water. As a result, the building structure, the utilization and the system technology are evaluated with the help of an energy balance and with regard to their interactions. In this section the computation core implemented and used to calculate the net energy demand is presented and described.

Looking at the typically used calculation methods for the energy demand of buildings in Germany, two possibilities are common: on the one hand, the German technical standard DIN V 4108-6 [2003] gives a method for residential buildings with a monthly or yearly balancing method (the balancing period is either one month or the whole year). On the other hand, the technical standard DIN V 18599 [2005] prescribes a monthly balance for residential and non-residential buildings. In both methods the focus of the calculations is the yearly energy demand to evaluate the building’s energetic quality.

Besides the calculation of the yearly energy demand, it could also be necessary to compare the calculated energy demand with the real energy consumption, because these often differ from each other. Standard boundary conditions like weather or the behavior of the user are used for the calculation of the energy demand and often vary from the real weather and person's behavior. Recalling
the energetic evaluation of buildings and refurbishment possibilities, this difference between measured and calculated values may influence the results. For this reason, a demand-consumption-match is necessary where monthly or yearly values can be too imprecise and lead to wrong assumptions. Therefore, higher resolutions in the calculation method for the energy demand and the measurement of energy consumption values may be helpful.

Hence the calculation method should enable a more detailed approach. It should allow the computation of yearly and monthly energy needs as well as the computation of daily or hourly values. Therefore, a wide variety of different calculation techniques exists within the building branch which will not, however, be explained in detail in this report. Taking into account the computation speed on the one hand and the accuracy on the other hand, we implemented the so-called "two-capacity model" ("2-c-model") as our main computation core.

The "2-c-model" is a thermodynamic model in which an equivalent model for each wall component is determined with the help of a matrix calculation. Following this approach, other solution methods to calculate the temporal and local temperature distribution in walls, like Fourier or Laplace transformation, are no longer necessary. A further simplification is the reduction to internal walls and outside surfaces. This results in a "two-capacity model", where the outside and inside walls are both represented as one capacity.

![Figure 3.4: Validation with a test example from VDI 6007-1 [2012]. Test example 5, day 60.](image)

This thermodynamic model is described in detail in the standard VDI 6007-1 [2012] and allows a validation of the calculation method with the aid of 12 test examples. It is also mentioned in the German technical standard for "Requirements on methods of calculation to thermal and energy simulation of buildings and plants" (VDI 6020-1 [2001]) and is considered to be sufficiently adequate for building simulations. Since March 2012 it is also a component unit of the German standard VDI 2078 [2012] which is used for the calculation of the cooling load and indoor temperatures of rooms and buildings. It describes a method to calculate the heating and cooling load, and
meets the following conditions as described in VDI 6007-1 [2012]:

- The thermal response of the building components is simulated with sufficient precision, taking into account the actual wall structure.
- The radiant-convective heat exchange between the building components forming the room is simulated with sufficient precision.
- The heat exchange between exterior building components and the environment is simulated with sufficient precision.
- A correct heat balance for the room is established, taking into account all radiant and convective heat sources and sinks.

Figure 3.5: Validation with a second calculation method. Comparison with monthly values of the German standard DIN V 4108-6.

In order to verify the implemented algorithms, the calculation methods were validated with the 12 test examples included in VDI 6007-1 [2012]. One example of the comparison between the given and simulated temperature profiles is shown in Figure 3.4. They match very well with the default values given in the guidelines. In Figure 3.5 the outcomes of a monthly balance calculation (DIN V 4108-6 [2003]), which is normally used to calculate the energy demand of residential buildings, is compared with the monthly sums of the implemented computation and shows very similar results. Figure 3.5 shows the adjustment of measured and simulated data. The course of the heating power of a university building is compared with the simulated hourly values. A comparable daily trend is clearly visible and thereby a sufficient precision of representing reality is possible.

Facility technology

Final energy demand is the amount of energy that includes the net energy demand calculated with the computation core described in the last paragraph, plus the losses of the facility management
technology. It can be calculated on two levels of detail within the evaluation tool. One way is the use of the real system technology, the other way is the estimation of typically used settings and equipment.

For the implementation of the facility management technology and to calculate the final energy demand in this tool, the algorithms from the German standard DIN V 18599 [2005] were used. These algorithms follow the demand development method described in Figure 3.8. Based on the net energy demand of the room, the supply losses are added. With this energy demand further losses from the distribution, storage and generation can be calculated step by step. If proven information is available, this can be used to describe the system technology more accurately.

Determining and evaluating the existing system technology can be difficult if revision plans do not exist or if not all rooms of a building can be examined. To estimate the existing air conditioning, type of heat generation etc., the German "Bundesministerium für Verkehr-, Bau- und Stadtenwicklung" (BMVBS) released several online publications which cover this subject. The content of BMVBS [2009] and BMVBS [2011] is used in the retrofit tool in order to give a first estimation of the expectable system technology. For several building types, like offices or schools, characteristics and parameters for the processing sections delivery, distribution, storage and generation are given. As an example, a typical supply temperature for the distribution in office buildings of 70 °C is assumed.

Zoning and enveloping surfaces

Figures 3.9 and 3.10 show the different levels of detail for the zoning and the enveloping surfaces. For both situations, varying levels of detail can be used. In the following, the purpose and the typical procedure of zoning in non-residential buildings are described and the necessity for sim-
The classification of zones in non-residential buildings forms the basis for later calculations. A zone includes all rooms of a building with consistent user requirements. Therefore, areas of the same utilization and conditioning are summarized in usage profiles defined in the standard DIN V 18599 [2005] (like offices, toilets, etc.). For each defined zone a list of parameters must be determined and documented. This list includes the zones base area, length and width, height of the storey, volume, and the enveloping surface. If the complexity and extension of buildings increases, the zoning and data acquisition takes into account more and more time and builds the main possibility of time conservation. In Lichtmeß [2010] the time to calculate the energy demand for non-residential buildings according to the standard DIN V 18599 [2005] was measured. The proportion of time for zoning and the data acquisition of the enveloping surfaces amounted to 56
Because of that, many simplification methods for zoning were examined and discussed in this field in the last couple of years. Generally, these methods can be divided into two main classes and are described in more detail in BMVBS [2010b]:

- Reduction of the balancing areas of the building.
- Simplified allocation of the enveloping surface.

In view of the possibility to change the level of precision, as described in chapter 3.1, the method of a **zone-area-weighted allocation of the enveloping surfaces** has been found the most promising one (BMVBS [2010b]). It is examined in the dissertation "Vereinfachungen für die energetische Bewertung von Gebäuden" of Markus Lichtmeß (Lichtmeß [2010]) and consists of two basic hypotheses:

- There is a sufficiently precise correlation between the thermal enveloping surface and the zoning area.
• An automated distribution of the enveloping surface to the zones causes a negligible mistake in the calculated power consumption.

In the course of his investigations, Lichtmeß showed that the errors in calculating the energy needs with these simplifications are minor and that the results are sufficiently adequate for an energy evaluation. In comparison with a more detailed analysis, an average deviation of 6% of the primary energy needs occurred. Using an extended method with a simple correction factor, the mean error could be reduced to 1%. Using the preliminary findings of Lichtmeß, an office-specific method was developed, considering typical office structures and historical design methods. The method of a zone-area-weighted allocation of the enveloping surface with a simple correction factor and the combination with an office-specific method is described in the following.

Figure 3.11: Schematic representation of the simplification method of Lichtmeß [2010]

The simplifications described in Lichtmeß [2010] work on two levels, which are shown in Figure 3.11. Level one is the level of the building. The enveloping surfaces of the entire building are not allocated to the zones in the first step. Values for the orientation, the construction or the surface area are acquired just like for a one-zone building. Level two is the level of zones. As already described in the beginning of this chapter, areas with the same utilization and conditioning are summarized in usage profiles. The difference is that, at this step, no enveloping surfaces are allocated to the zones. The advantage of this method is that for additional energy balances the enveloping surface and the zones can be edited separately and the time for the data acquisition can be reduced.

In a further step, the building and the zone level are combined. The enveloping surfaces $A_{i,all}$ are defined at the building level and then, dependent on the size of the zone, allocated to the zones with the following equation:
On this simplification level, the zone-area-weighted allocation is based on the percentage distribution of one particular zone area $A_{N,i,Z}$ to the area of all zones $A_{N,i,all}$. Therefore, each category of component (outer wall, roof, window or floor) is allocated to a zone $A_{i,Z}$.

In an extended method (see eq. 3.2), correction factors are introduced to offer a more accurate allocation. Each zone area $A_{B,Z}$ can be influenced by a weighting factor $f_{i,Z}$ in order to account for the actual component’s existence in a specific zone. These correction factors are binary, i.e. are limited to the numbers 0 and 1, in order to come up with a relevant and clear statement. As mentioned above, this extended method of a zone-area-weighted allocation of enveloping surfaces with simple correction factors leads to a relatively small average deviation of 1% of the primary energy needs.

$$A_{N,i,Z} = A_{B,Z} \cdot f_{i,Z}$$ (3.2)

The following tables, figures and equations show the assumptions made for the office-specific simplification method with predefined correction factors. The enveloping surfaces for a specific type of office building were estimated with the functions taken from BMVBS [2010a]. In this study, using a simplification of the geometrical survey of non-residential buildings, the dependencies between the net floor space (NFS) or the gross floor space (GFS) and the enveloping surfaces are examined. For office buildings a clear mathematical relationship for windows $A_W$, outer walls $A_{OW}$, roofs $A_R$ and floors $A_F$ was found:

$$A_W = 0.074 \cdot A_{NFS}^{1.0889} \quad A_{OW} = 0.7658 \cdot A_{NFS}^{0.9206}$$ (3.3)

$$A_{OW} = 0.7658 \cdot A_{NFS}^{0.9206}$$ (3.4)

$$A_R = Max(A_{GFS, floor})$$ (3.5)

$$A_F = Max(A_{GFS, floor})$$ (3.6)

A first assumption of typical zones in office buildings and zone divisions can be made with information taken from DIN 277 [2005] and BMVBS [2010a]. In BMVBS [2010a] a characteristic number of zones for office buildings with a net floor space up to 15000 m² (4 zones), and a characteristic zone number for buildings larger than 20000 m² (8-12 zones), were found. The largest
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Percentage shares had offices with 40% to 55% and circulation areas with shares between 25% to 30%. Some 15% of the net floor space was used for storage/archive and 5% for further zones (meeting/discussion, sanitary, server). On the basis of these outcomes and data from DIN 277 [2005], a characteristic zone distribution for office buildings was defined. The zone distribution includes the usage profiles office (50%), circulation area (25%), storage/archive (15%), discussion/meeting/seminar (4%), sanitary (4%), and server (2%).

Table 3.1: Office-specific ground plan structures.

<table>
<thead>
<tr>
<th>Office layout type</th>
<th>Double–depth</th>
<th>Triple–depth</th>
<th>Central</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building width</td>
<td>13.0 m</td>
<td>15.0 m</td>
<td>width = length</td>
</tr>
<tr>
<td>Inner zones</td>
<td>circulation area</td>
<td>ancillary spaces, circulation area</td>
<td></td>
</tr>
<tr>
<td>Access form</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In order to map the enveloping surfaces and the allocation of the enveloping surfaces to the zones more correctly, the building structure is queried with the help of three selection possibilities based on typical ground plan structures of office buildings (see PROsab [2008]). As shown in Table 3.1, a distinction is made between a double–depth floor plan, a triple-loaded building, and a central structured house. Therewith, a conclusion to typical building widths and zones that are not located on the outer walls can be derived. For example, a triple–loaded floor plan has an expected building width of 15.0 m and the ancillary spaces and circulation areas are located somewhere in the middle of the building. With the help of this information the ancillary spaces and circulation areas can be weighted with a correction factor of zero for the outer walls and windows. All other zones can be allocated according to the percentage share of the zone area.

Construction and materials

To calculate the losses through transmission, the storing behavior of the construction, the solar gains, and details of the construction and materials used are necessary. In the following, the three levels of detail for the construction and materials are explained (see Figure 3.12).

If information of the building materials and construction products are available, it is possible to integrate own building structures to map the real construction. On the basis of two German standards (see DIN EN 12524 [2000] and DIN V 4108-4 [2007]) the program offers a database of characteristic building materials for the construction of individual wall mountings. The database comprises component properties like thermal conductivity, heat capacity, or density. Furthermore,
default values for the parameters of glasses and sun protection devices are deposited. The parameters are taken from the standard DIN V 18599-2 and contain heat transition coefficients and overall transmission values.

Due to a lack of plans or further information about the building envelope, it may be necessary to guess the component’s constructions and the materials used. Therefore, the German "Bundesministerium für Verkehr, Bau und Stadtentwicklung" provides additional information concerning typical constructions of different building eras (BMVBS [2007] and BMVBS [2009]). These so-called "Baualtersklassen" are based on historical and political circumstances as manifested in the Ordinances on Thermal Insulation (WSchV [1984] or WSchV [1995]) and give general, statistically validated information about heat transition coefficients for a specific year of construction.

In addition to the simplification method to estimate the construction and the materials, and to integrate the real component constructions, it is possible to enter a more detailed description of the building physics. As an example, the heat transfer rate can be changed and mapped more precisely. Taking this path, the thermal behavior of a building might be described more precisely and realistically.

Costs

The basis for the economic efficiency calculations are energy-related structural and plant-specific costs. For the first cost estimation functions from IWU [2009] are used. The identified key figures in this publication are based on practical knowledge and come from the "CO2-Gebäudesanierungsprogramm" of the KfW and the dena project "Niedrigenergiehaus im Bestand". The data used were normed with regional factors to compensate regional inequalities. For further cost estimations, mainly for the plant technology, values from Meyer [2010] are used. These estimations are
based on surveys of companies and data of the energy-advisor program "Energieberater 7 [2009]". **Cost functions** for each retrofit option used were defined and deposited in the program as default values.

More detailed information about costs can be used after tendering procedures or after real commissions. Thus, the knowledge about the expected costs can be adapted and statements to the economic efficiency can be adjusted piece by piece.

### 3.1.2 User level

In the last section, the calculation methods as well as the data basis of the retrofit tool were explained. The following discussion focuses on explanations of the visually accessible part and the practical use of the program. This includes the selection and calculation of retrofit options on the one hand, and the data evaluation and visualization on the other hand.

**Retrofit options**

To calculate different retrofit options, the current state of the building needs to be mapped first. Then refurbished states can be calculated and the results can be evaluated and compared with each other. Figure 3.14 shows the change in the operation sequence if several retrofit options are calculated (cf. Figure 3.1). The significant parts of the functional principles remain constant and only the input parameters are varied depending on the refurbishment combinations. For instance, the outer wall construction can be varied by adding extra insulation, which leads to a reduction of the heating requirements.

For the program, six typical retrofit options were implemented. These refurbishment options include the improvement of the enveloping surface (wall, roof, floor, and windows) as well as the
exchange of the current heating system and the replacement of the lighting system. The single options can be varied and different retrofit qualities can be selected. For example, the thickness of the outer wall insulation can be chosen. To consider possible interactions between the single retrofit options, all options are calculated in each possible combination, so that **64 refurbishment possibilities** are in principle feasible.

**Evaluation and visualization**

As described in the last section, the variation of input parameters provides a maximum of 64 refurbishment results. Each of these results contain information on

- Final energy savings
- Primary energy savings
- Overall costs
- \( CO_2 \) reduction
- Net Present Value
- Real Options Investment Appraisal

To evaluate the best results and the best measures of calculation, all findings are visualized and compared. An example of such an automated visualization is shown in Figure 3.15. The total investment costs in euros are plotted against the savings per invested euro. This way, the best ratio between performance and price is displayed and the three best measures are marked with green dots. Furthermore, the details of the three best packages of measures are described underneath the figure. Individual measures in the package of measures, total energy savings and investment

**Figure 3.14:** Program structure of the retrofit tool to calculate retrofit options.
Results

costs, as well as the savings in percentages are listed. The visualization in one figure enables a fast and obvious evaluation of the optimal retrofit possibilities and provides the most relevant results.

Figure 3.15: Example of the evaluation method.
3.2 Cost-optimized retrofit path

This chapter contains the methodology developed and implemented for the different elements of the economic analysis, as well as the selection and setting of parameters. A discussion of energy prices forms a separate section within the latter part. Results from employing the economic analysis tool are described in chapter 3.5.

3.2.1 Methodology

The methodology employed for the economic evaluation of the different retrofit alternatives consists of three elements

- The Net Present Value method is used to compare investments with different initial and future costs and benefits. Thereby, future cash flows are discounted to their current value. Costs and benefits vary, depending on whether the investor is the future user or the landlord who benefits from energy cost savings.

- The uncertainty in the energy price development is considered both by simultaneously evaluating different scenarios and by using Monte Carlo simulation to determine possible outcomes based on historical price developments.

- The owner of a building may be advised as to whether to wait before investing or not. This real options investment appraisal is based on Monte Carlo forecasts of stochastic variables and determines the probability of achieving a higher net present value at a later time.

In the case where the owner does not benefit from (uncertain) energy cost savings, e.g. in a let building, only the first element is applied.

Net present value calculation

The underlying principle of the net present value (NPV) method is the assumption that one euro today is worth more than one euro tomorrow. This is because today’s euro can be invested and will generate future income, such as interest payments. Thus, future cash flows must be discounted to their present values in order to compare them appropriately to present investment expenditures. Using the discount factor $i$, the NPV results from the sum of future cash inflows or benefits $B$, the sum of future cash outflows or costs $C$ of the investment, and the initial investment expenditure $I_0$ (Milanowski [2011], pp.59 ff.) as

$$ NPV = -I_0 + \sum_{t=1}^{T} \frac{B(t) - C(t)}{(1 + i)^r} + R_V - I_{repl} $$

(3.7)
where $T$ is the time horizon over which the investment is to be evaluated. $R_V$ and $I_{repl}$ are the residual value and replacement expenditures, respectively, which have to be considered when the time horizon is not identical to the service life $T_{SL}$ of the respective components. According to the German guideline VDI 2067 “Economic efficiency of building installations” $R_V$ and $I_{repl}$ are determined as

$$R_V = I_0 \cdot r^{NR} \cdot T_{SL} \cdot \frac{(NR + 1) \cdot T_{SL} - T}{T_{SL}} \cdot \frac{1}{(1 + i)^T}$$

and

$$I_{repl} = I_0 \cdot \sum_{n=1}^{NR} \frac{r^{nr} \cdot T_{SL}}{(1 + i)^T}$$

where $NR$ is the number of replacements during the time horizon and $r$ is the price change rate for capital-related expenditures (VDI 2067-1 [2010]).

If the NPV is positive, the investment is profitable and leads to an increase in capital. NPVs of zero (below zero) indicate that the return on investment will be the same as (below) the discount factor, respectively. Among the investment alternatives, the one with the highest NPV will be the most favorable.

The value of the discount rate $i$, or required rate of return, will be determined by the investor depending on the market interest rate, the method of financing, and risk aspects of the investment. Guidelines for choosing the discount rate are given in section 3.2.2

When making investment decisions, it is important to correct for the loss of purchasing power or inflation $p$, which reduces the real value of the return on an investment such that

$$1 + i_{real} = \frac{1 + i_{nom}}{1 + p} \rightarrow i_{real} = \frac{1 + i_{nom}}{1 + p} - 1.$$  

In the following calculations, $i$ refers to the real discount rate $i_{real}$. Note that if discounting is done with the real rate, the individual cash flows have to be represented in their real forms, i.e. without inflation (Brigham and Ehrhardt [2008], pp.429 ff.). Consequently, as an inflation premium is already included in the interest rate paid for debt, interest payments have to be discounted with the nominal rate.

Types of costs and benefits included in the model follow the guideline VDI 2067, with the addition of transaction costs (TC). The latter are costs for trading across a market (Erdmann and Zweifel [2008], p.157). With respect to retrofit investments, TC may occur in “gathering, assessing and applying information on characteristics and performance of energy using equipment” (Sanstad and
Howarth [1994] in Milanowski [2011], p.815). Origin and quantification of TC are further explained in section 3.2.2.

Costs and benefits entering the net present value determination are calculated in comparison to the state of the building before the investment (base case).

**Costs.** Besides transaction costs, elements of the net present value on the cost side are the initial investment $I_0$, the costs of external financing (interest payments $C_{IP}$), and the costs of maintenance and operation, $C_{IM}$ and $C_{OP}$. The latter do not apply in a let building, as they are borne by the tenant. Thus, annual payments for year $t$ in a self-used building are

$$ C(t = 0) = I_0 + C_{TC} $$  \hspace{1cm} (3.11)

$$ C(t > 0) = C_{IP} + C_{IM} + C_{OP}. $$  \hspace{1cm} (3.12)

As transaction costs are proportional to the investment costs,

$$ C_{TC} = f_{TC} \cdot I_0. $$  \hspace{1cm} (3.13)

Interest payments with nominal interest rate $i_{IP,nom}$ are computed as follows:

$$ C_{IP}(t) = I_0 \cdot f_{IP}(t) \text{ where } f_{IP}(t) = \begin{cases} i_{IP} \\ i_{IP,nom} \frac{(1+i_{IP})^{T_{IP}}-T_{gp}-1}{(1+i_{IP})^{T_{IP}}-T_{gp}} \end{cases} \text{ for } \begin{cases} t \leq T_{gp} \\ T_{gp} \leq t \leq T_{IP} \end{cases} $$  \hspace{1cm} (3.14)

where $T_{gp}$ is the grace period during which only interest, but no redemption of credit is paid. After the grace period, the annual interest payments diminish in line with the remainder of the debt during the period of the loan $T_{IP}$.

As costs for inspection, maintenance and operation would also occur in the absence of a retrofit, only the difference to this base case enters the calculation. Costs are subject to a price change rate $r$.

In the case of building installations, standard costs are given as a percentage factor of investment costs in VDI 2067. Thus,

$$ C_{IM}(t) = (C_{IM} - C_{IM,base}) \cdot r_{IM}^{I} = (I_0 \cdot f_{IM} - C_{IM,base}) \cdot r_{IM}^{I}; $$  \hspace{1cm} (3.15)

$$ C_{OP}(t) = (C_{OP} - C_{OP,base}) \cdot r_{OP}^{I} = (I_0 \cdot f_{OP} - C_{OP,base}) \cdot r_{OP}^{I}. $$  \hspace{1cm} (3.16)
Benefits. On the benefit side, the investor may gain from subsidies, the calculation of which is given in section 3.2.2. Further income may be generated by operating a combined heat and power generation (CHP) unit. The largest contribution to recouping the investment is expected from avoided energy costs, at least in the case of buildings used by the investor. In the case of a let building, however, an energy efficiency gap may be induced, arising from split incentives: The user benefits from the retrofit, whereas the owner (investor) pays for it. The investor benefits merely from a rent increase, which in Germany is limited to 11% of the investment costs ($\S 559$ BGB [2011]). Thus, benefits are calculated as follows. The initial benefit generated from subsidies is

\[ B_0 = B_{0,\text{gen}} + B_{HP} + B_{\text{Pellet}} + B_{CHP}, \]  

where $B_{0,\text{gen}}$ is a general investment subsidy and $B_{HP}$, $B_{\text{Pellet}}$, and $B_{CHP}$ are investment subsidies for a heat pump, a pellet boiler, and a CHP unit, respectively. These have to be subtracted from the investment cost when determining the rent increase ($\S 559a$ BGB [2011]).

The annual benefit of an investor in a let building where the rent can be increased by a percentage $f_{RI}$ is

\[ B(t) = (I_0 - B_0) \cdot f_{RI} \]  

The annual benefit in the case of a building used by the investor is determined by the avoided energy costs compared to the base case. The latter depend on the final energy demand $Q_{EE}$, energy carrier $ec$ and price $p_{EE}$ for each of the number of energy carriers $EC$ in year $t$, specified as

\[ B(t) = \sum_{ec=1}^{EC} (Q_{EE,\text{base}}(ec) \cdot p_{EE}(ec,t) - Q_{EE,\text{san}}(ec) \cdot p_{EE}(ec,t)), \]  

where $p_{EE}(t)$ is determined by the energy price scenario, for example as $p_{EE}(t) = p_{EE,0} \cdot r_{EE}^{t}$ (see section 3.2.3).

In the case of a CHP unit, additional cash flows can be generated from electricity sales at a price $p_{el,CHP}$ plus bonus $p_{CHP,\text{bonus}}$ and an energy tax break for the CHP fuel (in Germany).

\[ B(t) = B(t) + W_{el,CHP} \cdot (p_{el,CHP}(t) + p_{CHP,\text{bonus}}(t) + \frac{p_{CHP,\text{taxbreak}}}{\eta_{el,CHP}}) \]  

Here, $W_{el,CHP}$ is the amount of electricity produced and sold. The electrical efficiency $\eta_{el,CHP}$ is needed to determine the amount of fuel used.

Net present value result. The NPV results from summing up the discounted costs and benefits over the evaluation period $T$ such that
• for the user as investor

\[
NPV = -I_0 \cdot (1 + f_{TC}) + R_V - I_{repl} - (I_0 - B_0) \cdot \sum_{t=1}^{T} \frac{f_{IP}(t)}{(1 + i_{nom})^t} - (C_{IM} - C_{IM,\text{base}}) \cdot \sum_{t=1}^{T} \frac{r^I_{IM}}{(1 + i)^t} - (C_{OP} - C_{OP,\text{base}}) \cdot \sum_{t=1}^{T} \frac{r^I_{OP}}{(1 + i)^t} + B_0 + \sum_{t=1}^{T} \sum_{ec=1}^{EC} \left( Q_{EE,\text{base}}(ec) - Q_{EE,\text{retrofit}}(ec) \right) \cdot p_{EE}(ec, t) + W_{el,\text{CHP}} \cdot p_{CHP}(t) + p_{CHP,\text{bonus}}(t) + p_{\text{CHP,taxbreak}}/\eta_{el,\text{CHP}}/(1 + i_{nom})^t
\]  

(3.21)

\[
B_0 + (I_0 - B_0) \cdot \sum_{t=1}^{T} \frac{f_{RI}(t)}{(1 + i_{nom})^t}
\]

(3.22)

\[
+ B_0 + \sum_{t=1}^{T} \sum_{ec=1}^{EC} \left( Q_{EE,\text{base}}(ec) - Q_{EE,\text{retrofit}}(ec) \right) \cdot p_{EE}(ec, t) + W_{el,\text{CHP}} \cdot p_{CHP}(t) + p_{CHP,\text{bonus}}(t) + p_{\text{CHP,taxbreak}}/\eta_{el,\text{CHP}}/(1 + i_{nom})^t
\]

(3.23)

(3.24)

• for the investor in a let building

\[
NPV = -I_0 \cdot (1 + f_{TC}) + R_V - I_{repl} - (I_0 - B_0) \cdot \sum_{t=1}^{T} \frac{f_{IP}(t)}{(1 + i_{nom})^t} + B_0 + (I_0 - B_0) \cdot \sum_{t=1}^{T} \frac{f_{RI}(t)}{(1 + i_{nom})^t}
\]

(3.25)

(3.26)

Uncertainties of energy price development

Future energy prices are the major factor determining the return on energy retrofit investments in self-used buildings and at the same time very difficult to predict. Historical price developments show a dramatic increase during the last decade both for end-user prices and imported energy, on which Germany relies for the greatest part of its supply. Prices for energy imports, moreover, show increasing fluctuations, which are partly reflected in end-user prices (see Figure 3.16 and Figure 3.17). Thus, a single assumption, especially a linear increase, would be very inaccurate in predicting the possible investment outcomes and the relative merits of the investment alternatives.

Within the retrofit evaluation tool, the problem of uncertain energy price trends is treated in two ways:

(a) different scenarios for energy prices are evaluated at the same time,

(b) a range of possible outcomes is simulated using a Monte Carlo technique.

For the discrete energy price development scenarios (a), yearly price change factors are calculated from the latest German Lead Study projections (Nitsch et al. [2010]) and applied to the end-user prices collected by the German Federal Ministry for Economics and Technology (BMWi [2011]) or alternative sources named in section 3.2.3, Table 3.5. Results are shown in section 3.2.3, Figure 3.19. Additionally, a user scenario can be generated where \( p_{EE}(t) = p_{EE,0} \cdot r_{EE}^t \).

\(^{1}\)In 2009 74% of Germany’s domestic energy supply was imported (AG Energiebilanzen, cited in Milanowski [2011]). In particular, 97% of the crude oil demand, 87% of the natural gas demand and 75% of the hard coal demand was brought into the country (BMWi, cited by Milanowski [2011]).
The same end-user price data are used when applying a Monte Carlo simulation to deal with the uncertainty inherent in energy price projections. In general, Monte Carlo simulations of a system furnish a set of possible outcomes when input parameters are not given as discrete values, but characterized by probability distributions. Random sampling of the latter and a sufficient number of repetitions lead to a statistically viable range of possible outcomes and the probabilities of their occurrence.

For the retrofit tool, historical energy price data \( p_{EE}(t) \) (BMWi [2011]), normalized with the 2011 consumer price index, and price change rates \( r_{EE}(t) \) were analyzed with the CrystalBall software (CrystalBall [2010]) in order to describe them by using probability distributions. These were sampled by a Monte Carlo routine performing repeated calculations of the net present value, using \( p_{EE}(t) = p_{EE,0} \cdot r_{EE}^t \). A mean NPV was then determined from the results.

**The value of waiting: Real Options Investment Appraisal**

All of the above considerations assume that the user of the retrofit tool is faced with the choice between investment alternatives now, i.e. he/she will invest now or never. However, rising energy prices may turn a non-profitable retrofit alternative into a profitable one if the savings from energy conservation start to outweigh the costs in due time. Thus, the investor may be well advised to delay the investment, if feasible. Since the case for a rented building is not affected from energy

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**Figure 3.16:** Price development of imported energy sources (Source: BMWi [2010]).

Note: Prices not including taxes and duties.
price uncertainty, the option of increased profit as a result of delayed investment is evaluated only for the case that the owner uses the building him-/herself.

The possibility to delay the investment is considered on a sequential basis, period by period. For each period, the probability of achieving a higher NPV in the following period, \( p_t = Pr\{NPV_{t+\Delta t} > NPV_t\} \), is determined. This is used to compute the succeeding period’s expected NPV, \( E(NPV_{t+\Delta t}) = p_t \cdot NPV_t \). \( NPV_t \) and \( NPV_{t+\Delta t} \) both result from a Monte Carlo simulation, with the difference being the progress of a period \( \Delta t \).

The decision criterion to wait/invest is then defined as indicated by the inequality shown in equation 3.27. If the following period’s expected NPV is greater than the preceding period’s NPV, the investor is recommended to wait.

\[
NPV_t \leq \frac{1}{(1 + i)^{\Delta t}} \cdot E(NPV_{t+\Delta t})
\]  

(3.27)

Figure 3.18 provides an illustration of the sequential decision framework. An immediate investment occurs at \( t=0 \) if \( NPV_t \) is positive and \( NPV_t > \frac{1}{1+i} \cdot E(NPV_{t+1}) \). Otherwise, if \( NPV_t \leq \frac{1}{1+i} \cdot E(NPV_{t+1}) \), the investor waits up to the next period; meanwhile, some uncertainty dissolves. In this case, the same decision loop continues in the succeeding period as \( NPV_{t+1} \) is compared with \( E(NPV_{t+2}) \) to decide whether to invest at \( t=1 \) or wait until \( t=2 \). If it is recommended to wait, the comparison continues.

A more comprehensive treatment of the real options approach used here is provided in Kumbasaroglu and Madlener [2012].
3.2.2 Parameters

This section comments on the choice of parameters included in the model and explains standard values and reasonable value ranges. A shortened German version of this explanation is provided to the user within the tool itself (see appendix 6.3). Additional information can be found in Milanowski [2011].

Parameters used in the model fall into the areas (1) general economic considerations, (2) general project characteristics, (3) financing, (4) subsidies, and (5) parameters specific to let and self-used buildings, respectively.

(1) General economic parameters

Inflation rate. When assessing medium-to-long-term investments such as retrofit measures, it is important to take into account not only the overall price changes, but also the real ones. Otherwise, the value of future cash flows in terms of buying power may be misinterpreted. Price stability is a prime objective of monetary policy. The European Central Bank aims at an inflation rate “below but close to 2%”, which is also the value used in studies on retrofit appraisal commissioned by the KfW group of banks (Milanowski [2011]). Thus 2% is the standard value for the inflation rate within the retrofit tool. If the investor expects higher or lower inflation rates, the values should be in the 0.5% - 3% range (cf. German inflation rates between 0.4% and 2.6% since the introduction of the Euro in 1998). In addition, price changes for different kinds of cash flows can be adjusted to be higher or lower than the inflation rate.

(2) General project parameters.

Transaction costs. This term describes costs for trading across a market (Erdmann and Zweifel [2008], p.157). With respect to retrofit investments, they may occur in “gathering, assessing and
applying information on characteristics and performance of energy using equipment” (Sanstad and Howarth [1994] p.815, cited in Milanowski [2011]). Though the tool described here aims at reducing information deficiencies, actual application of the selected measures will require further analysis. Likewise, costs for communication, enforcing agreements and making of contracts, and monitoring are to be considered in the initial investment. Transaction costs will decline with rising frequency of similar transactions undertaken (Milanowski [2011]).

There is only a small number of studies quantifying the level of transaction costs of energy efficiency measures in companies. The most suitable one was undertaken by Blok and Hein [1995] in twelve firms. It revealed transaction costs of 3-8% of the total investment, with information retrieval causing 2-6% of capital expenditure (Milanowski [2011]). Since this tool reduces the information retrieval effort, we suggest staying below the maximum value when setting the transaction cost level.

**Discount rate.** The required rate of return or discount rate is used to determine the present value of future cash flows. It represents the costs for the use of capital and can be understood as the expected rate of return of a comparable investment. Its value is dependent on the market interest rate, the method of financing, and the risk aspects of the investment. When financing is through equity capital, the interest rate should reflect the alternative riskless investment, which could have been made at the open market. If there is no pre-defined return on equity set within the user’s company, the interest rate of a ten-year federal bond can be used (König et al. [2009], p.72, cited in Milanowski [2011]). When financing is external, the discount rate is the interest rate paid for debt. Risk aspects of the investment can be reflected by adding a risk factor to the real interest rate. However, as in our case the main risk derives from the uncertainty of future energy prices, which is incorporated through the Monte-Carlo and scenario methods, we suggest to refrain from any risk adjustment here.

Thus, for equity financing, the discount rate should be set between 2.25% and 5%, following the interest rates of the German federal bond since 2011 (Milanowski [2011]). For external financing, the suggested values are based on the loan programs offered by the German Reconstruction Loan Corporation (Kreditanstalt für Wiederaufbau, KfW) for small- to medium-sized enterprises. Depending on the maturity of the loan, the degree of creditworthiness and securities provided, effective interest rates varied between 2.17% and 7.87% in 2011. As a standard value, we use 4.22%, corresponding to a standard credit package (see financing parameters below and in Milanowski [2011]). If financing is mixed, the discount rate has to be calculated according to the shares of equity and debt financing (Enseling [2003], cited in Milanowski [2011]).

**Period of review.** Retrofit investments are typically a trade-off between high short-term costs and long-term benefits. In this context, high discount rates have negative effects on the assessment of energy efficiency investments, since the present value of highly discounted future benefits is outweighed by high initial costs. Consequently, the longer the period of review is for the investment,
Results

the less important distant future benefits will be (Milanowski [2011]). On the other hand, short review periods also distort the balance between initial costs and future benefits.

Different perspectives can be applied when deciding on the review period. From an engineer’s point of view, it complies with the service life of the retrofitted component, with residual values applied for longer-lasting components in a bundle of measures. This can lead to very long periods of review. From an economist’s point of view, the time horizon of financing is a reasonable period, i.e. the investment will be executed if it gives a good return within the period of financing, which usually varies between 5 and 20 years (Milanowski [2011]).

**Building user.** If the retrofit investment is planned for a building used by the investor, calculation of costs and benefits is straightforward since all can be attributed to the investor. In the case of a rented building, split incentives arise since the party bearing the costs, usually the landlord, is not the one benefitting. The tenant him-/herself will not invest either since the lease may be terminated before the tenant benefits fully. This investor-user dilemma is one of the market barriers in energy conservation.\(^2\) Thus, the differentiation between a “self-used building” and “let building” is one of the most important parameters of the investment appraisal. In the first case, savings in energy cost and possibly operation and maintenance will be a part of the benefits, whereas in the second case only the increased rental income will. The height of the possible rent increase is set forth in the corresponding parameter description.

**(3) Financing parameters**

If the investment is financed by equity capital, the costs for its use are included in the discount rate. In order to calculate the yearly costs of a bank credit, its parameters **maturity**, **interest rate** and **grace period** have to be specified. The latter is the time period during which only interest, but no redemption payments have to be made. If individual conditions are not known to the user, we suggest to employ those of the KfW loan programs (see the discussion on the discount rate above). As a standard value, we use an interest rate of 4.22% which is available for a loan with a maturity of ten years, a grace period of two years, supposing a good to satisfactory credit rating, and a high recoverability of securities (Milanowski [2011]).

**(4) Subsidies**

Although promotional programs for energy-efficient buildings in the commercial, service and industry sectors are fewer than in the residential sector\(^3\), they can still benefit from subsidies under the Federal Ministry of Environment’s “Renewable Energy Incentive Program” (in German “Marktanreizprogramm zur Förderung erneuerbarer Energien”). At the time of writing, non-recurring basic funding was available for brine-water heat pumps and wood pellet boilers according to Table

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\(^2\) In theory, the dilemma could be avoided by using a contract that aligns the interests of both parties. However, reality shows that transaction and verification costs are prohibitive. For further details see Milanowski [2011].

\(^3\) See for example www.energiefoerderung.info by BINE Informationsdients and the German Energy Agency (dena).
3.2. These are implemented within the retrofit tool. The parameter “Include subsidies” (yes/no) allows to do the calculation without them in case they are not or no longer applicable. The parameter “additional subsidy” allows specification of a non-recurring basic funding for each investment alternative. Furthermore, bonus payments for CHP electricity sales as well as tax breaks for fossil-fuel plants are implemented. Biomass-fuelled CHP can be analyzed using “additional subsidies”. CHP investment subsidies were discontinued at the time of programming, but can easily be reintroduced into the calculations.\(^4\)

**Table 3.2:** Non-recurring financial aid for wood pellet boilers and brine-water heat pumps.
Source: BMU [2011]

<table>
<thead>
<tr>
<th>Capacity</th>
<th>EUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat pump</td>
<td></td>
</tr>
<tr>
<td>(\leq 10) kW</td>
<td>2400</td>
</tr>
<tr>
<td>(&gt; 10) kW (\ldots \leq 20) kW</td>
<td>2400 + 120/additional kW</td>
</tr>
<tr>
<td>(&gt; 20) kW (\ldots \leq 100) kW</td>
<td>100/kW</td>
</tr>
<tr>
<td>Pellet boiler (\geq 5) kW (\ldots \leq 100) kW</td>
<td>36/kW with a minimum of 2000</td>
</tr>
</tbody>
</table>

**Table 3.3:** Bonus payments for CHP electricity and energy tax breaks for fossil-fuelled CHP.
Source: BKWK [2011] and EnergieStG [2011], §2, Abs. 3

<table>
<thead>
<tr>
<th>Type and size</th>
<th>CHP bonus</th>
<th>Limitation</th>
<th>CHP fuel</th>
<th>Energy tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP (\leq 50) kW(_{el}) fuel cell CHP</td>
<td>5.11 cent / kWh</td>
<td>10 years</td>
<td>Natural gas</td>
<td>0.55 cent/kWh</td>
</tr>
<tr>
<td>CHP (50) kW – 2 MW</td>
<td>2.11 cent/kWh</td>
<td>30,000 usage hours</td>
<td>Light fuel oil</td>
<td>5.725 cent/kWh</td>
</tr>
<tr>
<td>CHP (&gt; 2) MW</td>
<td>1.5 cent/kWh</td>
<td>30,000 usage hours</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(5) **Case-specific parameters**

**Let building: Investment allocation.** In a private-sector let building, an investor may partially pass on the costs of energy retrofit measures to the tenant by increasing the rental fee. In Germany, the increase in the annual fee is limited to 11% of the retrofit investment costs after deducting subsidies (§559 and §559a BGB [2011]). This limit does not apply if there is a change in tenant, in which case the possible rent increase has to be estimated by the user with the help of rent indices (e.g. IVD [2011]). Similarly, in the case of leases between public institutions, the increases are arranged individually (Milanowski [2011]). As a standard value, we propose to use an investment allocation of 11%, i.e. the maximum allowable increase of the annual rental fee in the private sector.

**Self-used building: Energy price scenario.** The user can specify whether calculations for the self-used building are to be performed with the built-in energy price scenarios (“Basisszenario”) de-
Results

scribed in section 3.2.3 or a user-generated scenario (“Eigenes Energiepreisszenario”). The latter requires specification of the base price and the yearly price change rate for the five energy carriers considered in the retrofit tool, namely natural gas, light fuel oil, wood pellets, electricity, and district heat. Prices and change rates had to be normalized with the 2011 consumer price index in order to fit with the other price data used in the model.

**Self-used building: Maintenance and operation (optional).** Costs for inspection and maintenance as well as operation of the retrofitted building are included in the model using technology-dependent factors from VDI 2067-1 [2010] (see section 3.2.1). In order not to overestimate the yearly costs after the retrofit, the present costs in these areas must also be considered. This is done by using the technology-based factor for the non-retrofitted building, but assuming current prices. The user can replace these estimates by the real current costs, if known.

Standard values and range recommendations for the parameters described above are summarized in Table 3.4.

### 3.2.3 Energy prices and scenarios

Historical energy prices are used in the model both as a starting point for the scenario projections and as a basis for the Monte Carlo simulations. End user prices have been converted to real values by using the German Federal Office for Statistics’ consumer price index, converted to 2011 prices. Table 3.5 gives an overview of the data and sources. The starting points for the scenario projections are the same as the standard values shown in Table 3.4.

![Figure 3.19: Price development scenarios.](image)

*Source: Own design; prices derived from Nitsch et al. [2010].
Note: Price trajectories start at 2010 consumer prices including VAT, converted to 2011 values.*
**Table 3.4:** Parameters of investment appraisal and value recommendations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard value</th>
<th>Suggested range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation rate</td>
<td>$p$</td>
<td>2%</td>
</tr>
<tr>
<td>Transaction costs</td>
<td>$f_{TC}$</td>
<td>7%</td>
</tr>
<tr>
<td>Discount rate</td>
<td>$i_{nom}$</td>
<td>4.22%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equal to interest rate for credit for external financing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.25 – 5% for equity financing</td>
</tr>
<tr>
<td>Period of review</td>
<td>$T$</td>
<td>10 years</td>
</tr>
<tr>
<td>Building user</td>
<td></td>
<td>Self-used or let building</td>
</tr>
<tr>
<td>Maturity of loan</td>
<td>$T_{IP}$</td>
<td>10 years</td>
</tr>
<tr>
<td>Grace period</td>
<td>$T_{GP}$</td>
<td>2 years</td>
</tr>
<tr>
<td>Interest rate for credit</td>
<td>$i_{IP}$</td>
<td>4.22%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KfW interest rates are 2.17% - 7.78%, depending on maturity, credit rating and securities</td>
</tr>
<tr>
<td>Include subsidies?</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Additional subsidies</td>
<td>$B_{gen}$</td>
<td>0 EUR</td>
</tr>
<tr>
<td>Investment allocation</td>
<td>$f_{RI}$</td>
<td>11%</td>
</tr>
<tr>
<td>Energy price scenario</td>
<td></td>
<td>Base scenarios, user-generated scenario, or Monte Carlo Simulation</td>
</tr>
<tr>
<td>Energy prices (optional)</td>
<td></td>
<td>Latest available values for energy prices according to Table 3.5, price basis 2011.</td>
</tr>
<tr>
<td></td>
<td>$p_{E, gas}$</td>
<td>5.9 c/kWh</td>
</tr>
<tr>
<td></td>
<td>$p_{E, oil}$</td>
<td>6.3 c/kWh</td>
</tr>
<tr>
<td></td>
<td>$p_{E, pellets}$</td>
<td>4.8 c/kWh</td>
</tr>
<tr>
<td></td>
<td>$p_{E, electricity}$</td>
<td>25.3 c/kWh</td>
</tr>
<tr>
<td></td>
<td>$p_{E, heat}$</td>
<td>7.8 c/kWh</td>
</tr>
<tr>
<td>Price change rates for energy (optional)</td>
<td>$r_{E, gas}$</td>
<td>Yearly change rates derived from Nitsch et al. [2010]; Natural gas and oil 1.01 - 1.05, electricity 1.01 – 1.03</td>
</tr>
<tr>
<td></td>
<td>$r_{E, oil}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r_{E, pellets}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r_{E, electricity}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r_{E, heat}$</td>
<td></td>
</tr>
<tr>
<td>Maintenance and inspection costs, operation costs before retrofit (optional)</td>
<td>$C_{IM, base}$</td>
<td>Can be used if known, otherwise determined from standard factors in VDI2067</td>
</tr>
<tr>
<td></td>
<td>$C_{OP, base}$</td>
<td></td>
</tr>
<tr>
<td>Price change rate for capital-related costs</td>
<td>$r_{CAP, nom}$</td>
<td>1.02</td>
</tr>
<tr>
<td>Price change rate for maintenance and inspection</td>
<td>$r_{OP, nom}$</td>
<td>1.02</td>
</tr>
<tr>
<td>Price change rate for operation</td>
<td>$r_{IM, nom}$</td>
<td>1.02</td>
</tr>
</tbody>
</table>
Table 3.5: Energy price data employed in the retrofit evaluation tool

<table>
<thead>
<tr>
<th>Energy carrier</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>Consumer price including VAT(^2), yearly values 1991-2010, converted to Ho basis</td>
<td>BMWi [2011]</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>Consumer prices including VAT, trimester values 2002-2012, converted to Ho values</td>
<td>CARMEN [2012]</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>Consumer price including VAT, yearly values 1991-2010</td>
<td>BMWi [2011]</td>
</tr>
<tr>
<td>Electricity</td>
<td>Consumer price including VAT, yearly values 1991-2010</td>
<td>BMWi [2011]</td>
</tr>
</tbody>
</table>

Energy price projections have been generated from Nitsch et al. [2010]. The study aims at developing strategies for reaching the German government climate protection goals and is based on a simulation of electricity supply with different generation technologies. Price change rates have been determined from the price scenarios for natural gas, crude oil, and electricity. The price change rates for wood pellets follow those for oil using an elasticity of 0.25 (Schmitt and Forsbach [2007], cited in Wäschenbach [2008]). The price change rate for heat has been assumed to be the same as for natural gas. CHP sales prices are assumed to change according to the electricity price for households. Figure 3.19 shows the resulting price trajectories using historical prices as starting points. The values implemented in the retrofit tool are yearly factors, allowing for easy adaptation of starting values.
3.3 Software development

Building management systems (BMS) are a computer-based control system. They are commonly installed and used in a number of non-residential buildings to control and monitor the building functions. All building management systems consist of hardware, like measurement technology, and software programs, which process the recorded data. The software tool explained in this chapter extracts measured data from a data management system and stores the data in a product-independent format to evaluate the building operation. A short view on the graphical user interface is given in section 3.3.1. The universal Hierarchical Data Format (HDF 5), which is used to store the energy-related data as well as building stock data, and the benefits of this storage format are also described in this chapter. Several evaluation scripts and advanced data mining routines, which are implemented in the Graphical User Interface, are listed and explained in section 3.3.2.

3.3.1 Graphical User Interface and data storage

**HDF 5**, or Hierarchical Data Format, is a data format for the flexible and efficient storage of large data objects (for example measurement data) that offers an alternative to other typical database formats. It was developed by the National Center for Supercomputing Applications in 1995 and is currently available under a free license for general use. HDF5 is supported by several commercial and non-commercial software platforms, including the programming language Python, in which the analysis tool has been implemented.

The main advantages of the Hierarchical Data Format format are:

- Complete portability
- No limit of data objects and size
- Open standard
- Runs on a range of computational platforms

Figure 3.20 shows the current status of the Python-based **Graphical User Interface**. On the left side, marked with the number 1, is the visualization of the HDF 5 tree structure. New measurement files and hierarchies can be added and existing data can be viewed, edited or deleted. On the right-hand side of the program, marked with number 2, lies the evaluation interface. Several scripts, also written in Python and described in section 3.3.2, can be chosen. Script-specific input parameters are requested and necessary data series can be placed in corresponding fields. The graphical representations of the evaluations are displayed in additional output boxes and can be saved or plotted (see number 3).
3.3.2 Evaluation scripts

The stored data of the building operation can be examined and evaluated to find incorrect settings or energy-saving potentials. For this purpose, several evaluation methods in the programming language Python were developed. The developed evaluation scripts, which are implemented in the Graphical User Interface mentioned above, are listed and described in the following.

Data cleaning

Considering the data measurement, stored values are often incomplete or incorrect due to measurement failures, operation interruptions, or further unexpected events. Because of that the data mining routines should only be used if the stored data is assessed. To verify the data the program offers the possibility to check and visualize the data quality with the following methods. To uncover incorrect data it is possible to manually set maximum or minimum values. Furthermore, the program offers a second option which forms the median of 80% of the "inner" measured values. This means that the smallest and largest values are not taken into account. From these values the standard deviation to the median is determined. This standard deviation is multiplied with a chosen factor and for this reason defines the limits in which the values are valid. All values which exceed these borders are rejected. Figure 3.21 displays this failure detection method. After check-
Results

Figure 3.21: Visualization of incorrect data detection.

ing the data quality, the outcomes are illustrated weekly and in an overview of the whole observing time. Figure 3.22 shows an exemplary visualization of incorrect, missing and complete data. Hourly values are visualized for each day of a week. Incorrect data are marked with red squares, missing data with yellow squares, and complete data with green squares. In case some hours are not assessed, they are marked as grey squares.

All missing and incorrect data can be filled up with estimated and interpolated values. Therefore, the mean of the values before and thereafter as well as the values one week before and thereafter are calculated. With larger data gaps this method is getting more and more imprecise, and the proper use should be dependent on the data quality and personal opinion.

In addition to missing or incorrect values, some of the measured data need to be revised in a second way. The heating consumption, for example, is influenced by alternating weather conditions. To compare the measured values with benchmarks or further measurements, the data need to be weather-adjusted. The program offers two possibilities of weather adjustments. The first one refers to climatic factors for several regions in Germany, provided by the "Deutscher Wetterdienst" DWD [2012]. These factors are available for the last couple of years in a monthly time interval. The second method enables the computation with the aim of the heating threshold temperature and the indoor temperature and uses the measured data (see BMVBS [2009] and VDI 3807 [2007]).

Benchmarking

After the data cleaning one of the first steps in the field of the optimization of operation is a benchmark of energy consumption. It enables a first estimation of how much saving is feasible and how
the building’s performance can be evaluated in the building stock. Only after a first benchmark-check further investigations with the following evaluation algorithms should be considered.

Figure 3.23 and Figure 3.24 show two benchmark methods used. In the first plot, the weather-adjusted consumption values for heat and electricity are compared with consumption values of the specific building category (e.g. office buildings) and building type (e.g. heated or fully air-conditioned) from BMVBS [2007]. The benchmark illustrates the contrast to the average energy consumption of the specific building. The second plot depicts a comparison between the actual heat consumption of the regarded building and the heat consumption of typical building categories in Germany (see EnEV [2009]). Possible energy savings through refurbishment targets are listed above.

A more detailed examination method based on VDI 3807 [2007] is demonstrated in Figure 3.25. If the basis of the measured electrical data is more complex, it is possible to compare particular electricity consumption types, like the consumption for ventilation or cooling, with specific needs. So, partial energy consumption in detail can be compared with specific parameters and the saving potential for single sections can be evaluated.

Energy visualization

The most excessive energy consumption is commonly caused through ignorance or a lack of knowledge (BINE [2010]). Incorrect or improvable control settings, enabling simultaneous heating and cooling, a non-existing night-time temperature drop, or simply a wrong adjustment of the operating time often lead to increased energy consumption. These easy-to-understand control settings can be controlled by comparing the operating hours with the energy data. One example of these
implemented control setting evaluations is shown in Figure 3.26, where the energy consumption during the occupancy time is visualized and calculated. For a range of days the hourly consumption values are color-coded. High consumption periods are marked in red, average consumption levels in yellow and low energy consumption levels in green. For a better understanding the occupancy time is visualized as a shaded area. Observed and occupancy hours as well as the percentage of energy used during the occupancy time are listed in the legend. A percentage of energy used that is too high indicates inadequate control settings.

**Evaluation of comfort**

The analysis of comfort is not obviously a part of the energy analysis. However, the thermal comfort plays an important role in the field of energy efficiency and is directly related. A high quality in wellbeing can, on the one hand, lead to a better mental performance and reduce absenteeism at work. On the other hand, thermal discomfort leads to corrective actions, like higher ventilation rates, and thus to higher energy costs (see DIN EN 15251 [2007]). Therefore, the evaluation of the building operation needs to include the observation of the thermal comfort which is implemented through three different standards:
Results

Figure 3.24: Benchmark of energy consumption. Comparison of the heat consumption with typical German energy efficiency categories

- DIN EN 15251 [2007], which follows an adaptive approach and is used in non-industrial buildings.
- DIN EN ISO 7730 [2006], which uses a static evaluation method for work environments.
- VDI 4706 [2011] applies to living, office and meeting rooms and also uses an adaptive method.

Figure 3.27 shows the graphical visualization of the thermal comfort on the basis of the standard DIN EN 15251 [2007]. The wellbeing can be categorized into several boundaries, which are dependent on the indoor and outdoor temperatures. Additional to the graphical visualization, the transgression of the categories are calculated and displayed. The program computes the hourly and percentage exceedances as well as the degree hours. The classification in overshoots and undershoots for summer and winter cases allows closer evaluations. This way, inefficient settings of the heating or cooling system, like too much heating, can be readily detected.

Heat production

The main focus of this key issue is to uncover the optimization potentials for the control engineering and the system technology. Figure 3.28 shows the heat generator examination. With the "standardized energy consumption" method described in Deutscher and Rouvel [2003] and Optimus [2005], it is possible to evaluate the measured energy data and generate an equation for the
Results

Figure 3.25: Partial energy consumption based on VDI 3807 [2007]

part of efficiency. To assess the existing boiler with comparative values as shown in Figure 3.28, benchmark parameters based on DIN V 4701 [2003] and DIN V 18599 [2005] are used. As shown in Figure 3.28 the heat generator is, on the one hand, compared with the same boiler type and the same construction year and, on the other hand, with an optimally used condensing boiler. The comparative values as well as the saving potentials for the optimization and the boiler exchange are displayed.

The heating threshold temperature describes the outdoor temperature beyond which the building does not have to be heated. At that point the internal heat gains are appropriate to retain a desired room temperature. The heating threshold temperature is dependent on the building insulation standard and ranges between 15 °C for old existing buildings to 10 °C for passive houses. As shown in Figure 3.29 the real heating threshold temperature can be calculated by contrasting the outdoor temperature with the thermal output. Furthermore, this representation enables the calculation of the maximum needed heating power which can be compared with the real net power of the boiler. By reducing the heating threshold temperature the boiler can be switched on later in the fall and switched off earlier in spring so that energy losses can be avoided. The evaluation method suggests a new adjustable heating threshold temperature which leads to a more efficient use of energy.

The heating curve describes the connection between the outdoor temperature and the supply temperature. Due to different outdoor temperatures the supply temperature needs to vary to keep the building on a constant temperature level. Depending on the heating system, different heating curves are possible. Concerning the energy efficiency, a well-adjusted heating curve reduces en-
Results

Figure 3.26: Visualization of energy consumption.

Figure 3.27: Evaluation of comfort with standard DIN EN 15251 [2007].

ergy losses and ensures a proper room temperature control. Figure 3.30 illustrates a fast check of the heating curve parameters (tendency and parallel shift). With the aid of the measured data a typical heating curve can be calculated and compared with standard parameters of typical heating systems.
3.4 Data acquisition at RWTH Aachen University

For the exemplary application of the evaluation tools, two buildings at RWTH Aachen University were selected. With the help of the BLB ("Bau- und Liegenschaftsbetrieb NRW"), which manages the real estate of the university, the necessary plans and drawings could be obtained. The measured data of the management system came from the "Abteilung 10.3 - Technisches Gebäudemanagement der RWTH", which is responsible for the maintenance, repair and operation of the installation engineering of the university buildings. A short description of the available building data and measurement points is shown in Tables 3.6 and 3.7.

Both buildings are mainly used as office buildings and, furthermore, as lecture buildings for the university. Heating energy is provided by district heat (see Figure 3.31), but the supply is different for the two buildings. Building A is located in the area close to the city center which is supplied by the district heat of the power plant "Weisweiler" (combined heat and power generation, CHP). The second building is in the area "Melaten" in the north-west of Aachen. It is supplied by an own heating, cooling and power plant (mainly heating plant) located within the same area. The drawing portfolio for the two buildings is almost complete. Plans, elevations and sections are available but construction and material details are missing. The measured data of the management system is more incomplete. Flow and return temperatures as well as power values for heating and ventilation could be retrieved from the building management system of the university. For building A these measurement devices are only available for a period of two weeks. The available measurements for building B are 11 months long.
Results

Figure 3.29: Visualisation of the heating threshold temperature.

Table 3.6: Available information on building A

<table>
<thead>
<tr>
<th>Building information</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Building type</td>
<td>office building</td>
</tr>
<tr>
<td>Net floor space</td>
<td>8840 m²</td>
</tr>
<tr>
<td>Construction year</td>
<td>1962</td>
</tr>
<tr>
<td>Number of storeys</td>
<td>7</td>
</tr>
<tr>
<td>Plans</td>
<td>available</td>
</tr>
<tr>
<td>Elevations</td>
<td>available</td>
</tr>
<tr>
<td>Sections</td>
<td>available</td>
</tr>
<tr>
<td>Construction and materials</td>
<td>unavailable</td>
</tr>
<tr>
<td>Heat supply</td>
<td>district heating</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured data</th>
<th>time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating - power</td>
<td>Jan 01, 2011 - Jan 17, 2011</td>
</tr>
<tr>
<td>Heating - supply temperature</td>
<td>Jan 04, 2011 - Jan 17, 2011</td>
</tr>
<tr>
<td>Heating - return temperature</td>
<td>Jan 04, 2011 - Jan 17, 2011</td>
</tr>
<tr>
<td>Ventilation - power</td>
<td>Jan 04, 2011 - Jan 17, 2011</td>
</tr>
<tr>
<td>Ventilation - supply temperature</td>
<td>Jan 04, 2011 - Jan 17, 2011</td>
</tr>
<tr>
<td>Ventilation - return temperature</td>
<td>Jan 04, 2011 - Jan 17, 2011</td>
</tr>
</tbody>
</table>
Figure 3.30: Visualisation of the heating curve.

Table 3.7: Available information on building B

<table>
<thead>
<tr>
<th>Building information</th>
<th>ss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building type</td>
<td>office building</td>
</tr>
<tr>
<td>Net floor space</td>
<td>12200 m²</td>
</tr>
<tr>
<td>Construction year</td>
<td>1975</td>
</tr>
<tr>
<td>Number of storeys</td>
<td>5</td>
</tr>
<tr>
<td>Plans</td>
<td>available</td>
</tr>
<tr>
<td>Elevations</td>
<td>available</td>
</tr>
<tr>
<td>Sections</td>
<td>available</td>
</tr>
<tr>
<td>Construction and materials</td>
<td>unavailable</td>
</tr>
<tr>
<td>Heat supply</td>
<td>district heating</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured data</th>
<th>time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating - power</td>
<td>Dec 06, 2010 - Nov 28, 2011</td>
</tr>
<tr>
<td>Heating - supply temperature</td>
<td>Dec 06, 2010 - Oct 26, 2011</td>
</tr>
<tr>
<td>Heating - return temperature</td>
<td>Dec 06, 2010 - Oct 26, 2011</td>
</tr>
<tr>
<td>Ventilation - power</td>
<td>Dec 06, 2010 - Nov 28, 2011</td>
</tr>
<tr>
<td>Ventilation - supply temperature</td>
<td>Dec 06, 2010 - Nov 28, 2011</td>
</tr>
<tr>
<td>Ventilation - return temperature</td>
<td>Dec 06, 2010 - Nov 28, 2011</td>
</tr>
</tbody>
</table>
3.5 Evaluation of two buildings from RWTH Aachen University.

The developed methods and gathered information of the last four sections are used in the following to evaluate the energy-saving potential of two buildings from RWTH Aachen University. The two buildings are presented in chapter 3.4.

3.5.1 Building operation

The evaluation of the building operation is based on the methods described in Section 3.3 and is shown exemplarily for two buildings. Closer information on the two buildings and the measured data are given in chapter 3.4.

Building A offers a very limited measurement period of two weeks which goes from Jan 4, 2011, to Jan 18, 2011, with some incorrect and missing data (see data quality in Figure 3.32). This leads to a possibly imprecise and unreliable operational evaluation. The following analysis was made only for parts of the building structure. Figure 3.33 shows the visualization of the operating time of the power consumption of the ventilation system. Most of the energy is used during the occupancy time. Nevertheless, the operation on Saturdays as well as early and late operation hours during the week should be reviewed and possibly customized. A heating curve with a slope of the line of 3.3 was determined (see Figure 3.34). This high value matches roughly with existing building
but improvements should be made by reducing the supply temperature. Looking at the heating-threshold temperature in Figure 3.35 a very high default value of 22.4 °C was calculated (see section 3.3.2) which possibly can be reduced to a value of 9.8 °C. In summary, the first evaluations of building A show several possibilities for improvements but due to the insufficient database these results should be confirmed by additional measurements and investigations.

The available measurements for building B reach over a period of 11 months; but, in contrast to the data of building A, these measurements are much more incomplete. Figure 3.36 shows the data quality of the existing measurements where several months are missing. Like for building A a visualization of the operating time of the ventilation system could be produced (Figure 3.37). It shows that there is absolutely no dependence between the occupancy time of the building user and the operation time of the ventilation system. The energy consumption during the occupancy time is, on average, as high as during the absence and so offers an enormous potential for en-
Results

Figure 3.34: Evaluation of building A - heating curve.

Energy savings. Further optimization possibilities can be done within the field of heat distribution. Currently the heating-threshold temperature is set to a value of 19.9 °C (see picture 3.39). The evaluation method described in section 3.3.2 demands a reduction of this high value to 12.7 °C, which would lead to a premature shutdown of the heat generation and a high energy consumption reduction. Improvements could also be carried out for the supply temperature regulation where no heating curve could be determined at the moment. The measured values visualized in Figure 3.38 demonstrate this and show two constant temperature levels (around 70 °C and 75 °C) for the whole year.

3.5.2 Retrofit options

In the following, the calculation results of the energetic analysis are visualized and explained. The evaluations of the two exemplary buildings were performed for six typical single retrofit measures and every possible combination thereof. These single refurbishment options are

- Outer wall insulation, 20 cm
- Roof insulation, 20 cm
- Bottom-side cellar ceiling insulation, 20 cm
- Double-pane heat insulating glass
- Gas-fired condensing boiler
- TL-5 surface mounted light

The calculated measures, or packages of measures, are displayed and compared regarding the total savings per investment costs in kWh/EUR. CO₂ savings, final energy savings as well as primary
energy savings are considered. The three best retrofit options are marked as green dots and further information about savings and investment costs are listed in detail below the visualization.

Figure 3.40 shows the final energy evaluation as one example of building A. The CO₂ as well as the primary energy evaluation yield equivalent results. Due to the supply of heat through district heating of a combined heat and power system, other heat generation alternatives proved to be undesirable. Hence, the exchange possibility through a gas-fired condensing boiler does not matter. Besides the heat generation, insulation measures of the building envelope proved to be the best retrofit options for CO₂, final energy, and primary energy savings. Above all, the bottom-side ceiling insulation emerged as the best variant. As a main reason the low investment costs per square meter can be made responsible.

Building B shows differentiated results within the three evaluation types which are presented in Figure 3.41 for the final energy and in Figure 3.42 for the primary energy savings. The district heat from a heating plant is not as precisely evaluated as the district heat for building A and so strongly influences the assessment results. Low investment costs and high primary energy savings makes the use of a gas-fired condensing boiler the best measure in the primary energy evaluation. Other well-rated retrofit packages (see Figure 3.42) are based on the accurate evaluation of the heat supply exchange. The final energy evaluation mainly follows the results of building A and rates measures on the building envelope as optimal. A tendency for the best retrofit order can be seen in the high dependency on the investment costs. The higher the investment cost per square meter, the less effective is the retrofit measure.
3.5.3 Economic evaluation

As described above, the measures evaluated for the sample buildings concern the different parts of the building envelope (cellar ceiling, outer walls, windows, roof), the lighting, and heat supply. Here, condensing boilers were considered, being the most common heat supply for retrofit projects. The investment costs for the individual measures are shown in Figure 3.43. Investment costs for combinations of measures are taken as additive.

The parameters for the economic evaluation and the user energy price scenario were set according to Table 3.4. Parameter variations were performed for

- the discount rate (nominal values 3.0% | 4.25% | 5.5%) as well as
The results of the conventional evaluation using energy price scenarios are summarized in two figures for each building, showing the influence of discount rates and energy prices in the first and of the heat price in the second figure. As there are 63 retrofit alternatives consisting of different combinations of measures, the figures only show the individual measures as well as those combinations giving a positive net present value. Since the standard user energy price scenario results are very close to those from base scenario B, only the latter are depicted. The Monte Carlo simulation results are shown by using the results graph from the retrofit tool.

Apart from investment costs, the fact that both buildings are currently supplied with district heat has the greatest influence on the results from the economic analysis. While energy efficiency measures on the building envelope result in energy savings, none of them is advisable economically at the heat prices assumed here. Energy costs are too low for energy savings to offset the high investment costs. This holds true for all variants of the energy price scenario. In the present case, the latter have much less influence on the net present value than the discount rate (see Figure 3.47). However, costs are such that all of the building envelope measures would be sound in a let building for discount rates up to 4.9%. The same results apply for energy-efficient lighting, which has both the second-smallest cost and return values and the least savings of all retrofit alternatives.

Conversely, changing the heat supply to a fossil-fuelled condensing boiler would present an economic advantage. This is due to both low investment costs (4% to 50% of the envelope measures

Figure 3.38: Evaluation of building B - heating curve.
in the case of a gas boiler) and high energy cost savings due to the lower price for gas (and fuel oil) compared to heat. Thus, in the present case, it would be more economical to forego energy savings when assuming the energy prices as set forth in section 3.2.3. If the current heat price would be 0.02 EUR/kWh lower, bringing it close to the gas price, the gas boiler would of course lose its advantage as there would be no energy cost savings. A higher heat price, on the other hand, would make a number of combined measures financially worthwhile (see Figure 3.45). Yet, all of them still include the condensing gas boiler. Thus, the economic advantage of the gas boiler investment can be used to offset the negative present value of building envelope and lighting investments, resulting in retrofit packages that offer both energy savings and a positive return on investment. The combination offering the highest NPV, while still giving significant end-use energy savings, is the retrofit package boiler + roof + cellar ceiling + outer walls.

In order to obtain a positive NPV even for the most cost-efficient individual envelope retrofit option without the gas boiler (cellar ceiling), the current heat price would have to be about 75% higher or the yearly price change close to 12%.

The Monte Carlo simulations give a similarly shaped field of results as the conventional evaluation, in that the mean NPVs are arranged in strings with and without the boiler (see Figure 3.46). However, note that there are two significant differences:

- Mean NPVs are consistently lower than in the scenario cases, giving a slightly negative value even for the economically best measure “condensing boiler”.
- The difference between envelope measures and packages containing the boiler is much smaller than in the scenario results, making the “cellar ceiling insulation” a very close second.

Both phenomena result from the descriptions of the historical energy price data used in the simulations. As outlined in chapter 3.2, price data are described as $p_E(t) = p_{E,\text{base}} \cdot r_E^t$, where $p_{E,\text{base}}$
and \( r_E \) are given as distributions. While the latter’s mean values are not sufficient to describe them, they can still indicate differences to the user scenario, which is described in the same form (and is very similar to base scenario B when parameterized according to Table 3.4). In the sample case under consideration, the heat price is the most influential variable, and its mean value derived from the historical data is about 15% lower than the most recent price used as a starting point for the scenario projections. Furthermore, the change rate derived from the historical data is lower than in the scenario projections (1.012 vs. 1.03). Thus, energy costs in the sample building are both currently, and projected to remain, too low to economically warrant a retrofit investment. Furthermore, the price difference between heat and natural gas is slightly lower than in the scenarios, reducing the advantage of the condensing boiler.

Thus, the sample case under consideration illustrates the importance of both the absolute and relative energy price levels as well as of the method of analyzing the energy price data. It would be worthwhile to evaluate a different specification of the price data, namely leaving the base prices constant and using only the distribution of the change rates as input assumptions for the Monte Carlo simulation. However, a sample case where more options are economically worthwhile would better show the capabilities of the Monte Carlo analysis in selecting the most favorable option. Results from a different sample case analyzed during the project are described in Kumbaroglu and

**Figure 3.40:** Final energy saving potentials of building A.
Results

Figure 3.41: Final energy saving potentials of building B.

Madlener [2012].

The results for building B exhibit the same overall trends as above, but also some minor differences. Specific energy savings are higher than in building A for most individual retrofit measures (see section 3.5.2), thus the body of results is moved along the positive x-axis (compare Figures 3.45 and 3.47). This is especially true for the cellar ceiling insulation, which is the individual measure closest to cost effectiveness, and thus part of the three retrofit combinations offering a positive net present value.

Again, raising the assumed heat price by 0.02 EUR/kWh makes more measures worthwhile economically; however, there is a lesser number of both economically and energetically favorable combinations due to the lower NPV of substituting the district heat supply by a boiler.
Results

Figure 3.42: Primary energy saving potentials of building B.

Figure 3.43: Investment costs of retrofit measures for sample buildings (Data source: EBC).
Results

Figure 3.44: Net present values over final energy savings for individual retrofit measures and for combinations with positive NPVs (Building A). Data points show the base energy price scenario, path B. Paths A and C are depicted as error bars for the standard discount rate of 4.25% (Energy data: EBC).

Figure 3.45: Individual retrofit options and combinations with positive NPV for standard and raised heat price, sample building A. Data points for combinations are in groups of two, the second point (to the bottom and right) depicting the addition of new lighting to the retrofit package (Energy data: EBC).
**Results**

**Figure 3.46:** Results sheet for Monte Carlo simulation of standard case, building A (discount rate 4.25%). Source: Retrofit tool / EBC.

**Figure 3.47:** Net present values over final energy savings for individual retrofit measures and for combinations with positive NPVs (building B). Data points show the base energy price scenario, path B. Paths A and C are depicted as error bars for the standard discount rate of 4.25% (Energy data: EBC).
Figure 3.48: Individual retrofit options and combination with positive NPV for standard and raised heat price, sample building B. Data points for combinations are in groups of two, the second point (to the bottom and right) depicting the addition of new lighting to the retrofit package (Energy Data: EBC).
4 Conclusion

The energy efficiency of buildings can be significantly increased by an optimized building operation and an energetic enhancement of the building services and envelope. This project succeeded in providing two system-independent software tools to advise the optimization process for private and public office stock holders. Therefore, several simplification and evaluation measures were implemented and successfully tested.

A retrofit tool was developed, which includes a detailed analysis of typical retrofit options for the building envelope and its supply system. Solutions enabling a time-saving accelerated data input for non-residential buildings and a handling of incomplete and missing data were implemented. An automated calculation of retrofit options, leading to up to 64 combinations of measures which are evaluated and visualized according to energy- and CO\textsubscript{2}-saving criteria as well as economic ratings.

As for the economic evaluation, the project has succeeded in implementing both a detailed conventional as well as a more advanced real options-type analysis for choosing between retrofit alternatives. The conventional evaluation, using the net present value method, is already more comprehensive than existing tools. It accounts at the same time for all relevant cost factors, the time value of money, and the uncertainty in energy price trends. A further step has been taken by implementing a sequential decision framework and using a Monte Carlo simulation of energy price trends based on historical developments. Thus the user may choose a “wait and learn” approach for the highly irrevocable retrofit decision process. We recommend testing the latter approach against the conventional one for other sample buildings and several energy carriers since the sample cases described in the report exhibit a number of economically favorable retrofit options that is too small for a meaningful comparison.

Using measured data from building management systems, the evaluation tool stores the collected datasets in a hierarchical data format and allows the use of several evaluation methods. The functionality includes the calculation and visualization of optimization potentials in the field of heat generation and distribution as well as thermal comfort. Benchmarks of the heat and electricity consumption, monitoring of time schedules and misadjustments are further evaluation possibilities. Data quality plots give a fast check on the usability of data sources and the possibility of data cleaning.
5 Further steps, future developments and proposed actions

The retrofit tool offers a lot of further expansion options. The selection of retrofit options is actually limited to a small number of state-of-the-art measures. An enlargement of these provided choices with more unconventional measures as well as the possible utilization of renewable energy sources should be integrated. The use of optimization functions to accelerate the calculation of the best retrofit option is also conceivable. Besides the evaluation of office buildings, more building types should be integrated. One of the essential further developments within the retrofit tool has to be the integration of a more detailed system technology computation. For mapping the reality more accurately, simplified and fast algorithms need to be developed that allow at least hourly calculation steps. This way, the combination and comparison of high-resolution measurement data with simulations would greatly improve the energy efficiency evaluation of buildings.

Possible future additions within the economic analysis are a more detailed treatment of the let building case, for example, by allowing specification of rent increases independently of the investment. This would allow a consideration of the German Civil Law (§ 558 BGB) for increases with constant rent including heating (in German: “warmmietenneutraler Zuschlag”) and of the situation in different countries. A most valuable study beyond the scope of the present project would be a more detailed analysis of energy price trends, both historical and derived from energy scenario research. The latter would ameliorate the price scenarios implemented within the tool. The former could be used to hone the Monte Carlo simulation of future energy prices, which is based on distributions describing historical price trends. In this context, a different description of the energy price data should be explored, namely keeping the base price constant and using only the distribution of the change rate as an assumption for the Monte Carlo simulation.

One of the main problems for the evaluation of the building operation was the lack of information and the lack of data. Many of the developed evaluation methods could not be used due to incomplete or missing datasets. Future developments should also attempt to enhance the data quality and methods that require a minimum on information. Further evaluation methods should also enable to use of short measurement periods to estimate yearly patterns. Additionally, more evaluation scripts concerning specific parts of the system technology are necessary to get a better and faster insight into the building operation.
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6.3 Annex for the economic analysis

The following input guidance for choosing the parameters of the economic analysis is provided in the retrofit tool in its German version, following the English explanations given in section 3.3.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Einheit</th>
<th>Standardwert</th>
<th>Auswahlmöglichkeiten bzw. Informationen (für Eingabemaske)</th>
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<tr>
<td>Betrachtungszeitraum</td>
<td>Jahre</td>
<td>10</td>
<td>Frei wählbar. Entspricht üblicherweise dem Finanzierungszeitraum (Kreditlaufzeit), ggf. Lebensdauer der einzusetzenden Komponenten berücksichtigen.</td>
</tr>
<tr>
<td>Inflationsrate</td>
<td>%</td>
<td>2.00</td>
<td>Verwendet zur Berechnung der realen Preise (Inflationsbereinigung). Standardwert 2 % entspricht dem Zielwert der Europäischen Zentralbank. Kurzfristige Schwankungen können im Bereich 0.5% – 3 % liegen.</td>
</tr>
<tr>
<td>Transaktionskostenfaktor</td>
<td>%</td>
<td>7.00</td>
<td>Zusatzkosten i. H. v. 3 % – 8 % der eigentlichen Investition, z.B. für Informationsbeschaffung, Planung, Vertragsverhandlungen.</td>
</tr>
<tr>
<td>Kalkulationszinssatz (nicht inflationsbereinigt)</td>
<td>%</td>
<td>4.22</td>
<td>bei interner Finanzierung: 2.25 % - 5 % entsprechend den Zinssätzen der Bundesanleihen seit 2001. Bei externer Finanzierung: entsprechend Kreditzinssatz</td>
</tr>
<tr>
<td>Kredit: Laufzeit</td>
<td>Jahre</td>
<td>10</td>
<td>Anhaltswerte: KfW-Kreditlaufzeiten 5 – 20 Jahre, jedoch neue Kreditkonditionen nach 10 Jahren</td>
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<tr>
<td>Kredit: Tilgungsfreie Zeit</td>
<td>Jahre</td>
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<td>KfW-Zinssätze liegen bei 2.17 % - 7.78 % abhängig von Laufzeit, Kreditwürdigkeit und Sicherheiten</td>
</tr>
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<td>Selbstgenutzt oder vermietet</td>
<td></td>
<td></td>
<td>(Auswahlfeld: Selbstnutzung / Vermietung)</td>
</tr>
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</table>
Mieterhöhung (in % der Investitionskosten) | 11 |
---|---|
Bei vermieteten Gebäuden bis zu 11 % der Investitionskosten (abzüglich Zuschüsse). Bei Mieterwechsel frei wählbar.

Förderung betrachten | ja |
---|---|
Investitionszuschuss für Pelletkessel, Wärmepumpen berücksichtigen (ja/nein)

Fördersumme | EUR 0 |
---|---|
Weitere bzw. alternative Fördersummen je Sanierungsvariante

Energiepreisszenario | - |
---|---|
(Auswahlfeld: 1 – Basisszenarien, 2 - Monte Carlo Simulation, 3 – Preisänderungsraten Nutzer)

Verschieben der Investition prüfen? | nein |
---|---|
Prüfung, ob Investition zu einem späteren Zeitpunkt rentabler wäre (Realoptionen-Analyse). Nur möglich, wenn Energiepreisszenario = Monte Carlo Simulation

Wartungskosten vor Sanierung (EUR/a) | falls bekannt, sonst "nach VDI" ankreuzen |
---|---|
jährliche Kosten angeben, falls bekannt, sonst “nach VDI” ankreuzen

Betriebskosten vor Sanierung (EUR/a) | falls bekannt, sonst “nach VDI” ankreuzen |
---|---|
jährliche Kosten angeben, falls bekannt, sonst “nach VDI” ankreuzen

Preisänderungsraten Kapital / Betrieb / Wartung | 1.02 |
---|---|
Standardwert 1+Inflationsrate entspricht Änderung lediglich entsprechend allgemeiner Inflation

Ist-Energiepreise EUR/kWh | für eigenes Energiepreisszenario. Angaben bezogen auf Ho. |
---|---|
jährliche Preiseänderungen der Energieträger, z.B. 1.05 für 5% Preissteigerung pro Jahr.

Preisänderungsraten Energie | - |
---|---|
Für eigenes Energiepreisszenario. Muss, real, d.h. inflationskorrigiert, angegeben werden.
6.4 Short CV of scientists involved in the project

**Gregor Hillebrand, M. Sc.** studied Architecture at the HTWG Konstanz and Mechanical Engineering (Renewable Energies and Energy Efficiency) at the University of Kassel. He joined the Institute for Energy Efficient Buildings and Indoor Climate (EBC) in 2010 and has worked in the field of energy concepts for buildings and communities.

**Dr.-Ing. Gesine Arends** studied Mechanical Engineering at RWTH Aachen. After doctoral studies at Forschungszentrum Jülich, she joined Corporate Research at Robert Bosch GmbH, Stuttgart, where she worked on fuel cell and small CHP systems. During her parental leave, she joined E.ON ERC’s EBC and FCN institutes in 2009 and has worked on district heating, microgrid and retrofit projects.

**Dr.-Ing. Rita Streblow** studied Building Services Engineering at the Technical University Berlin. She worked as research associate at the Hermann-Rietschel-Institute at Technische Universität Berlin (2003-2007). In 2007 she joined the Institute for Energy Efficient Buildings and Indoor Climate at RWTH Aachen University. In 2011 she finished her PhD studies at RWTH Aachen University. Nowadays she leads the research group for energy efficient buildings and city quarters.

**Prof. Dr. rer. soc. oec. Reinhard Madlener** studied Commerce and Finance as well as Pedagogics at the Vienna University of Economics and Business Administration (WU Wien) and then also Economics at the Institute for Advanced Studies Vienna (IHS). He obtained his PhD at WU Wien in Economics and the Social Sciences (Dr. rer. soc. oec.), specializing in General Economics, Environmental Economics, and Statistics. Before taking up his position at RWTH Aachen University in June 2007, he was Managing Director of the Institute for Advanced Studies Carinthia (1999-2000), Assistant Professor at the Centre for Energy Policy and Economics (CEPE), ETH Zurich (2001-2007), Lecturer at the Faculty of Economics, University of Zurich (since 2003), and Senior Researcher at the German Institute of Economic Research / DIW Berlin (2007). Among others, he was Visiting Fellow at the University of Illinois (Urbana-Champaign), the European University Institute (Florence, Italy), and the University of Warwick (Coventry, UK). Prof. Madlener is one of five full professors of the E.ON Energy Research Center (E.ON ERC), Director of the Institute for Future Energy Consumer Needs and Behavior (FCN) founded by him in June 2007, honorary Research Professor at the German Institute of Economic Research (DIW Berlin), and RWTH director of JARA-Energy.

**Prof. Dr.-Ing. Dirk Müller** studied Mechanical Engineering at RWTH Aachen University. He obtained his Doctoral Degree at RWTH Aachen University at the Institute for Heat and Mass Transfer. Before taking up his position at RWTH Aachen University in 2007, he was Project Leader for Research and Advanced Engineering, Robert Bosch GmbH (1999-2002), Manager in the field of Advanced Simulation Tools and Processes, Behr GmbH & Co. (2002-2003), and Head of the Hermann-Rietschel-Institute at the Technical University of Berlin (2003-2007). Prof. Dr.-Ing. Dirk Müller is one of five full professors of the E.ON Energy Research Center (E.ON ERC), established at RWTH
where she worked on fuel cell and small CHP systems. During her parental leave, she joined E.ON ERC’s EBC and FCN institutes in 2009 and has worked on district heating, microgrid and retrofit projects.

6.5 Project timeline

<table>
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<th>2010</th>
<th>2011</th>
<th>2012</th>
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</thead>
<tbody>
<tr>
<td>1 11</td>
<td>2 12</td>
<td>3 1</td>
</tr>
</tbody>
</table>

WP 1: Development and design of a retrofit matrix

WP 2: Data acquisition at RWTH Aachen University

WP 3: Cost optimized retrofit path

WP 4: Software development for building stock analysis

WP 5: Evaluation of two buildings from RWTH Aachen University
Project synopsis

Gregor Hillebrand, Gesine Arends, Rita Streblow, Reinhard Madlener, Dirk Müller

E.ON Energy Research Center (E.ON ERC), RWTH Aachen University
Mathieustr. 10
52074 Aachen, Germany

Gregor Hillebrand, M.Sc.  Univ.-Prof. Dr.-Ing. Dirk Müller
Dr.-Ing. Rita Streblow  Tel.: +49 241/80 49767
Tel.: +49 241/80 49769  Fax: +49 241/80 49769
rstreblow@eonerc.rwth-aachen.de  dmueller@eonerc.rwth-aachen.de

Dr.-Ing. Gesine Arends  Univ.-Prof. Dr. rer. soc. oec. Reinhard Madlener
Tel.: +49 241/80 49833  Tel.: +49 241/80 49820
Fax: +49 241/80 49829  Fax: +49 241/80 49829
garends@eonerc.rwth-aachen.de  rmadlener@eonerc.rwth-aachen.de

Categories E.ON ERC focus

☐ Small Scale CHP  ☐ Large Power Plants
☐ Energy Storage  ☞ Energy Efficiency
☑ Consumer Behavior  ☑ Energy Economics Modeling
☑ Energy and Buildings  ☐ Power Electronics
☐ Distribution Networks  ☐ Renewable Energy
☐ Carbon Storage (CCS)  ☐ Others: Medium-Size Power Plants

Type of project report:  Final Project Report

Start and end date of project:  November 2010 - April 2012

Project in planned timelines:  ☑ yes  ☐ no (see Section 6.5)

Participating Chairs of E.ON ERC

☐ Automation of Complex Power Systems (ACS)
☑ Energy Efficient Buildings and Indoor Climate (EBC)
☑ Future Energy Consumer Needs and Behavior (FCN)
☐ Applied Geophysics and Geothermal Energy (GGE)
☐ Power Generation and Storage Systems (PGS)
Acknowledgments

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Ergonomie der thermischen Umgebung – Analytische Bestimmung und Interpretation der thermischen Behaglichkeit durch Berechnung des PMV- und des PPD-Indexes und Kriterien der lokalen thermischen Behaglichkeit
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