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Development and design of a retrofit matrix for office buildings☆

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ABSTRACT

This paper describes the methodology developed and the calculation steps used to evaluate the energy efficiency potential of office buildings. The methodology enables a detailed analysis of retrofit options for the building envelope and its energy supply system. Different simplification measures accelerate the data acquisition process for office building stock owners and allow a data handling according to the existing building information, thus enabling office building structures to be prompted to design typical building constructions. We implement solutions enabling both a time-saving accelerated data input for office buildings and the handling of incomplete data. An automated calculation of the most common refurbishment measures allows a comparison of up to 64 combinations of measures, the illustration of energy and CO_2 savings, and an economic evaluation. The latter 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 and a real options analysis are implemented, enabling a comparison of retrofit alternatives with different initial and future cash flows both for buildings occupied by the investor (owner-occupier perspective) and for rented buildings (tenant perspective). Energy price scenarios as well as a Monte Carlo simulation account for the uncertainty in energy price trends. For a university building used as a test case, the simplified and time-saving data input methods were successfully tested and an automated evaluation of 64 typical retrofit combinations carried out. The results of the energy, ecological and economic efficiency evaluation shows that a generally preferred retrofit option cannot always be identified. Specifically, for the test case, the best-rated economic refurbishment possibility leads to the largest increase in final energy demand amongst all options considered, which points out the necessity of a multi-criteria evaluation.

1. Introduction

As a consequence of the Kyoto Protocol and the required reduction in CO_2 emissions therein, huge efforts must be made to save high quality or primary energy resources. Besides the discussion about the kind of energy production, a key role comes up to the efficient use of energy in all economic areas [2]. This is also reflected in the climate policy plans of the European Union. By 2020, a reduction of the greenhouse gas emissions of around 20%, a rise in the renewable energies as a share of gross final demand to 20%, as well as an increase in the energy efficiency of up to 20% are planned [3]. Especially in the building stock there is still considerable energy-saving potential. With a portion of 37% in the German CO_2 emissions [4] and a similar portion in the primary and final energy consumption [5], the relevance of energy use in buildings becomes clear. The fact that more than 80% of all buildings are older than 25 years and have not yet been refurbished underlines this hypothesis [6]. This study focuses on office buildings because these buildings consume approximately 10% of the final energy consumption in Germany.

To organize and advise the retrofit process for private and public office building stock holders, this paper describes a tool for a detailed analysis of different retrofit options for the building envelope and its energy supply systems. Different measures, potential energy and CO_2 savings, cost estimates, and additional information, including special user demands and internal building ratings, can be selected and calculated to indicate possible pathways for enhancing the building's energy efficiency. In addition, the tool enables a reliable estimate of the economic impact of each investment alternative. To this end, not only the investment itself, but future cost savings arising from each retrofit measure are also taken into account. The most important of these are (saved) payments for energy or rental income/expenditures (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 are made comparable by

☆ Further details on this research can be found in [1].

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employing a dynamic evaluation method, i.e. by considering the time value of money, where prior art mostly used static methods. Furthermore, the problem of uncertainty regarding energy price development, which is the most influential parameter, is addressed in two ways: The simultaneous evaluation of different scenarios and 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 refurbishment.

The remainder of this paper is structured as follows. Section 2 introduces the methodology. Section 3 describes the economic analysis, Section 4 presents a sample application and result visualization, while Section 5 concludes.

2. Development and design of a retrofit matrix

For the energy evaluation of buildings, the European Union has implemented the Energy Performance of Buildings Directive [7]. This EU directive was implemented at the national level in Germany with a set of preliminary standards defined in DIN V 18599 [8]. This standard allows the calculation of the energy efficiency of entire buildings and also considers energy refurbishment potentials. Since the introduction of regulation EnEV 2007 [9], the calculation methodology has been prescribed according to this standard and later been expanded by the coverage of residential buildings with regulation EnEV 2009 [10]. However, the ordinance DIN V 18599 describes a far-reaching and complicated approach to assessing the building envelope and facility technology, which leads to cumbersome procedures and high monetary expenditures. Several studies have examined the time needed for the so-called "requirement certificate", which evaluates the energy demand of a building and shows alternative retrofit possibilities. It became apparent that the average time needed ranges from 78 [11] to 80 h [12] up to 240 h [13], depending on the building size. Besides the vast amount of time, it was shown that the required data, e.g. concerning construction materials and surfaces, were often either unavailable or inexistent. Based on these outcomes, the future energy evaluation or retrofit tools need to focus on simplification measures in order to accelerate the assessment process and to be more adaptive to the available data stock.

The overall objective of the retrofit tool is the energy analysis of existing non-residential buildings. To implement this, energetic qualities and weaknesses of the building envelope and the system technology need to be assessed and identified. The energy demand of the current building state and refurbished states needs to be calculated. Also, energy losses through ventilation and transmission as well as energy gains through solar irradiation and waste heat of persons or technical equipment need to be balanced. In order to set up an energy balance, detailed information about the building must be available. Data on the size and the characteristic building shell, and details about the functional areas as well as information on the installed technical equipment are needed. Furthermore, a calculation methodology is required that merges the building data and yields an energy balance.

In practice, the parameters for the energy balance need to be extracted from floor plans, views, and detail drawings. As highlighted above, this procedure is very time-consuming and precise information for existing buildings, especially older ones, is typically unavailable. Therefore, it is necessary to enable two possibilities for a fast refurbishment examination: First, simplification measures for a quicker data acquisition have to be adopted. Second, a data stock adaptation due to incomplete building information should be implemented.

The basis of the method developed in this research is not the complete, detailed building data, but instead standardized building types. In a first step, and with a minimal set of data, enveloping surface areas, functional areas, etc. are estimated. Characteristics

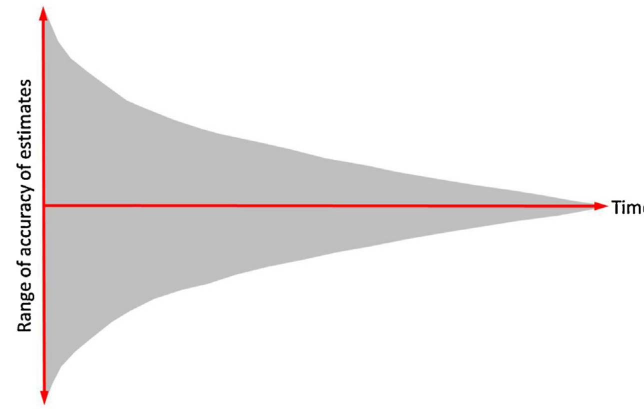


Fig. 1. Concept of the retrofit matrix.

of the building type can then be shown and typical, common refurbishment possibilities calculated. If more detailed information is available, this can be used to calculate the building performance in a more accurate way. Fig. 1 shows this procedure schematically. On the basis of very limited data, first estimations can be made and a small amount of time is needed for the audit. Depending on the time and available data, a smooth transition according to the depth of detail of the data acquisition is possible. The following analysis exemplarily outlines this approach and explains the implemented calculation core as well as the zoning method.

The *computation core* forms the basis for the calculation of the energy demand, with the help of an energy balance. Scrutiniting calculation methods typically used in Germany reveals that monthly or yearly balancing methods are common [8,14]. Besides the calculation of the yearly energy demand, it might also be necessary to compare the energy demand with the real energy consumption. Standard boundary conditions, such as the weather or the behavior of building occupants are used for the calculation of the energy demand, and often deviate considerably from the real weather and the real persons' behavior. Recalling the energetic evaluation of buildings and refurbishment possibilities, those different boundary conditions may influence the results. For this reason, matching expected demand and actual consumption is necessary. Carrying out such a matching between demand and actual consumption, monthly or yearly values can be 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. For this reason, the calculation method for determining the useful energy needs 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. In practice, a wide variety of different calculation techniques exists within the building industry.

Taking into account the computational speed on the one hand and the accuracy on the other hand, a so-called "two capacity model" (2-c-model) was implemented as the main computation core. This dynamic thermal model is described in detail in the German directive VDI 6007-1 [15] and allows a validation of the calculation method with the aid of 12 test examples. It is also mentioned in the standard for 'Requirements of methods for calculating thermal and energy simulation of buildings and plants' [16] and considered there as being sufficiently adequate for building simulations. Since March 2012, it has also become a part of the German standard VDI 2078 [17], which is used for the calculation of the cooling load and room temperatures of rooms and buildings. To verify the implemented algorithms, the calculation methods were validated with the 12 test examples included in the standard VDI 6007-1 [15]. In Fig. 2 the outcomes of a monthly balance

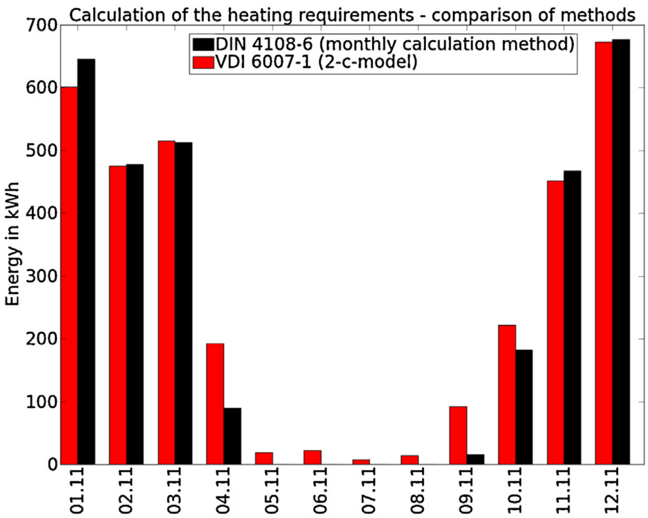


Fig. 2. Validation of the "two capacity model" with a monthly calculation method.

calculation [14], which is normally used to calculate the energy demand of residential buildings, are compared with the monthly sums of the implemented computation, showing very similar results. Fig. 3 depicts the adjustment of measured and simulated data. The temporal course of the heat load of a university building is compared with the simulated hourly values. An obvious and likely trend is clearly visible, and thus a sufficient precision of representing reality is achievable.

The *classification of zones* in non-residential buildings is 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 (like offices, toilets, etc.) are summarized in usage profiles defined in the standard DIN V 18599 [8]. For each defined zone, a list of parameters must be determined and documented (like volume, area, orientation, etc.). If the complexity and extension of buildings increase, the zoning and data acquisition will take more and more time and constitute the main opportunity of time savings during the assessments. Because of that, in the last couple of years a number of simplification methods have been examined and discussed in the literature [18,19].

In view of the possibility to change the level of precision, the method of a zone area-weighted allocation of the enveloping surfaces has been found to be the most promising one [18]. It is examined in Lichtmeß [12] and consists of two basic hypotheses: First, there is a sufficiently precise correlation between the thermal

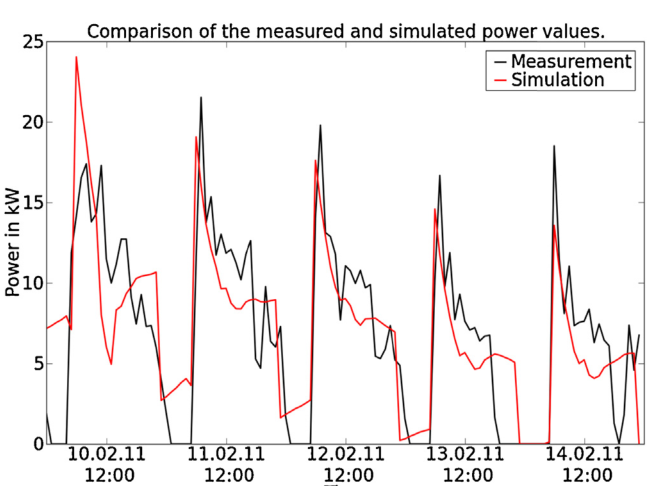


Fig. 3. Validation of the "two capacity model" with measured data.

enveloping surface and the zoning area. Second, an automated distribution of the enveloping surface to the zones causes a negligible error in the calculated power consumption. The study of Lichtmeß showed that the errors in calculating the energy needs with these simplifications are indeed minor and that the results are sufficiently precise for an evaluation of energy use. 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.

The simplifications described in Lichtmeß [12] work on two levels, as shown in Fig. 4. Level one is the level of the enveloping surfaces of the building. Values for the orientation, the type of construction, or the surface area are acquired just as for a one-zone-building. Level two is the level of zones. As already described at the beginning of this section, areas of the same utilization and conditioning are summarized in usage profiles. At this step, no enveloping surfaces are allocated to the zones. The advantage of this method is that for further energy balances, the enveloping surface and the zones can be edited separately and the time for the data acquisition reduced. In a further step, the building and the zone level are combined. The enveloping surfaces are defined at the building level and, then, depending on the size of the zone, allocated to the zones. On this simplification level, the zone area-weighted allocation is based on the percentage distribution of one zone area to the area of all zones. In an extended method, correction factors are introduced to offer a more accurate allocation. Each zone area can be influenced over a weighting factor to consider the actual component's existence in a zone. For a relevant and clear statement these correction factors are binary, i.e. limited to the numbers 0 and 1. With the help of this information, the office-specific method is reduced to gather data for a standardized building on three points:

- Estimation of office-specific enveloping surfaces.
- Estimation of typical zone area allocations.
- Definition of office-specific correction factors.

The *enveloping surfaces* for a specific type of office building were estimated with the functions taken from BMVBS [20]. In this study, by means of a simplification of the geometrical survey of non-residential buildings, the dependencies between the net floor space or the gross floor space and the enveloping surfaces are examined. For office buildings, a clear mathematical relationship for windows, outer walls, roofs, and floors was found.

A first characterization of *typical zones* in office buildings and zone divisions can be made with the information from BMVBS [20]. On the basis of this information, 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%).

To map the enveloping surfaces and the *allocation* of the enveloping surfaces more correctly to the zones, the building structure is queried with the help of three different selection possibilities that are based on typical ground plan structures of office buildings [21]. As shown in Fig. 5, a distinction is made between a double-depth floor plan, a triple-loaded building and a centrally structured house. Therewith, a relationship to typical building widths, and zones which are not located on the outer walls, can be derived. For example, a triple-loaded floor plan has an expected building width of 15 m and the ancillary spaces and circulation areas are located somewhere in the middle of the

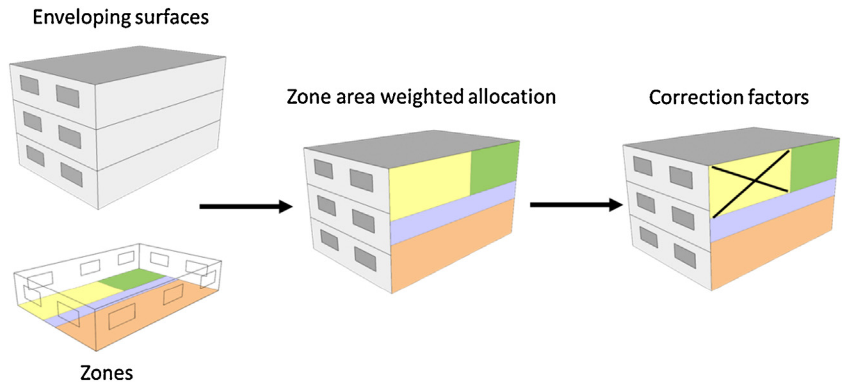


Fig. 4. Method of a zone area weighted allocation of enveloping surfaces with correction factors.

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.

3. Cost-optimized retrofit path

Various decision aid tools were developed in the past to support and advise building stock owners with respect to retrofitting options. An early example is the TOBUS software [22], which implements the results of a European research project on building diagnosis and selecting upgrading solutions [23]. Jakob et al. [24] 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, and deplore the lack of "computer-based tools which identify the relevant cost-benefit-relations and allow optimization in the first place" [24]. A review of tools for the residential sector performed by Mills [25] finds that indeed only few offer substantial decision support content.

One such methodological attempt was made in Greece by Doukas et al. [26], 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. [27]. Like Jakob's study, it uses building archetypes and energy simulation software. The problem of multiple objectives influencing retrofit decisions was addressed by Diakaki et al. [28], whose model allows the user to evaluate alternatives according to criteria influenced by user preferences.

While many of these retrofit tools offer a fairly complex treatment of technical and energy aspects, economic evaluations are typically considerably less comprehensive (for a critical review see [29]). For instance, [22] as well as [28] use investment cost only, thereby neglecting expected future cash flows. This is inadequate for comparing retrofit investment alternatives, since they generate costs and benefits, such as maintenance and energy costs

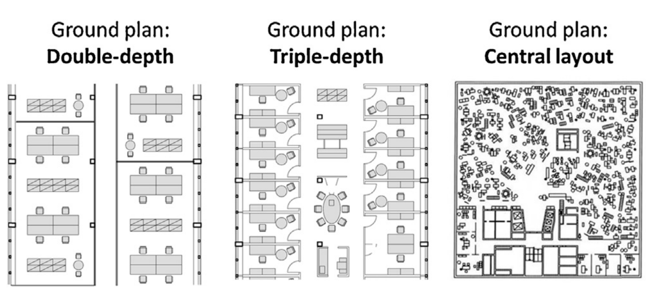


Fig. 5. Office-specific ground plan structures.

savings, far into the future. A static approach, such as the computation of the payback period based on first-year costs, disregards both cost changes and the different value of present and future payments. Even where the time value of money is accounted for by using net present values [26] or a discounted payback period [27], relevant cost factors, such as maintenance costs, have mostly been neglected. Furthermore, all of these tools employ deterministic energy prices, ignoring both the uncertainty inherent in this often most influencing factor and also the value of the managerial flexibility to optimize the timing of the retrofit. Historical data for energy prices show fluctuations and trend reversals, indicating that simply assuming a linear trend is often only a very crude approximation. Verbruggen et al. [30] and Kumbaroğlu and Madlener [29], therefore, argue for the dynamic economic modeling of decision-making processes related to energy retrofit investments. Since many retrofit decisions are highly irreversible and preclude later changes, in their opinion, a dynamic approach which accounts for the value of waiting may provide better guidance. Real options analysis can be very useful for that.

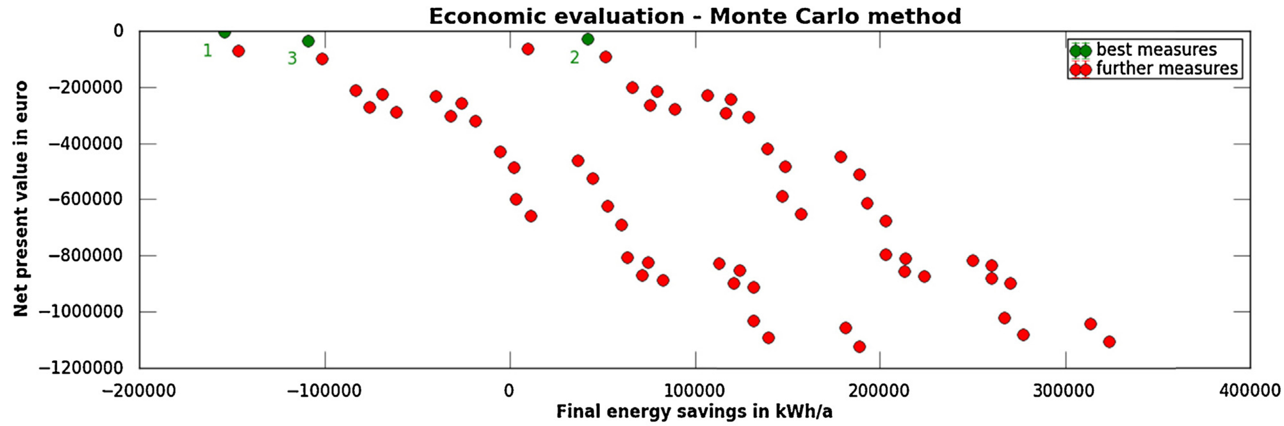
The methodology employed for the economic evaluation of the different retrofit alternatives comprises three elements: a Net Present Value method, uncertainties of energy price development, and a Real Options Investment Appraisal (on the latter see [8]).

The Net Present Value (NPV) method is used to compare investments with different initial and future costs and benefits. The underlying principle 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. Thus, future cash flows must be discounted to their present values in order to compare them appropriately with present investment expenditures [31]. Using the discount rate 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 as

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

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, which have to be considered when the time horizon is not identical to the service life of the respective components. If the NPV is positive, the investment is profitable and leads to an increase of capital. NPVs of zero (below zero) indicate that the return on investment will be the same as (lower than) the discount factor, respectively. Among all investment alternatives, the one with the highest NPV will be the most favorable.

Future energy prices are often the major factor determining the return on energy retrofit investments in self-used buildings



	Net present value in euro	Investment costs in euro	Energy savings in %	Waiting time in years
Measure 1: -Gas fired condensing boiler	-3494.6	32500.0	-6.2	0.0
Measure 2: -Bottom side cellar ceiling insulation, 20cm	-26691.7	65770.0	1.7	0.0
Measure 3: -Bottom side cellar ceiling insulation, 20cm -Gas fired condensing boiler	-34953.5	98270.0	-4.4	0.0

Fig. 6. Automatically created result sheet for the Monte Carlo simulation, shown for the case of the retrofit of an exemplary university building.

and are very difficult to predict. Historical price developments have shown a dramatic increase during the last decade, both for end-user prices and for 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. 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. For the discrete energy price development scenarios, yearly price change factors are calculated from the latest German Lead Study projections [2] and applied to the end-user prices collected by the German Federal Ministry of Economics and Technology [32]. 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.

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, it may be rational for the investor to postpone the investment, if feasible. The possibility to delay the investment is considered on a sequential basis through a *Real Options Investment Appraisal* [29]. For each period, the probability of achieving a higher NPV in the following period is determined. This is used to compute the succeeding period's expected NPV. If the following period's expected NPV is greater than that of the preceding period, it is recommended that the investor should wait.

4. Sample application and assessment visualization

To demonstrate the merits of the approach, the algorithms and assessment methods were tested for two buildings of RWTH Aachen University. The evaluations were performed for six typical single retrofit measures and every possible combination of these measures (for details see [1]). The retrofit measures contain the building envelope, the heat production, and the lighting system. Each of the calculated measures, or each bundle of measures, is automatically displayed and compared regarding the total energy savings per unit of investment costs in kWh/euro. CO_2 savings, final energy savings as well as primary energy savings are considered. In addition, the results of the NPV, Monte Carlo, and Real Options investment calculations are plotted over the final energy savings.

Fig. 6 shows the results and a typical plot from applying the Monte Carlo simulation method. The building analyzed as a test case for the new methodology is one of the above-mentioned office buildings of RWTH Aachen University. It was constructed in 1962, with a net floor space of 8840 m^2, and 7 storeys, and is connected to a district heating system. The six single retrofit options "20 cm outer wall insulation", "20 cm roof insulation", "20 cm bottom-side cellar ceiling insulation", "double-pane heat insulation glass", "gas–fired condensing boiler" and "TL-5 surface mounted lights" were chosen for this exemplary calculation. Each single retrofit option as well as each possible combination of the retrofit options is displayed in the plot as a dot. The three best-rated measures are marked as green dots, further measures as red dots. Further information on the three best-rated options, such as savings and investment costs, is provided below the visualization.

Results for this office building show that the best retrofit option cannot always be clearly classified. The best-rated economic refurbishment possibility could lead to the largest increase in the final energy demand (i.e. negative energy savings). This is possible, because the option "gas-fired condensing boiler" is the most cost-effective in this case, but is energetically worse rated than the currently installed heating system. Similar results were obtained when comparing further assessment criteria, like CO_2 or primary energy savings.

5. Conclusion

The energy efficiency of buildings can be significantly increased by an energetic enhancement of the building's technical equipment and envelope. In this paper, we introduce a new system-independent software tool to guide the optimization process for private and public office stock holders. For computational efficiency, several simplification and evaluation measures were implemented and successfully tested. The tool 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. In an automated calculation of retrofit options resulting in up to 64 combinations of measures, these bundles of measures are evaluated and visualized according to energy and CO_2-saving criteria as well as economic ratings. Regarding the economic evaluation, the project has succeeded in implementing into a usable format both a detailed conventional economic analysis and a more advanced real options analysis for choosing between retrofit alternatives. The conventional evaluation, using the NPV 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 making framework, and by using a Monte Carlo simulation of energy price trends based on historical developments. Thus, the user may choose a "wait and learn" strategy for the highly irreversible retrofit investment decision, instead of taking a yes-no decision only.

Based on a building of RWTH Aachen University, six typical retrofit possibilities as well as each possible combination of these were calculated and graphically displayed as an example evaluation. Each retrofit option was rated regarding its energy, CO_2 mitigation and cost effectiveness. It was shown that each criteria by itself can offer an evaluation of the top-rated retrofit options. The evaluation with more than one criterion has shown that each criterion may deliver different retrofit orders, which might show an alternative retrofit path. It also illustrates that an evaluation with more than one criterion is essential to assess the best retrofit process.

The paper shows the potential and advantages of the developed tool, which enables a simplified and fast calculation of alternative refurbishment possibilities and the use of a multi-criteria evaluation. One of the most desirable further developments within the retrofit tool presented is an extension of the usable retrofit options. Currently, these are limited to a small number of commonly used methods. Moreover, a detailed system technology computation should be integrated. To map the reality more accurately, simplified and fast algorithms need to be developed which allow at least hourly calculation steps. In doing so, the combination and comparison of measured high-resolution data with simulations would greatly improve the energy efficiency evaluation of buildings. Possible future additions within the economic analysis are a more detailed analysis of energy price trends, derived from both historical data and 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 trajectories.

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