Simulation-based energy efficiency retrofit of listed building ensembles: An alternative solution with a climate envelope

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Abstract. This article draws an innovative architectural solution for enhanced energy efficiency by retrofitting ensembles of listed buildings. A combination of various simulation tools and a self-developed feasibility tool has been used at the preliminary design stage to develop a measure at an urban scale within the campus of TU Berlin.

First, a potential analysis for 48 buildings within the campus has been run using multi-zone simulations with Modelica. Afterward, with the feasibility analysis tool based on Python, called HCBC-Tool, all possible measures have been ranked at the pre-stage of this project. As a conclusion, by buildings where standard measures are not feasible, alternative solutions have been developed using DesignBuilder, where not only energy-related issues but also architectural ones were considered. Additionally, energy substitution measures have been simulated with SunnyDesign to complete the concept. Here, a “climate envelope (CE)”, which is an additional transparent envelope covering the buildings partially, has been developed for a building ensemble built between 1883-1975. Enhancing the energy efficiency of all five buildings within the ensemble with standard measures up to the new building level according to the German energy efficiency regulations would reduce their energy consumption app. 32%. Nevertheless, this regulation is not mandatory by listed buildings. Besides, 12,152 m² external envelope surface should be retrofitted. By comparison, a CE could lead to enhanced energy efficiency and it alone could reduce the energy demand of the building ensemble up to 33% and combining it with standard measures could increase the savings up to 60%.

Keywords: Retrofit, Climate Envelope, Listed Building

1. Introduction

Within the EnEff: Hochschulcampus Berlin Charlottenburg: 1. Umsetzungsphase (HCBC) research project, funded by the Ministry of Federal Ministry of Economic Affairs and Energy, Technische Universität Berlin and Universität der Künste Berlin together aim to become an ecologically innovative and climate-friendly campus fulfilling the government program goals with innovative solutions that consist energy network, energy systems and building envelope retrofitting.

The government aims till 2050 80% increase in energy efficiency compared to the 2008 level [1]. Universities, as role models, should use their cumulative know-how to obtain and to sustain a high energy efficiency and comfort level [2]. Within the research framework called “EnEff: Campus” (energy-efficient campus), many universities have been running research and development projects to reach this goal [3]. Various national universities have taken part in the same program. For instance, regarding their own campuses, the TU Braunschweig has aimed to enhance 80-90% of its buildings up...
to the plus-energy level [4], where the RWTH Aachen 50% savings for feasible declares [5]. Both universities have taken state-of-the-art measures into consideration. Compared to them, according to the results of the first stage of this research project, the full implementation of the measures in the developed masterplan of energy could reduce the primary energy demand of the whole campus by 90%, respectively 40% through energy savings and 50% through energy substitution.

Nevertheless, the campus of the TU Berlin consists of 48 buildings and building ensembles with a net floor area of 580T m² and 460T m² building envelope surface. With standard measures, like state-of-the-art thermal insulation of the building envelope, replacement of the windows, optimizing the HVAC, it will be impossible to implement whole measures related to the envelope within a reasonable time-frame and budget considering that 28 of the buildings are listed.

1.1. Energy efficiency of listed buildings

Many old listed buildings have an unsatisfactory thermal performance compared to the standards of today [6]. As usual by such buildings, their energy efficiency is according to high levels of air leakage and inadequate insulation very low [7]. Also reaching high energy efficiency levels are rarely possible by such buildings [8]. For this reason, innovative solutions should be implemented to overcome the complications and reach more energy efficiency compared with the potential through standard measures.

Besides, according to the German Preservation Law, each interference in listed buildings should follow rules like maintaining old building fabric, best visible integration, less visibility from the street-side or surrounding buildings, etc. [9].

Nevertheless, the main issue by retrofitting a building ensemble compared to a single building is selecting the measures and accordingly the distribution of budget. The classical approach, retrofitting building by building, could lead to a false investment and time lag. Therefore, it is immensely important to be able to identify most energy-efficient measures and prioritize them according to feasibility and developing alternative measures that are more feasible compared to standard solutions.

1.2. Alternative: Building with climate envelope

As an alternative, climate envelopes have been considered. As described in many publications by the authors [10], it is a permanently climate-adapted space, that can be described as a combination of a building with an additional transparent external envelope. The envelope is utilized as an architectural means of adapting to climate change and to mitigating the effects thereof. One of the first climate envelope with integrated ventilation system has been built in Berlin [11]. Furthermore, a townhouse concept using climate envelopes has been presented in Italy [12]. It is stated that they provide a more efficient option for solar space heating than state of the art solar thermal technologies. Another small-scale demonstration of a CE is being used as laboratory since 2013 in Berlin (Blankenfelde-Mahlow). It aims to mitivate noise and reduce energy consumption [13]. According to such scientifically proven benefits, they have been analyzed as alternative solutions for listed buildings.

Figure 1 A climate envelope prototype of TU Berlin. Besides passive solar gains, the humid air can be converted with hygroscopic air conditioners to heating energy, or vice versa the rooms can be cooled through dehumidification.

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1.3. Objectives and Hypothesis
In order to reach governmental energy-saving goals in Germany, first it is highly necessary to study the following topics:

- how to enhance the feasibility of standard retrofitting measures, and
- how to retrofit listed buildings, although it is not mandatory and related to structural-physical difficulties?

In this manner, it is possible to enhance the energy efficiency of particular buildings or building groups optimizing the climatic conditions around them with an additional envelope that is a less invasive and more efficient method regarding energy efficiency and feasibility. Based on a previous study, this article presents the developed methodology in order to deal with the mentioned situation above, where the following topics have been studied:

- combining various tools and software to enhance time efficiency both for simulations and the implementation of the measure afterward.
- developing another feasibility criterion that enables to compare both energy-saving and energy-substitution measures.
- analyzing the interaction of architecture, preservation order and energy efficiency analyzing climate envelopes.

2. Methodology
The research project bases on three-stage analysis with different tools considering varying aims. The first stage, called pre-stage, consist of simulations with Modelica with simplified building geometry in order to enhance time efficiency, where a whole campus has been simulated, following by the feasibility analysis using the HCBC tool in the first stage. Here the aim is first to be able to compare every different measure type with each other and also to find out a ranking. The second stage, which is the focal part of this paper, consists of in-depth simulations using DesignBuilder for particular buildings with high energy efficiency potential combined with SunnyDesign for photovoltaic integration to the CE.

2.1. Pre-stage: Data-gathering and potential analysis
When dealing with ensembles of buildings, i.e. districts, campuses, etc., model preparation and simulation times become a concern [14]. Regarding that, Modelica has been chosen for the first stage simulations, based on previously developed models. A relational database running on a MySQL database management system has been implemented as a central data-handling tool consisting of detailed building information that collected manually. Then, building models based on the BuildingSystems Modelica library [15] has been created. As described by Inderfurth et. al in Detail, to ensure a fast and especially error-free translation of building information from the database into ready-to-simulate building models, an automatic Modelica code generation has been implemented in the Python programming language with help of the Mako template module\(^1\). Python classes for existing buildings, zones, walls, windows and various component connections have been developed. Instantiated with a corresponding database-ID, objects query the database directly to get their attribute values. For each thermal zone in 48 buildings, energy-saving potential for each kind of measure, totally app. 1,000, has been calculated and listed using Python.

2.2. First-stage: Feasibility analysis for the whole district
The outputs about the potential have been recorded in the HCBC tool that is also created with Python. It enables to sort out or filter the measures according to its energy-saving potential or cost specification. Further, it compares or prioritizes a large number of energy-related measures. In this way, it is possible to develop a masterplan for energy-related measures, that can be customized with

\(^1\) www.makotemplates.org
various parameters and quantitively outcomes like energy price, investment costs, amortization period, etc.

Different criteria like CO₂-savings, maximum savings regarding primary energy, and minimum amortization period have been considered during feasibility analysis, whereas costs per saved primary energy (€/kWha) has been chosen as relevant evaluation criteria for the first time by such analysis.

2.3. Second-stage: in-depth analysis for particular buildings
Following the potential analysis with Modelica, the simulations are deepened with DesignBuilder. Various simulations of climate envelopes have been run, that varied in form and material until achieving an optimal alternative. As the models by Modelica were not geometrical, switching to DesignBuilder enabled, to work on the geometry of the CE in order to analyze the interaction of architecture and energy efficiency.

The simulations have been started with the alternative “a CE between parallel blocks” enhancing the volume of the CE and covered space under it gradually. This results in a surface between 2,240-5,015 m² that corresponds to up to 41% of the existing building surface.

3. Results
The results presented here correspond to the second stage the “in-depth analysis” described in the methodology with inputs from the pre-stage and first stage for comparisons. During the simulations, the model details and the number of the criteria to be calculated or simulated have been enhanced gradually. Hereby, not only energy-related criteria but also architectural and restrictions related criteria have been concerned. This methodology follows operating principles of integral planning and is essential for research and development projects in the field of architecture.

3.1. In-depth simulation of the energy saving potential with DesignBuilder
After simulations with Modelica multi-zone models at the pre-stage, a building ensemble consisting of five buildings as seen in Figure 2 have been identified. According to the simulation results and further analysis, they have common characteristics, as follow:

- all five buildings have a high energy saving potential up to 40.3%,
- they have been built around 1883-1901 (only one in 1950), and are all under preservation,
- a standard retrofitting during running operations is related to major difficulties, and not economically efficient for these buildings according to the simulations, and
- a climate envelope can enhance the usage of this ensemble practically.

![Figure 2](image_url) Building ensemble with five buildings that host different departments of the university.
Afterward, as shown in Figure 3, the CE has been simulated with various alternatives covering different parts of the parallel blocks. According to the simulation results, the option V-IV as the most energy-efficient CE could lead the highest heating energy savings of 32.7%. In this regard, this option has been simulated in the second stage in a combination of standard retrofitting measures to find out the potential of the interaction.

The CE alone (2) could lead to 0.7% energy efficiency compared to complete retrofitting of two building blocks with standard measures according to EnEV. The combination of both CE and standard retrofitting could reduce the heating energy consumption by up to 55% (3). Nevertheless, the difference of the option (3) and (4) show clearly, that retrofitting the walls under the CE is not necessary. Then in order to save 17T kWh/a more in the option (3), it is necessary to retrofit the 7,138 m² surface area, which is economically not efficient.

Figure 4 shows the energy-saving potential of particular buildings according to the options during phase 2 of the simulations. Building 4 shows the highest potential as it is almost completely covered by the CE and over 50% heating energy savings is possible. The CE would have less impact on building 3 as it is not under the climate envelope but touching it with one wall. By all buildings
(except building 3) is the difference between standard retrofitting (1) and retrofitting with the CE (2) is clearly to see and it proves the advantage of a CE by retrofitting.

### 3.2. Simulation of energy substitution with SunnyDesign

By energy substitution, the available place for solar panels plays an important role. Therefore, a climate envelope is more advantageous compared to existing roofs of the buildings. A shown in Figure 5, a standard retrofitting additionally with PV panels on the existing roof (1) could reduce the primary energy consumption for heat about 300T kWh/a. In comparison, a CE with integrated PV panels (2) could have this reduction 33% up to 400T kWh/a. as the energy substitution is related to the available surface area, the options (3) and (4) would not change the amount of the substation but as mentioned before the heating energy saving.

![Figure 5](image_url)

**Figure 5** Comparison of energy savings and energy substitution of the standard measures (1) with climate envelopes variations (2,3,4) with integrated PV panels (blue: final energy, orange: primary energy)

### 3.3. Calculation of feasibility with HCBC tool

The investment costs of the options (1-4) have been compared according to the selection criteria of the HCBC tool that is investment costs per saved primary energy (€/kWha). Figure 6 shows that a complete retrofit with standard measures (1) would cost double high if compared with the climate envelope (2) which proves the economic efficiency of the CEs. By all options with standard measures, the costs are at least twice as much compared to the recent energy price for heating that means retrofitting buildings related to the energy manners would not be feasible. Nevertheless, a solution with CE (2) is considerably more feasible (44%) than standard measures. If the energy prices get higher, the option (2) could be declared as a feasible measure and the amortization period could be lower compared to the recent time.

![Figure 6](image_url)

**Figure 6** Comparison of the costs: saved primary energy (€/kWh) in each alternative
3.4. In-depth simulations with DesignBuilder

After finding out the most feasible options, the next step is to find out solutions related to the budget and preservation order. As seen in Figure 7, a concept has been developed in relation to the budget, where the CE should be built in three stages. All these stages have been simulated to check the difference by energy savings compared to a whole climate envelope. Besides the shape of the CE has been optimized to have minimally invasive measure regarding preservation order.

According to the simulation results, expanding the CE (S I) with S II and S III would enhance the energy savings of related parts of the buildings about 2.5%, respectively. Nevertheless, in absolute numbers, the difference in the savings is negligible. With other words, the interaction between the stages enhances the efficiency of the adjacent climate envelope approximately 2.5%. Nevertheless, the absolute savings are growing exponentially as the climate envelope covers more parts of the related buildings. The energy savings at the first stage are 12.4% of the whole consumption. The second and third stages enhance these potential savings additionally 12.1% and 20.5% respectively.

In conclusion, a comprise between best-case option for a climate envelope and preservation regulations has been simulated. In this regard, the volume of the climate envelope has been reduced 4,300m$^3$ (21.8%), where it has been designed less visible from the street side. Following the inclination of the roof of the front building block allowed such an option. In order to compensate for the loss of the energy savings through higher passive solar gains, the ceiling of the building block that is now not under the CE has been simulated with a standard measure. In both cases, PV panels are implemented to the southern part (as marked with a blue line in Figure 8) of the roof of the CE or retrofitted building block roof.

![Figure 7](LEFT) three stages for the climate envelope starting from the east wing of the building ensemble: First stage (S I), the second stage (S II) and complete climate envelope (S III)

![Figure 8](RIGHT) adapting the building volume of the climate envelope in order to reduce the visibility from the street side

If compared, on one hand, the option with lower visibility, thus with less volume, but additional standard measures would save 3% less than the CE with higher volume. On the other hand, according to the results of Sunnydesign, the same amount of PV panels could have 6% more annual yield according to the 6° inclination (as they are placed with 0°by the CE with bigger volume) that leads to 6 MWh/a more yield.

4. Conclusion

Both regarding energy efficiency and feasibility, a climate envelope draws a better solution by retrofitting listed buildings if compared energy efficiency and feasibility. As it is not an intervention to the working life within the buildings, it does not interrupt the operation of the building. Therefore, the next step should be working on the acceptance of such innovative solutions. Furthermore, planning such a new approach require detailed analysis as described in this paper. Regarding the data volume, variety and the amount of the buildings, it is essential to combine different tools to overcome technical issues and time limit. The
simulations on the third step are comparable with the initial simulations in the first step. For instance, the option VII in Phase I (see Section 3.1) is comparable with option two in Section 3.4. The difference is the level of detail. Nevertheless, this similarity between the stages of the simulations allows a counter-check of the results and shows that the stages are actually not following each other, rather integrated to each other, as it should be by integral design.

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