Optimisation of buildings and building elements from life cycle and building physics perspective based on complex numeric modelling (Project FK 128663)

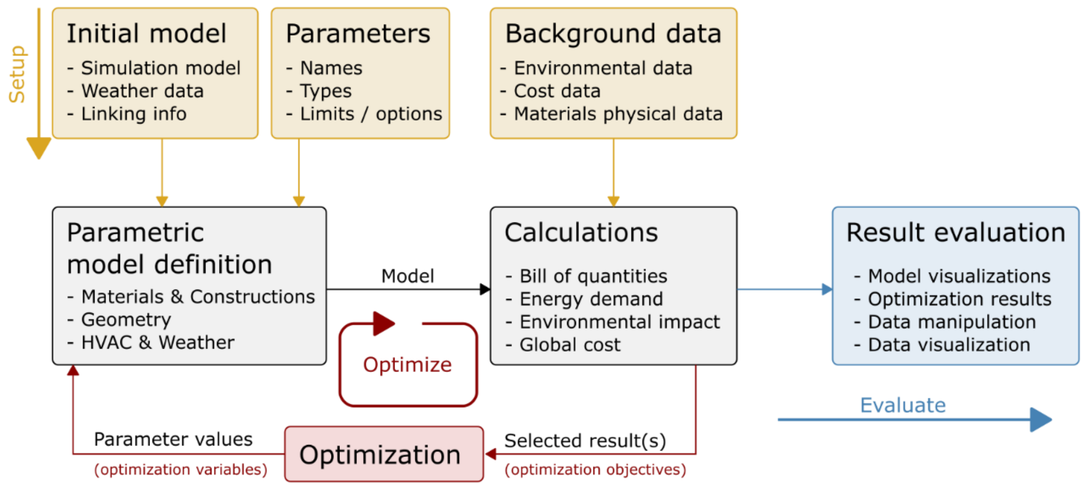
Épületek és épületszerkezetek életciklus- és épületfizikai szemléletű optimalizációja komplex numerikus modellezéssel (FK 128663)

The goal of this research was to develop a framework for the optimisation of buildings and building elements at different levels of detail. The objective was the minimisation of energy use and environmental impacts while maintaining adequate thermal comfort. The project is summarised according to the four interconnected work packages that we defined:

A) optimisation framework
B) life cycle assessment
C) building physics
D) thermal comfort

A) Optimisation framework

The developed optimisation framework has a modular structure, which allows individual modules to be exchanged and perform calculations at different levels of detail. The main elements are the background database, the model generation, the calculation, the evaluation and the optimisation modules. The background database includes environmental, material properties and cost data. The model generation module displays the building as a surface model. The calculation module determines energy use and comfort parameters with seasonal (Hungarian national method), monthly (EN ISO 52016 standard) or hourly methods (EnergyPlus dynamic energy simulation engine), environmental impacts with Life Cycle Assessment (LCA) and investment and operational costs with Life Cycle Cost (LCC) method. In the optimisation module, different mathematical algorithms (NSGA-II, Direct Multi-Search) are applied to evaluate a large number of alternatives. Several visualisation techniques have been implemented to support decision-making based on a review (Hollberg et al 2021). The implementation of the framework and the use of evolutionary algorithms allow for parallel computing that significantly reduces the calculation time of each optimisation. The framework has been implemented in Python programming language.

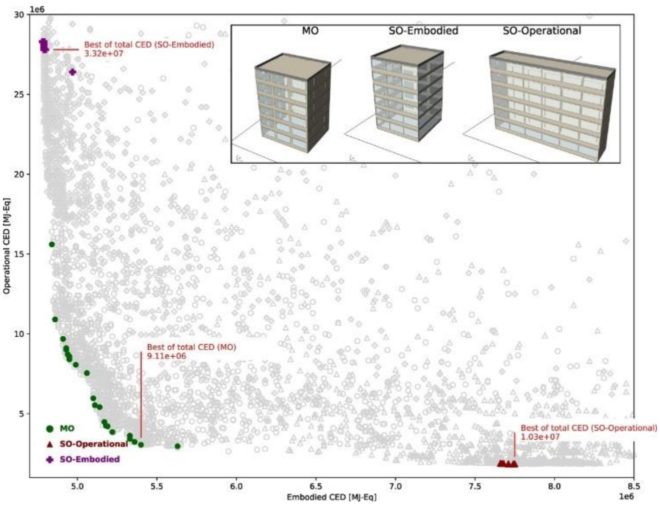


Structure of the calculation framework and illustration of the workflow steps (Kiss, 2021)

Our tool has been included in the collection of an international collaboration project, IEA EBC Annex 72 where methodologies, applications and results of multi-objective optimisation have been compared and published in a Springer book chapter (Montana et al 2021).

B) Life Cycle Assessment (LCA)

The optimisation framework has been applied for the environmental optimisation of a case study building. The variables of the optimisation comprised geometry and envelope, as well as the heating energy source. The results showed that a relatively compact shape, large windows to south equipped with shading and very high levels of insulation are optimal from an environmental perspective. Through the optimisation, significant environmental savings of 60–80% were achieved compared to the initial design options. The results have been presented in a Q1 journal paper with 47 independent citations up to now (Kiss, Szalay 2020).



Results of the multi- (MO) and single-objective (SO) optimisations on the objective space for cumulative energy demand and preview of the best solutions for the three different optimisations (Kiss, Szalay 2020)

The composition of the electricity mix was studied in detail in the project, as it was expected to have a high influence on the results. We combined LCA and the European Electricity Market Model of Corvinus - Regional Centre for Energy Policy Research (REKK) to calculate the environmental impact of electricity at different temporal resolutions for the present and for future scenarios. These results are relevant as the variation in the environmental impact of electricity is usually highly simplified in current LCA practice. Our paper has been published in a Q1 journal (Kiss, Kácsor, Szalay 2020) with 24 independent citations up to now. The electricity scenarios have been used for an optimisation case study that investigates how the detailed modelling of electricity may influence the optimum design of a building (Kiss, Szalay 2022). The results show the significant role of electricity decarbonization in a low carbon future, but also prove that energy efficiency will remain important and today's cost-optimal building envelope will be both cost and environmentally optimal in the long run.

The sensitivity of the optimisation was tested to different parameters and to climatic and national differences. In a milder climate and cleaner electricity mix (Portugal), environmental impact and cost were less conflicting objectives and the trade-off was smaller than for Hungary (Kiss, Silvestre, Santos, Szalay 2021).

The framework has also been applied in the design of an innovative, carbon neutral compact house that achieved net zero greenhouse gas emissions over the whole life cycle. We applied dynamic energy simulation, LCA, LCC and conjugated heat and moisture (HAM) modelling for the comprehensive assessment of the concept (Szalay et al, 2022).

C) Building physics

In the building physics work package, different detailed methods have been applied and developed to test the validity of simplified methods and show their accuracy in an optimisation process.

A new approach was introduced to evaluate the performance of building constructions by using hygrothermal simulations in COMSOL Multiphysics. The moisture transmittance and the effective water vapour diffusion resistance factor of walls and wall corner joints were calculated (Nagy, Stocker 2019). The variation in the hygrothermal performance of thermal insulation filled masonry blocks was analysed with laboratory measurements and numerical modelling. We compared steady-state and dynamic simulations, as well as thermal and hygrothermal models that we can use for multi-level optimisation. It has been shown that even when the thermal insulation filler does not have any significant effect on the thermal performance of the blocks, it could have serious effects on the moisture performance of the blocks. We introduced the term 'linear moisture transmittance', which could be a good parameter to help designers plan appropriate constructions not only according to thermal aspects but also considering the effect of moisture transport. Using the moisture transmittance value, we showed that there are significant differences between walls and wall corner joints depending on the insulation filler, and moisture transmittance shows greater variation than thermal transmittance.

Our research had a focus on the calculation methods of thermal bridges. A new national thermal bridge catalogue has been developed that includes 13 constructions and details with a total of 21.617 thermal transmittance values. This catalogue is now available on our website free of charge for energy certification (https://em.bme.hu/em/emkek). We compared several methods, including the national simplified method, the new national thermal bridge catalogue, two-dimensional thermal modelling as well as a conjugated heat and moisture (HAM) modelling considering steady-state and dynamic conditions with different boundary conditions (Marosvölgyi, Nagy, Szalay 2021). The national catalogue proved to be a fast and reliable solution for the estimation of thermal bridges, while the HAM modeling delivered valuable information on the effect of moisture on the thermal performance. This analysis has been further developed where also the Global Warming Potential of a construction detail considering the whole life cycle was assessed (Nagy, Marosvölgyi, Szalay 2021). Point thermal transmittance of different ventilated facade cladding fastening systems has been evaluated by 3D numerical thermal modelling (Petresevics, Nagy 2022). For ground contact structures, we compared the temperature distribution results of a numerical modelling tool, KIVA, with a BIM-based finite element simulation workflow using Comsol Multiphysics (Fürtön, Szalay, Nagy 2022).

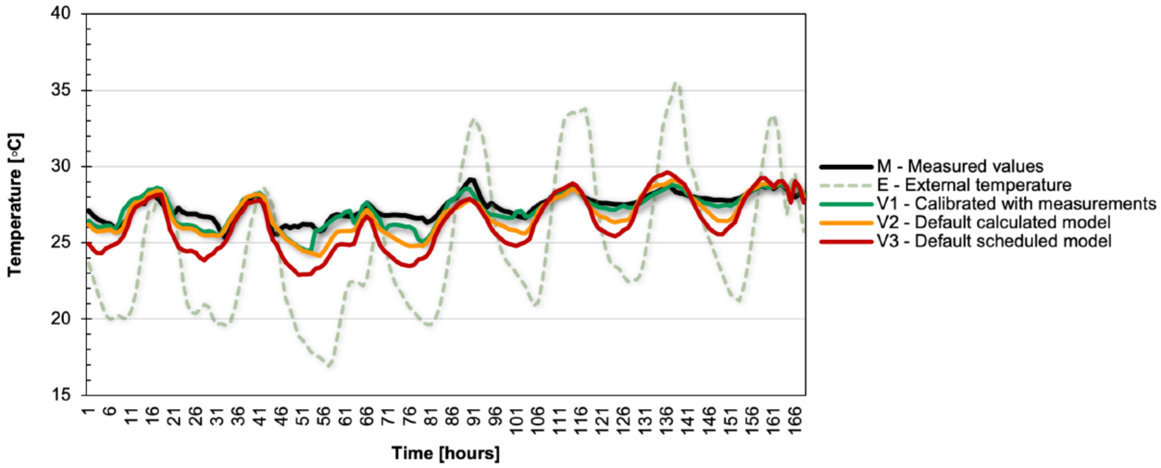
HAM modelling was combined with Life Cycle Assessment to optimise the internal geometry of thermal insulation filled blocks with a gradient-free geometry optimisation method (COBYLA) with the objectives of minimizing heat losses and total CO_2- emissions. The obtained new internal geometry designs have significantly less thermal transmittance and lower global warming potential over their service life than the reference design (Nagy, Quintana, Szalay 2019).

D) Thermal comfort

In the thermal comfort work package, the focus was on the validation of the optimisation cases and on the analysis of the risk of summer overheating for present and future climate scenarios. Climate models predict that the number of summer and heatwave days will significantly increase over time. The objective is to design optimal buildings with minimum energy use and environmental impact at an adequate level of thermal comfort.

First, we focused on homes for the elderly because people living in these buildings are among the most vulnerable (Szagri, Nagy, Szalay 2019). Later, overheating of residential buildings was assessed with dynamic simulation of building archetypes. We developed a new method for evaluating heat vulnerability of buildings (Szagri, Szalay 2022). Weather data were used to examine the occurrence of hazard (high temperatures) and create hazard curves to describe the probability of occurrence. The internal temperature in different building archetypes was assessed in various weather conditions with dynamic whole-building simulations to determine the fragility curve that shows the conditional probability of overheating. The convolution of the two sides (hazard and fragility) gives an objective picture of the probability of overheating occurring during a reference period. This information can be integrated in a spatial heat vulnerability assessment of a city to detect where the buildings prone to overheating are located. It was found that precast concrete panel buildings are the most vulnerable, while the least vulnerable category is the single-family house and this result was visualized in a pilot area in Budapest.
In another application, the thermal behaviour and overheating of an innovative building construction with bamboo composite has been analysed and compared with traditional brick construction with numerical simulation (Al-Rukaibawi; Szalay; Károlyi, 2021).

For the validation of the simulation results, a monitoring system was installed in two nearly identical multi-family apartment buildings in Budapest in July 2020, from our project budget. These buildings are very similar to the buildings applied in our optimisation case studies, so this experiment was suitable for validation. The two buildings are located on the same plot, were built at the same time but one of them went through an energetic retrofit with additional insulation and window exchange. Temperature, relative humidity, CO_2 concentration, window opening and operation of shading devices has been monitored in 6 flats. We analysed the summer datasets of a topmost apartment and modelled the building with a dynamic energy simulation software tool (Szagri, Kairlapova, Nagy, Szalay 2022). The model has been calibrated with the measured data. The results show a high correlation between the measured and monitored temperature data. We also measured summer comfort in a prefabricated panel building in Budapest (Szagri, Dobszay, Nagy, Szalay, 2022). The measurements showed that the average temperature in all rooms was above 26 °C, and there were several occasions when the temperature exceeded 30 °C.



Measured and simulated temperature in a multi-family apartment building (Szagri, Kairlapova, Nagy, Szalay 2022)

International dissemination and collaboration

As a result of the research, we have published 12 journal papers with impact factor, 10 of which have been published in Q1-Q2 international journals. The results of the research have also been presented at national and international conferences (IBPSA 2019, envibuild 2019, SB 2019, WSB 2020, CEES 2021, CESB 2022, CESBP 2022). Zsuzsa Szalay was invited to be member of the scientific committee at SB 2019, CESB 2019 and CESB 2022. Zsuzsa Szalay and Benedek Kiss have participated in the international project IEA EBC Annex 72 – Assessing Life Cycle Related Environmental Impacts Caused by Buildings. Here we disseminated the results of our project and received international feedback. Thanks to this international community, we had opportunities for collaboration, common research and publications.

A visiting PhD student, Alberto Quintana Gallardo from Polytechnic University of Valencia joined our work in 2019 for a short internship with funding from the Pioneers into Practice programme of the EIT Climate KIC. We also had a bilateral science and cooperation project (TÉT) with the researchers of the Instituto Superior Tecnico, University of Lisbon where we exchanged knowledge and built upon the results developed in this project.

Involvement of students

Several BSc, MSc and PhD students have been involved in the research project. Altogether eight students working on related topics have been awarded at the BME Scientific Student Conference (TDK) (2018: Dóra Szagri, Melinda Braun, Dalma Wildanger, 2019: Martin Marosvölgyi, 2020: Martin Marosvölgyi, Mercédesz Mirella Nagy, 2021: Fanni Petresevics, Ainur Kairlapova, János Gál) and at the National Scientific Student Conference (OTDK) (2019: Dóra Szagri 1st prize, 2021: Martin Marosvölgyi 2nd prize).

One of the researchers, Balázs Nagy, successfully defended his PhD in 2019, related to this research project. Benedek Kiss and Dóra Szagri PhD students have been actively involved in the project. Benedek Kiss successfully defended his PhD thesis in July 2022 entitled 'Multi-objective Environmental Optimization of Buildings', supervised by Zsuzsa Szalay. Balázs Nagy was awarded an UNKP scholarship in 2021 and Dóra Szagri in Sept 2022, which will help further research and utilization of project results.

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