REAL AND SIMULATION MODELLING OF THE SPECIFIC HEATING ENERGY DEMAND OF RESIDENTIAL BUILDINGS

Thesis of the doctoral (PhD) dissertation

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CONTENTS

NOMENCLATURE

List of symbols

A	*Surface*	[m^2]
a, b, c, d, e, f	*Parameters in the approximate equation*	[-]
A, B, C	*Symbols for small sample models*	[-]
A_b	*Useful internal gross floor area*	[m^2]
$A_{ceiling}$	*Slab surface*	[m^2]
A_{dw}	*Surface of doors and windows*	[m^2]
A_{floor}	*Underfloor heating surface*	[m^2]
A_{fur}	*Heat storage mass surface area*	[m^2]
A_N	*Net floor area*	[m^2]
A_{roof}	*Roof surface*	[m^2]
A_{wall}	*Wall surface*	[m^2]
A/V	Ratio of external surface area of a building to the volume of the interior	[m^2/m^3]
B1-B5	*Letters and serial numbers of real buildings*	[-]
C	*Heat capacity*	[J/K]
C_T	*Total heat capacity*	[J/K]
c	*Specific heat of structure*	[J/kgK]
c_{air}	*Specific heat of air*	[J/kgK]
$c_{ceiling}$	*Specific heat of slab*	[J/kgK]
c_{floor}	*Specific heat of floor*	[J/kgK]
c_{fur}	*Specific heat of futinture average*	[J/kgK]
c_{wall}	*Specific heat of wall*	[J/kgK]
d	*Thickness*	[m]
FI	*Line heat transfer coefficient between walls and subfloor*	[W/m]
$G_{20/12}$	*Heating temperature bridge*	[nap °C/a]
H	*Thousandth of the annual heating temp. bridge*	[khK/a]

$H_{20/12}$	*Thousandths of a heating temperature bridge expressed in hours 20 °C internal and 12 °C limit heating temperature*	*[khK/a]*
HY	*Hysteresis*	*[°C]*
k	*Fill factor*	*[%]*
k_{air_wall}	*Heat transfer coefficient air - wall*	*[W/m²K]*
$k_{ceiling}$	*Heat transfer factor slab*	*[W/m²K]*
k_{dw_atm}	*Heat transfer coefficient for doors and windows – environment*	*[W/m²K]*
k_{floor_air}	*Heat transfer coefficient air - floor*	*[W/m²K]*
k_{floor_ground}	*Heat transfer factor floor – ground*	*[W/m²K]*
k_{fur}	*Heat transfer factor heat storage masses*	*[W/m²K]*
k_l	*Its heat transfer coefficient is lth layer*	*[W/m²K]*
k_{wall_atm}	*Heat transfer coefficient environment - wall*	*[W/m²K]*
k_{wall_air}	*Heat transfer coefficient wall - air*	*[W/m²K]*
L	*Ventilated air volume*	*[m³]*
l	*Connection edge length or circumference*	*[m]*
L_{wall}	*Wall length*	*[m]*
m	*Direction factor*	*[-]*
m_{air}	*Air mass*	*[kg]*
$m_{ceiling}$	*Slab mass*	*[kg]*
m_{floor}	*Floor mass*	*[kg]*
m_{fur}	*Equipment weight*	*[kg]*
m_{wall}	*Wall mass*	*[kg]*
m_{water_fh}	*Underfloor heating water mass*	*[kg]*
m_{water_rh}	*Mass of water for radiator heating*	*[kg]*
nf_{house}	*Filtration factor*	*[1/h]*
p	*Heating system design factor*	*[-]*
P_h	*Heating power*	*[W]*
P_{rh}	*Radiator heating power*	*[W]*

q	*Specific heat loss factor*	$[W/m^3K]$
q_b	*Internal specific heat gain*	$[W/m^2]$
$Q_{belső\ hőnyereség}$	*Internal heat gain*	$[W]$
q_f	*Heating specific annual net heat energy demand*	$[kWh/m^2a]$
Q_F	*Heating net annual heat energy demand*	$[kWh/m^2a]$
$Q_{fűtési/hűtési\ hőigény}$	*Heating/cooling heat demand in my case heating heat demand*	$[W]$
$Q_{légcsere}$	*Air exchange heat loss*	$[W]$
q_m	*Specific heat loss factor*	$[W/m^3K]$
$Q_{napsugárzás}$	*Heat gain from solar radiation*	$[W]$
Q_{rad}	*Solar radiation*	$[W/m^2]$
$Q_{rétegrendi\ transzm.}$	*Transmission heat loss through boundary structures*	$[W]$
$Q_{vonalmenti}$	*Lineside heat transmission*	$[W]$
R^2	*Coefficient of determination:*	$[-]$
r_a	*Air heat transfer resistance*	$[m^2K/W]$
R_{se}	*External heat transfer resistance*	$[m^2K/W]$
slip	*Set signal time program offset*	$[h]$
T	*Time*	$[h]$
t	*Time*	$[s]$
T_SP	*Temperature setpoint*	$[°C]$
T_SP_H	*Temperature setpoint upper value*	$[°C]$
T_SP_L	*Temperature setpoint lower value*	$[°C]$
T_i	*Indoor air temperature*	$[°C]$
T_{air}	*Air temperature*	$[°C]$
T_{atm}	*Ambient temperature*	$[°C]$
T_e	*Outside temperature*	$[°C]$
T_{floor}	*Floor temperature*	$[°C]$
T_{fur}	*Heat storage mass temperature*	$[°C]$
T_{ground}	*Ground temperature*	$[°C]$
t_{max}	*Total measurement duration*	$[s]$

$T_{measured}$	*Measured temperature*	*[°C]*
$T_{simulated}$	*Simulated temperature*	*[°C]*
T_{wall}	*Wall temperature*	*[°C]*
U	*Heat transmission coefficient*	*[W/m^{2}K]*
U_R	*Resultant heat transmission coefficient*	*[W/m^{2}K]*
V	*Building volume*	*[m^3]*
V_{house}	*House air volume*	*[m^3]*
Z	*Length of heating season*	*[nap/a]*
Z_F	*Thousandth of the length of the heating season*	*[kh/a]*

Greek symbols

Δ_{SEC}	*Specific heating energy savings*	*[kWh/m^2 a]*
$\Delta_{SEC\%}$	*Percentage specific heating energy savings*	*[%]*
σ	*Correction factor expressing the effect of batch operation*	*[-]*
η_{Irad}	*Solar radiation utilization efficiency*	*[-]*
λ	*Thermal conductivity*	*[W/mK]*
ρ	*Density*	*[kg/m^3*
ρ_{air}	*Air density*	*[kg/m^3]*
ρ_l	*Density lth layer*	*[kg/m^3]*
ψ	*Line heat transmission coefficient*	*[W/mK]*
τ	*Time constant*	*[h]*

Abbrevations

SEC	*Specific heating energy consumption*	*[kWh/m^2 a]*
TTC	*Thermal Time Constant*	*[h]*

1. INTRODUCTION, OBJECTIVES

In my doctoral dissertation, I perform measurements in model and real residential buildings, evaluate and prepare physics-based mathematical models based on the measurements. After validating these models, I run further tests and simulations in the model space. The aim of these will be to establish the relationship between the thermal time constant and the expected energy consumption of buildings. I will also carry out my studies to examine the effect of constant and variable setpoint control mode and the effect of temperature reduction. I will examine the approximate solution for determining the expected specific heating energy demand for buildings in other locations. I will perform my studies on small sample models and real buildings as well.

1.1. Relevance and significance of the topic

40% of energy use in Europe comes from heating and cooling buildings. Similarly to other EU member states, residential energy consumption accounts for 19% of CO_2 emissions in Hungary. The priority area of reducing energy use and thus carbon dioxide emissions can be achieved by minimizing the energy demand of buildings. The current international and domestic regulations also justify that reducing the energy consumption of buildings is a priority area due to global energy consumption and harmful emissions. Regulations and directives contain continuously stricter requirements for boundary structures (7/2006 TNM Rendelet, 2006), (9/2023 ÉKM Rendelet, 2023).

With the modern design and renovation of our buildings, their energy demand can be reduced. The use of properly chosen building materials and thermal insulation, the modernization of doors and windows, and the utilization of solar profits are also among them. In addition, there are other options for reducing energy use. These are typically the utilization of heat generation equipment and renewable energies operating with higher efficiency. Fresh air ventilation with controlled heat recovery, which reduces unnecessary filtration losses. Changing consumer habits is also an effective element in reducing energy waste. Modernizing lighting, being present only to use the necessary lighting, or even maintaining a lower indoor temperature during the heating season promises significant savings. In modern or modernized buildings, building automation also appears, which can provide more accurate and comfortable operation with lower consumption.

To better understand the behavior of buildings, mathematical modelling and simulation provide a state-of-the-art tool. With the help of computer models, different scenarios and parameters can be tested, simulations can also be performed in case of different geographical locations.

1.2. Objectives

The objective of the research task is to determine the specific heating energy demand of residential buildings by simulation, to develop a physics-based mathematical model that can be used to describe the energy processes taking place in the residential building. The model should be suitable for other heating temperature bridges and other internal temperatures and be sufficiently flexible to allow easy expansion of the test area and aspects. The goal is to create a simplified model that is suitable for sufficiently accurate and fast simulation.

In addition to creating a theoretical model and running simulations, the aim of the research is also to measure the operation of the model in practice. Small sample supported by models and measurements in real buildings. During the tests, I perform a parameter sensitivity test. I examine the effects of temperature, heat storage mass and heat transmission factors of wall structures on the specific heating energy demand.

During the research, the goal is to develop a block-oriented model and simulation method that can be easily extended and extended to other fields of application, thus increasing the practical applicability of the block-oriented model.

During the modeling process, I emphasized the fact that taking into account different geographical location and weather data, several buildings should be modelled and simulated in order to define generalizable solutions to reduce heating energy demand.

Data-driven decision support Using advanced data analysis techniques to optimize energy use, identifying the factors that have the greatest impact on heating energy use.

Create a more accurate and simplified approximation equation based on measurement and simulation data, verified by five real-world buildings that help engineers and decision-makers design, renovate and optimize residential buildings in an energy-efficient way.

Extended real-world environmental assessments: Extend a wider range of real-world environmental measurements and integrate them into modelling processes to make simulation models more accurate and reliable.

2. MATERIAL AND METHODS

In this chapter I present the experimental methods and tools used for research, the programs used. Options for accessing weather data. The structure of the small sample model, the modification of the heat storage mass. I present the differential equations describing the real physical processes used in the study.

2.1. Measuring instruments used and measurement data series

Measurement data is required for modelling, model validation, and then comparison of validated models with real-world conditions. Proper resolution and accuracy of data is essential. Therefore, during the measurements, the following measuring devices and data recorders were used.

To measure the temperature and record the data, I used Almemo 2590-4S (Alhborn Messtechnik, Illmenau, Germany) and EBI 300-T measuring-data acquisition device (Ebro, Ingolstadt, Germany), which is capable of storing 40,000 measured data. The data logger is equipped with an NTC sensor and has USB connection for measuring data.

To measure and record electricity consumption data, I used a Voltcraft SEM5000 (Voltcraft, France) meter.

The gas consumption of the residential buildings was measured with the certified gas meter of the regionally competent gas supplier.

Meteorological data

I obtained weather data from several sources. By measurement, as well as from databases of external data providers.

I obtained the weather data I did not measure from a free, available data source to perform the simulations. For this, I used weather data provided by NASA.

Available data includes geolocated meteorological and solar parameters. Various applications are available: daily average data in various date ranges and parameters for a specific location. End users can view interactive graphs, data tables, and it is available in various tabular and geographic file formats.

2.2. Method for determining heating energy demand

The sum of the energy transport processes taking place through each structure represents the heating and cooling energy demand of the given building. In my case, the heating energy demand was determined.

$$\dot{Q}_{\frac{fűtési}{hűtési}hőigény} = \pm\dot{Q}_{rétegrendi\ transzmisszió} \pm \dot{Q}_{vonalmenti} \pm \dot{Q}_{légcsere} \pm \dot{Q}_{belső\ hőnyereség}\left(\pm\dot{Q}_{napsugárzás}\right) \quad (2.1)$$

The stratified transmission energy flow consists of energy flows passing through all the structures separating the inner boundary space from the environment. These are typically the values of walls, doors and windows, slabs and floor structures corrected by thermal bridges.

2.3. Small sample model buildings

To conduct experiments, it was necessary to take measurements. In order to be able to perform measurements not only in one case and setting, but also with comparative measurements, I made three small sample model buildings of the same size and structure. Measurements were made in the three small sample model buildings, during the measurements the same amount of heat storage mass was placed in all three buildings. All three small sample model buildings were placed in the same orientation.

The typical building physics values and their geometric dimensions are shown in Table 2.1.

2.1. Table Boundary structures of buildings of the small sample model

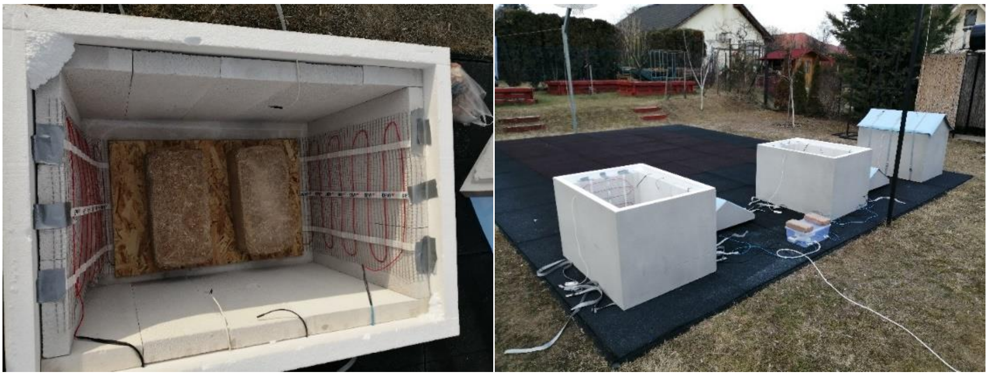
Surface	U [Wm^2/K]	A [m^2]	ρ [kg/m^3]	c [kJ/kgK]	l [m]	Ψ [W/mK]
External wall with insulation	0,535	2,2	260	1,23		
Floor	0,17	0,7875	200	0,86285	3,6	0,75
Roof slab	0,353	0,7575	20	1,45		

GPS coordinates of the measurement location: 47.61204835472161, 19.343435272717898 Gödöllő, Hungary. The placement of the small sample model buildings is shown in Figure 3.7.

2.1. Fig. Model buildings A, B, and C with the same orientation

The small sample model buildings A and B were created with electric heating. Small sample model building C was used as a reference building without heating during my measurements. The electric heating was provided by a DEVImat™ DSVF-150 (Danfoss, Denmark) type heating mat with a power of 150 W per square meter. In small sample model buildings A and B, I installed a heating surface of one square meter each.

Figure 2.2 shows the structure of the small sample model building, the heating and the sensors located in the interior.



2.2. Fig. Design and installation of small-sample model buildings

In the small-sample model buildings, the internal temperature was measured with 2-2 sensors, the outside temperature with 1-1 sensor. Their placement was at a height of 500mm. A reference outdoor temperature measurement was also made, which was located at a height of 1 m at a distance of 2 m from the buildings.

The heating was controlled using DEVIreg™ Opti (Danfoss, Denmark). During the measurements, one-minute sampling was performed.

The measurements were carried out as follows: in the small sample model building A a constant setpoint was maintained, in the small sample model building B a variable setpoint was used based on a time program, while in the small sample model building C it was unheated (reference). Its values are shown in Table 2.2. The regulator hysteresis is +/- 0.4°C. For the small sample model A, a temperature value of 17 °C and 21 °C was set according to the time program, while for the small sample model B a constant temperature value of 21 °C was set.

2.2. Table Heating program of small sample models A and B

Time program	Setpoint A [°C]	Setpoint B [°C]
00:00-05:59	17	21
06:00-07:59	21	
08:00-15:59	17	
16:00-22:29	21	
22:30-23:59	17	

Variation of heat storage mass in small sample models

The different heat storage masses of the buildings were modified with concrete bricks placed in the small sample model buildings. The purpose of the comparative measurements is to change the heat storage mass, what effect it has on energy consumption with a constant and time-varying setpoint. Figure 2.3 shows the heat storage masses changed during each measurement.

2.3. Fig. Modification of heat storage masses before different measurements

The measurement period ran from February 5 to March 16, 2023. The heat storage mass was changed several times during the measurements. Thus, measurement data are available with different heat storage masses, except for modification days.

Small sample block-oriented simulation model

In many cases, measurements taken in real environments are difficult to compare because weather phenomena are different when measuring at different locations, and a long series of measurements is needed to provide reliable data on extreme weather conditions. By using the simulation model, results can be achieved faster and we can take into account the wide possibilities provided by building structure and building engineering. The simulation can be run quickly, the test parameters can be easily changed.

I made a white-box model in MATLAB Simulink environment. I fitted the available temperature data to this, then I performed the validation of the model. During the construction of the model, I solved mathematical equations describing physical processes using MATLAB. The diferdental equations characteristic of the small sample model were solved by the Kelvin-Thomson method.

The differential equations describing the thermal engineering model of the small sample model buildings are as follows:

The differential equation (2.2) describing the air temperature in the interior is:

$$P_h + I_{rad} \cdot \eta_{I_{rad}} \cdot A_{roof} + q_B \cdot A_{floor} - (T_{air} - T_{ground}) \cdot A_{floor} \cdot k_{floor\_ground} -$$

$$(T_{air} - T_{atm}) \cdot A_{wall} \cdot k_{wall\_air} -$$

$$(T_{air} - T_{atm}) \cdot nf_{house} \cdot \rho_a \cdot c_{air} - (T_{air} - T_{atm}) \cdot A_{ceiling} \cdot k_{ceiling} -$$

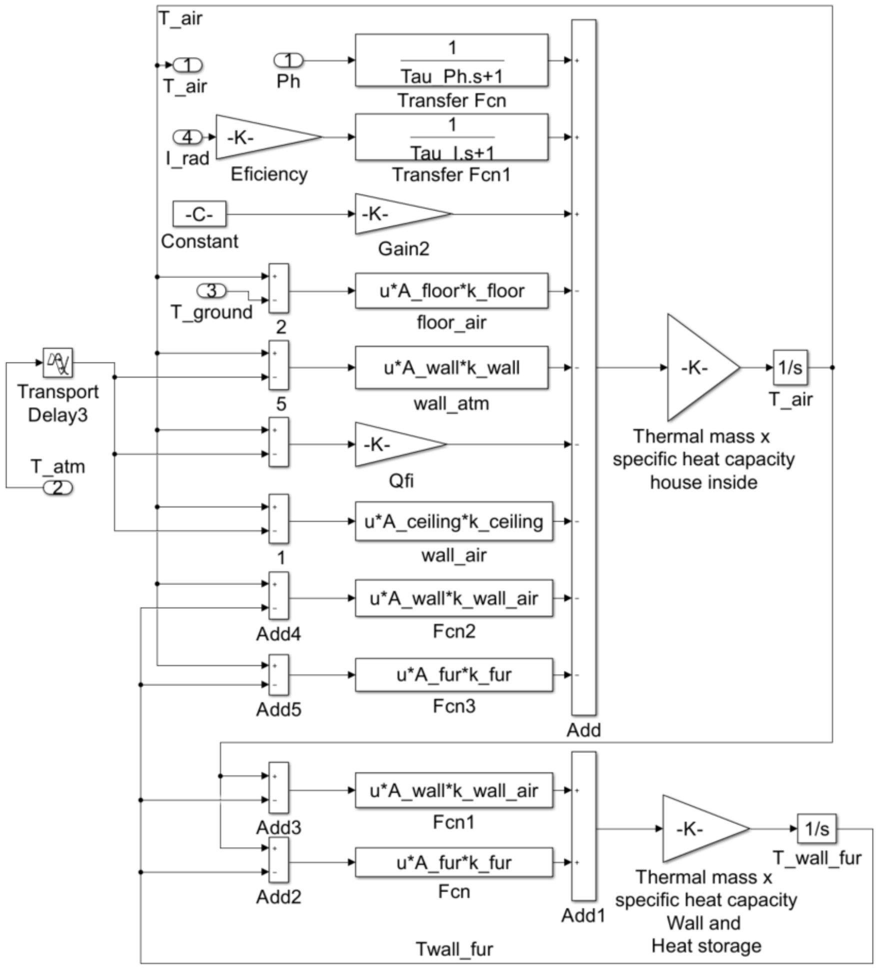
$$(T_{air} - T_{fur}) \cdot A_{fur} \cdot k_{fur} = (m_{air} \cdot c_{air}) \cdot \frac{dT_{air}}{dt} \tag{2.2}$$

The differential equation (2.3) describing the temperature of the limiting surfaces of the small sample model buildings is:

$$(T_{air} - T_{\boldsymbol{wall\_fur}}) \cdot A_{wall} \cdot k_{wall\_air} + (T_{air} - T_{wall\_fur}) \cdot A_{fur} \cdot k_{fur} =$$

$$(m_{fur} \cdot c_{fur} + m_{wall} \cdot c_{wall} + m_{floor} \cdot c_{floor} + m_{ceiling} \cdot c_{ceiling}) \cdot \frac{dT_{wall\_\mathrm{fur}}}{dt} \tag{2.4}$$

The details of the model structure with MATLAB Simulink elements are shown in Figure 2.4.



2.4. Fig. Block-oriented visualization detail of small sample model buildings

The prepared model takes into account the building physical characteristics of each boundary structure. Environmental, soil and indoor temperatures. Solar radiation, as well as the heating power supplied according to the method of regulation. The simulation of solar radiation and average daily temperature was applied based on a university note by Farkas (1999), using the small sample model of the solar thermal energy utilization system (Tóth, et al., 2019). After that, it is possible to perform calculations based on specific measurement data or simulated weather data.

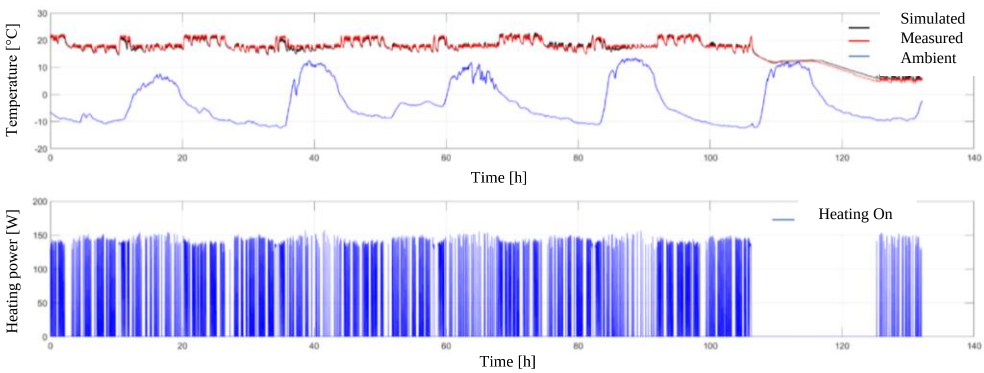
The methods of regulation of small sample buildings A, B and C were as follows. Small sample model building A had continuous base sign, small sample model building B had variable base signs according to the time program given in Table 3.6, while small sample model building C had no heating. These control methods were implemented in the MATLAB/Simulink model as well. Identification of small sample models

The parameter of the model was identified by comparing the completed model and the measurement results. The identified parameter is the heat transfer coefficient of the outer wall. To determine the value of parameters, MATLAB's Simulink ™ built-in fminsearch function was used to find the minimum of the target function based on a specified starting value. Its descriptive formula is as follows:

$$J(k_{wall}) = \int_0^{tmax} (T_{measured(t)} - T_{simulated(t,k)})^2 dt \ \rightarrow min \qquad (2.5)$$

The value of this parameter k_{wall}= 0,535 W/m^{2}K.

The model was validated based on measured indoor and outdoor temperatures, solar radiation data and electricity consumption. In the case of the simulated results, the on and off state of the heating was used as input parameters. Figure 2.5 shows the simulated and measured data for the small sample model building with variable base signs according to time program B.



2.5. Fig. B Small sample model building, measured and simulated values

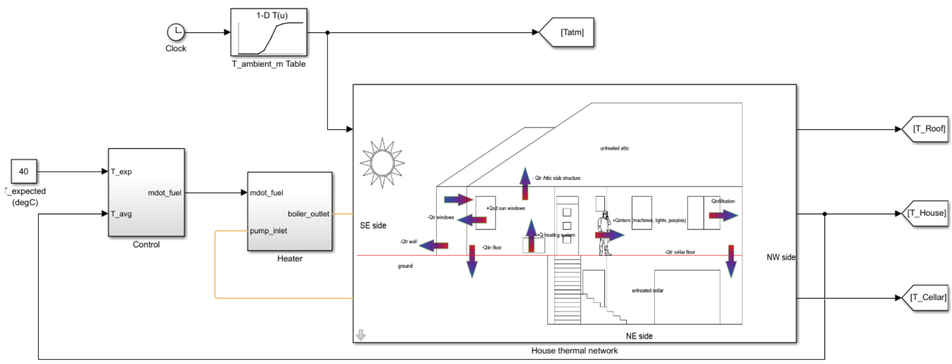
2.4. Real buildings

I examined the real conditions and buildings with five residential buildings in different use. Data on gas consumption were available, which represented heating energy demand. These data were provided to me by the owners of residential buildings. 3-5 people lived in residential buildings during the periods under review. Their floor area was between 100-170m^2 and their construction time was between 1960-2020. Their specific heat transmission coefficient ranged from 0.32 to 0.987 W/m^{2}K. The buildings are located in Hungary. No other heat generating equipment or ventilation system was in operation in residential buildings. According to the classification of building typology, they are divided into groups 6, 8, 10 and 12.

2.4.1 B2 – Identification – building

The real family house is located in Central Hungary, in Gödöllő. The year of construction is 2008, it was built from modern building materials of the given era, its HVAC systems contain modern technologies in 2008. Architectural documentation, energy calculation and mechanical plans are also available about the building.

The modeling and later the simulations were performed in MATLAB/Simulink environment. I divided the building into parts. Its most important unit is the living space, where the goal is to maintain the desired temperature. Below it is an unheated cellar, above it is also an unheated attic. Towards the outer space, energy flows pass through the boundary structures and indirectly through the two unheated spaces. As input data, I took into account external temperatures and global solar radiation. These data are taken from NASA's database described in Chapter 3.1 of the material and method. In the case of building B2, for short-term measurements, own outdoor temperature measurements were also made. For simplifications, I have taken the soil temperature into account with a constant value of 12 °C. The temperature data of the living space, attic and cellar are displayed as outputs. The section of the residential building under consideration is shown in Figure 2.6, where the arrows indicate the heat transport processes affecting the living space.

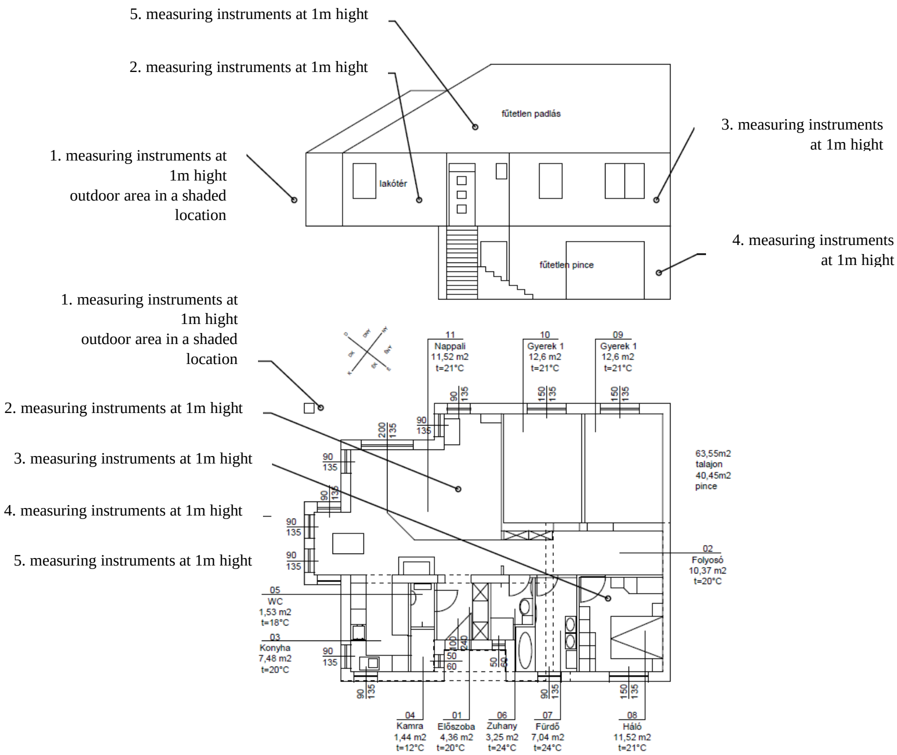


2.6. Fig. Overview diagram of the examined building in MATLAB/Simulink environment

Parameter sensitivity testing and validation of the examined building

Between 22.07.2021 and 15.08.2021 I made continuous measurements in the residential building examined. The building was unused at that time, so measurements were carried out with less disturbance. During the measurement, I measured the air temperature and relative humidity. The measuring instruments used were EBRO EBI 300 meters and data loggers

(Xylem Analytics, Germany), the measurement data (temperature and relative humidity) were recorded every 5 minutes. The location of the measuring devices is shown in Figure 2.7, where measurements were made simultaneously. Measuring instruments have been installed in two places inside and outside, as well as on the basement level and attic. Repeated internal temperature measurements were carried out under winter conditions with EBRO EBI 300 measuring and data recorder and ALMEMO 2590-4S measuring equipment from 13.11.2022 to 04.12.2022 and from 18.01.2023 to 12.02.2023.



2.7. Fig. Internal and ambient temperature measurement points

The measurement data was saved in tabular format, which was processed and organized into a file with the extension '.m' for MATLAB. When simulating the building, I operate the heating system below the limit heating temperature, from which it is turned off in case of a higher temperature. When building the model, I entered the building physical characteristics and geometry dimensions of the given structure in a file with the extension '.m' in each differential equation.

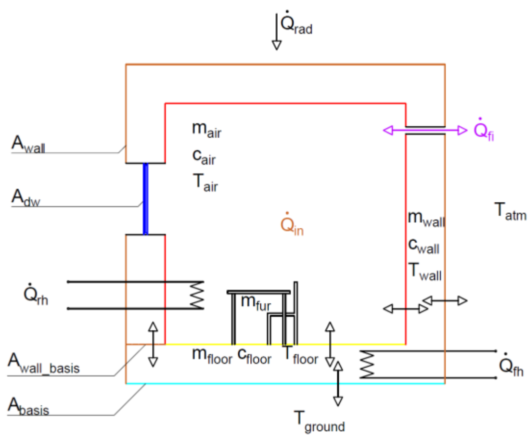
During the parameter sensitivity test, I examined what parameters affect the internal temperature. These were the following parameters: linear coefficient of thermal conductivity, specific internal heat gain is the filtration factor. I have omitted to take into account the heat gain from solar radiation because of the shading applied and because the gain from the sun is negligible and cannot always be counted on. The examined parameters were taken into account with the range of values in the literature, then I determined from the effects of a 10% modification that the internal specific heat gain is the parameter that resulted in the greatest temperature change among them. For this I did the identification and minimum search.

The identification of the internal specific heat gain and the validation of the model were performed as follows. By comparing the simulated temperature of the living space obtained with the completed model and the measured temperature of the living space, I checked the appropriate accuracy of the model. I am looking for the value of the internal specific heat gain q_b. Thus, one of the steps in the creation of the model included in the objective was to determine the smallest, maximum or optimal value of internal specific heat generation with the smallest difference between measured and calculated temperatures. I achieved this goal by searching for the minimum of the target function set up by the least squares method.

To determine the internal specific heat gain value q_b, I used the built-in fminsearch function of MATLAB/Simulink.

Simplified model

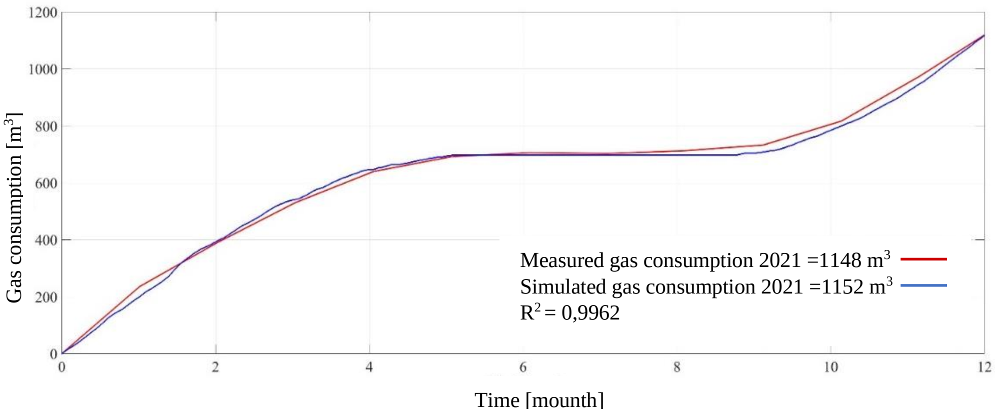
The simplification was necessary because running the model required large machine capacity, optimization and simulation experiments took several hours to run, and the theoretical scheme of the simplified model is shown in Figure 2.8.



2.8. Fig. Outline of the simplified model

The differential equations describing the internal temperature of the simplified model were presented in detail in my dissertation.

With the simplified model, I performed the identification for internal specific heat generation q_b based on the measured and simulated temperatures. The validation was carried out for a period of one year other than identification for five different buildings based on the measured and simulated gas consumption. For measured and calculated values of gas consumption. R^2 was 0.9962 and is therefore sufficiently accurate and suitable for further testing. The main advantage of the simplified model is that simulations performed with different settings, which are often repeated during research, can be performed faster with sufficient accuracy. Figure 2.9 shows the measured and calculated gas consumption.



2.9. Fig. Measured and calculated values of gas consumption for the period 01.01.2021-31.12.2021

2.4.2 Validation buildings

One of the biggest advantages of block-oriented modeling and the MATLAB/Simulink environment is its easy adaptability. The models contain the characteristics of the building under consideration in an .m file. Thus, the extension of the model to other buildings can be done by providing these data.

In order to be able to make the proper functioning of the simplified model described in Chapter 3.5 of my dissertation and to make further comparisons, I extended my research to five buildings where gas consumption data were available, as well as the input data – building physics and geometry – required for modeling buildings, as well as the temperature values set on the thermostat. The ambient temperature and global radiation values were obtained from the NASA data source presented in the Material and Method chapter. I also validated these models with the internal specific heat generation parameter q_b=4.9687 [W/m^2] previously identified according to Chapter 3.4.1 based on the gas consumption values. For reasons of identification, I will refer to them as B1-B5. In all cases, the buildings are family houses, which can be found in different parts of the country, some of them are outdated and modern. Details of the buildings can be found in Annex M5.

Extensions required for validation

In the buildings, different control methods and settings were used by the occupants. Therefore, I incorporated different control modes and time programs into the model. Thus, it is possible to use a constant setpoint, PID control, or a variable setpoint according to the time program.

In the rest of the research, I compared these buildings, their physical characteristics, location and control methods. The results of these are presented in the Results section.

The validation of B1-B5 buildings was carried out using the same method as the validation of the simplified model. The validation was carried out for each residential building based on one year's measured and simulated gas consumption data.

Identification and validation

In computer modelling and simulation, in the case of simulation of energy consumption in residential buildings, identification and validation are of paramount importance. Identification refers to the process by which relevant parameters and variables necessary for simulating the operation of a building are defined. This includes collecting and processing data needed to model different systems in a building and determining input parameters.

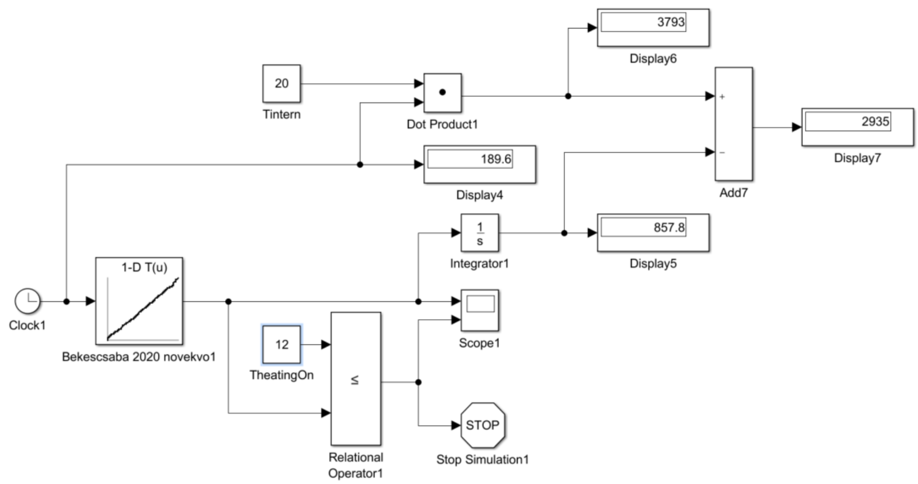
Validation in computer simulation is the process of verifying and verifying that a simulation model can accurately predict real-world behavior. This means that the results generated by the model are compared with real measurements or reference data.

The identification and validation were performed on different data series, so bias, the so-called overfitting, could be avoided. Overfitting causes the model to overadapt to the data set used, which reduces its ability to respond well to new, unknown data. Therefore, the identification was performed on a shorter measurement data set, while the validation was performed on a longer measurement data set.

Determination of the annual heating temperature bridge in MATLAB/Simulink environment

I processed the daily average temperature data required for calculating heating temperature bridges from the database available on NASA's website: for the years 2020-2023 for the county seats, as well as for Gödöllő and Zabar.

To process this, it was necessary to organize the data for MATLAB and create .m files. Figure 2.10. shows the implementation of MATLAB for calculating this temperature bridge, which uses MATLAB to determine the values belonging to the 20/12 °C temperature bridge based on the ordered temperature data.



2.10. Fig. Calculation of heating temperature bridge and heating days

2.5. Automate repetitive tasks in MATLAB/Simulink

When performing simulations, models must be run several times in succession, changing a parameter in increments. A solution developed for this is the creation and running of scripts, which can be used to automate these processes. Starting with automatically starting runs with different setting values, or continuing to capture data. Errors can also be minimized by using scripts, as data can be saved either on the MATLAB workspace or in an Excel file for further processing. In MATLAB, scripts also have a .m file extension. The main feature of scripts is sequencing, which means executing instructions in a given order. Variables are modified directly in the MATLAB workspace. Scripts can be run independently. They provide sufficient interactivity, as the results of the change are displayed directly through the MATLAB interface during execution, which is advantageous, e.g. when displaying graphs. During the research, I also used scripts. With the help of these, I changed the temperature setpoint or the heat capacity during the simulations. Save data to Excel format. Due to the limitations of the scripts, I present the most important details of the scripts I have created and applied in the annex.

3. RESULTS

During the presentation of the results, I present the results obtained on the basis of measurements and simulations, on the basis of which I formulate the new scientific results. These results, which deal with the specific energy demand of residential buildings for heating, are also useful in daily practice, clarifying processes that have not yet been known or sufficiently defined. During my research, I first made measurements on small sample model buildings and their simulation under real weather conditions. Then I modeled a real building, based on measurement results, I made the parameter identification. After that, I simplified, re-identified and validated the model for a one-year period of five buildings. With this multi-validated model, I performed the simulation experiments, analyzed the results and drew conclusions.

3.1. Results of small sample model buildings

The measurements were carried out as described in the material and method chapter in the three identical but operated small sample buildings with different settings. Tests were carried out on six different measuring lines with different cooling masses. The data series recorded during the measurements consist of 57406 rows and 18 measured values. The ambient average, minimum and maximum temperatures collected during the measurements were presented. The measurement period ran from 04.02.2023 to 16.03.2023. Based on the measurements of the small sample models, I recorded the external and internal temperatures and the number of heat storage elements. Based on the data, during the measurements, it was possible to track the change in the internal temperature of the buildings, as well as the state of the heating mode under the influence of the change in the outside temperature. I also observed the effects of modifying heat storage masses. I analyzed the energy consumption based on the data of electricity meters, where I also presented the differences in the consumption of systems with different setpoints. Based on the measurements, I also examined the effect of heat storage masses and thermal time constants, and based on the results, I analyzed the change in the rate of consumption.
Based on the simulation experiments, the identification of the small sample models was performed by comparing the measured and simulated results, then validated with independent measurement data series, and the proper operation of the simulation model was verified.

3.2. Effect of heat storage masses

The effect of modifying the heat storage masses was performed in the simulation models, where different numbers of heat storage elements were applied. Based on the results, I found that increasing the heat storage mass in the case of a constant setpoint minimally increases the heating energy savings, while in the case of a timeprogram-variable setpoint, it decreases it.

3.3. Real building results

The parameter identification of real buildings and the determination of the specific internal heat gain were performed in Matlab environment with a minimum search procedure. Based on the comparison of the measured and simulated results, the differences between the gas consumption data of real buildings and simulated consumption were presented.
During the parameter sensitivity tests, the application of different heating setpoints (T_SP_H, T_SP_L), other fill factor (k), time program offset (slip) was also examined. The effect of temperature and time programmes determined during the tests on the specific heating energy demand was also presented.
During parameter identification, I determined the value of the internal specific heat generation for building B2, based on the procedure, $q_b = 4.968$ W/m^2. For the simplified model, I performed validation based on gas consumption data available for five different buildings for a period of 1-1 year. Subsequently, I further investigated the behavior of buildings by running simulations with the validated model.

3.4. Effect of heat transfer coefficient of limiting structures

During the tests carried out by changing the heat transmission coefficient of the boundary structures, simulations were performed according to the requirements levels valid for each boundary structure. In the course of this, I got a comprehensive picture of the specific heating energy demand of the given buildings if their geometric design had not been built, but only with the boundary structures typical of the given period. This is also useful from a practical point of view, as it allows you to estimate the specific heating energy demand according to the construction time (or time and level of renovation) of the building, and to determine the expected energy savings depending on the renovation to be carried out. I supplemented my study with simulations with different temperature setpoints (T_SP), during which I performed it in steps from 17 °C to 21 °C in 0.5 °C increments. In practice, this means a simulation run for five buildings with nine temperature setpoints according to six requirement levels for a period of one year.

3.5. Effect of heat capacity modification

The influencing effect of heat capacity was analyzed by changing the density of the boundary structures. The density of the outer wall was varied between 200 and 3000 kg/m3 in increments of 100, and the heating temperature between 17-21 °C every 0.5 °C. Based on the results, it can be observed that the change in heat capacity has a different effect on heating energy demand with a constant and time-varying setpoint.

3.6. The effect of lowering the temperature setpoint

I also investigated the effect of changing the temperature setpoint to 1 °C and based on the results I found that lowering the temperature to 1 °C can result in significant energy savings that exceed the values given in the literature. According to both international and domestic literature, lowering the internal temperature by 1°C results in energy savings of approximately 5-6%. The range tested was between 15 and 28 °C internal temperature setpoint when tested in 0,5 °C increments.

3.7. Determination of specific heating energy demand

In order to determine the specific heating energy demand, I processed the daily average temperature data of the county seats, determined the heating temperature bridge and the number of heating days. Based on the results, I showed how energy demand changes with temperature changes and differences between years. Based on the measurements, simulations and analyses carried out during my research, I have come to a number of new scientific results that contribute to a more accurate determination of the heating energy demand of buildings and to the improvement of energy efficiency.

The results and their explanations are presented in detail in the new scientific results section.

4. CONCLUSIONS AND RECOMENDATIONS

During my research, based on the comparison of simulation and measurement results, I created a physics-based mathematical model. I examined which parameters have the greatest impact on heating energy consumption. To verify the proper operation, I performed comparative tests with small sample models and validated the model based on measurement results. I extended it to a real building, and later to other residential buildings, and based on gas consumption and temperature data, I applied and validated the model. As a conclusion, I concluded that these simulation tools are suitable for determining heating energy consumption and performing optimizations using heat transport processes in residential buildings. Thanks to block-oriented and white-box modeling, it can be easily applied in other applications. For example, tests related to cooling are carried out. The expandability and flexibility made it possible to perform simulations for several buildings and draw general conclusions from them. I was also able to take advantage of the additional advantages of the simulation environment. Fast results can be achieved without costly construction and alteration of buildings, a given residential building can be examined in other geographical environments, or even the effect of differences between regulatory methods on energy demand is a significant advantage already during planning, operation, but also during a planned renovation.

Comparative measurements were made on the small sample models under real weather conditions. The aim of the study was to compare the control mode with a constant setpoint and a variable setpoint. These tests were performed using different heat storage masses. As a conclusion, it could be concluded here that due to financial and time constraints it is not possible to conduct a complete examination, since there are not enough small sample models available for measurements in parallel under the same conditions, and it is very time-consuming to fully measure a single annual cycle. The simulation framework provides a solution for this as well. Based on the measurements made on small sample models, I made findings, which highlights the relationships between the studied control methods in case of different heat storage masses. The practical usefulness of this is to know the behavior of the building, to be able to apply a control method appropriate to it and the required comfort levels, thus reducing the heating energy demand of the residential building. When building new buildings or modernizing, we can achieve optimal solutions for user habits by optimizing the heat storage mass. For rarely used residential buildings or cottages, for example, lower heat storage mass should be considered, as greater savings can be achieved in intermittent operation. With an increase in the heat storage mass, the difference in savings between the constant and intermittent control mode decreases, but in any case, it is a saving to reduce the temperature setpoint. Increasing the heat storage mass reduces internal temperature fluctuations and ensures more uniform internal temperatures even under the influence of external disturbance. Another research goal may be to conduct tests for cooling mode and comfort parameters.

After measurements made in real buildings and validation of the model, I performed several simulations. I examined the effect of different parameters on heating energy demand. Based on the small sample models, these buildings were also examined by changing the wall structure to different heat capacities. As a result, I observed the same effects as the small sample models. I examined the effects of constant and variable setpoint, the percentage energy savings that can be achieved by lowering the temperature by 1°C. I also articulated the connections I experienced here in the theses. In residential buildings, savings can be achieved by controlling the temperature by lowering the setpoint by 1-1°C or by applying a time program. It would be appropriate to examine comfort and user habits in residential buildings and to encourage end-users to avoid unjustified overheating. I examined and developed a block-oriented solution for determining the heating temperature bridge, using these data, I performed the tests for 2020-2023 in 2020-2023 county seats, Gödöllő and Zabar, running the examined buildings to 15-28°C temperature setpoints with 0.5°C increments, which meant nearly 3000 simulation runs. The results obtained in this way were graphically processed, with the help of which I developed an approximate equation, which is suitable for determining heating energy consumption based on the internal temperature setpoints, heating temperature bridge and building physical characteristics. This is also of considerable practical use, as a procedure clarified by geographical features (temperature bridge) can be used even during energy calculations. A quick and easy computational solution, which is a five-parameter quadratic equation. As a continuation of the research, it would be advisable to expand it to other regions, as well as to include additional residential buildings and buildings with other functions. It could be used to improve a method for checking energy audits to detect erroneous energy certificates.

The new scientific results presented in the theses can be utilized well both from a research and practical point of view. The simulation model, unlike other energy software solutions, can be easily and quickly adapted to other buildings. Enter less data manually. Its advantage is that it can be run even on the basis of the given meteorological data, the results and measured values of a given moment can be determined from it, it can be tried with other control methods, all this on a mathematical basis and transparently.

The prepared mathematically-based block-oriented modeling framework is suitable for examining the specific energy consumption of residential buildings and various control algorithms in MATLAB Simulink environment. The advantage of the completed framework is its white-box based operation, extensibility and the possibility of simulation of different scenarios. Additional models and experimental simulations can be created using this model. The model can be extended to other geographical environments.

With the help of the relationship I identified, it is easy to determine with the help of a linear equation how much savings can be achieved in heating energy consumption in case of variable setpoint control instead of a constant setpoint, knowing the specific UR value of the outer walls. It enables fast estimation without running scales and simulations.

In the case of residential buildings, knowing the linear relationships between the control mode and the heat capacity of the building, the expected specific heating energy demand can be determined based on the heat capacity, with a constant setpoint and a variable setpoint. The heat capacity under consideration covers the building materials used. Based on these, its practical benefit is that the usage habit, comfort demand and consumption of residential buildings can be optimized. In the case of buildings that are rarely or intermittently used, it is advisable to use building structures with lower heat capacity, lower temperature fluctuations with higher comfort requirements and continuous operation, and buildings with higher heat constants are less sensitive to weather extremes due to higher time constants.

Results established on the basis of simulation runs show that significantly higher percentage energy savings can be achieved than the 1°C setpoint reduction referred to in the literature causes a ~5-6% reduction in heating energy demand. Based on simulations, this is not uniform, but decreases as the temperature of the setpoint rises. Its value results in savings of 13% at lower temperatures and ~6% at higher setpoint temperatures. This seems somewhat contradictory, but if we look at energy needs, energy savings higher than a higher setpoint belong to a higher baseline, and therefore the percentage savings are lower. In the future, it would be worth paying more attention to this area, examining the needs of cooling systems as well. By changing the habits of end users and keeping lower (but still comfortable) temperatures, heating energy demand and pollutant emissions could be reduced.

The problem identified during energy certifications in both the detailed and simplified calculation methods is that they do not take into account the heating temperature bridge. For this, it is necessary to know the heating temperature bridge characteristic of the given settlement and year. The methodology I use offers this possibility. As a first step, the typical heating temperature bridge can be determined on the basis of publicly available databases, there is no need to carry out separate measurements. It is easy to calculate the temperature bridge. Based on the data, a more accurate heating energy consumption can be calculated than the method described in the ÉKM Regulation. Expanding the method provides additional opportunities for expanding it with other geographical areas.

As a continuation of the research, it would be advisable to extend it to buildings of other purposes and sizes. To be examined supported by measurement results for buildings with other geographical features. By expanding the research area, further energy savings could be achieved, e.g. by investigating the use of phase change materials or by optimizing control methods. There is also room for further research in the mathematical field: by simplifying the applied differential equations, simulations could be significantly accelerated with the help of Laplace's transform.

5. NEW SCIENTIFIC RESULTS

1. Thesis

I developed a physics-based mathematical model that can be directly applied to model thermal processes in residential buildings. The model was implemented with a block-oriented model of differential equations describing the processes of heat transport on the boundary structures of residential buildings. The model was validated with real building and small sample models based on measurements.

The practical benefit of the developed model is that there is an accurate generally applicable mathematical model that is suitable for running simulations. Unlike other simulation methods, here it is enough just to specify the physical characteristics of the building. Quickly adaptable to additional buildings.

2. Thesis

I conclude that the physics-based mathematical model is able to determine the specific heating energy consumption of the building with a coefficient of determination R^2>0.99, based on external environmental parameters, internal characteristics and physical characteristics of the boundary structures, in the case of residential buildings in Hungary with a floor area of 100-170 m^2, UR = 0.32-0.987 W/m^2K, A/V = 0.59-1.1 m^2/m^3. The simulation results of the physics-based mathematical model were validated based on the measurement data of small sample and real buildings.

I used the model in Hungarian weather conditions. The environmental parameters considered: ambient temperature, solar radiation. Internal characteristics: internal specific heat generation, HVAC system and its control method, filtration. Characteristics of boundary structures: density, specific heat, geometric dimensions, specific heat transfer coefficient.

The prepared mathematically-based block-oriented modeling framework is suitable for examining the specific energy consumption of residential buildings and various control algorithms in MATLAB Simulink environment. I incorporated into the system the mathematical models describing the building energy processes of residential buildings found in the literature. I developed the procedures that are suitable for the simulation and identification of modules within the framework. These procedures were demonstrated by test runs on real buildings and small sample models under real weather conditions.

The advantage of the completed framework is its white-box based operation, extensibility and the possibility of simulation of different scenarios. Additional *models and experimental simulations can be created using this model. The model can be extended to other geographical environments.*

3. Thesis

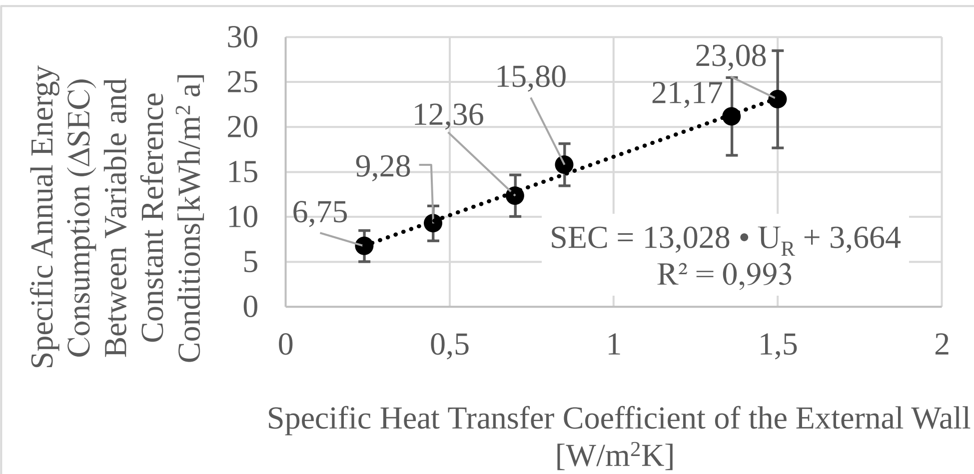
Based on simulation results, I proved that there is a linear relationship between the specific heat transmission coefficient of the external wall of residential buildings and the specific annual heating energy savings that can be achieved with a variable setpoint. The coefficient of determination is R^2=0.993 U_R= 0.32-0.987 W/m²K.

The general form of the descriptive equation is: $\Delta \boldsymbol{SEC} = \boldsymbol{m} \cdot \boldsymbol{U_R} + \boldsymbol{b}$

The slope varies according to temperature demand and time program, and the axis section depends on the internal heat load and filtration.

$\Delta SEC = 13{,}028 \cdot U_R + 3{,}665$ *A descriptive equation was given*. In the case of residential buildings *with a floor area of 100-170 m², U_R= 0.32-0.987 W/m²K, A/V = 0.59-1.1 m²/m³, when applying the variable base time program (between 6:00-8:00 and 16:00-22:30 21 °C (comfort), outside this period 19 °C (reduced) temperature, the slope is m=13.028. The axis section is considered average q_b=4.968 W/m², nf_{house}=0.5-0.8 1/h values b=3.665.*

The defined equation can be used to quickly check and calculate the expected energy savings of a residential building using a constant setpoint and a variable setpoint according to the time program described above. For the calculation, it is enough to determine the resultant U_R value, it is not necessary to carry out simulations and detailed calculations.



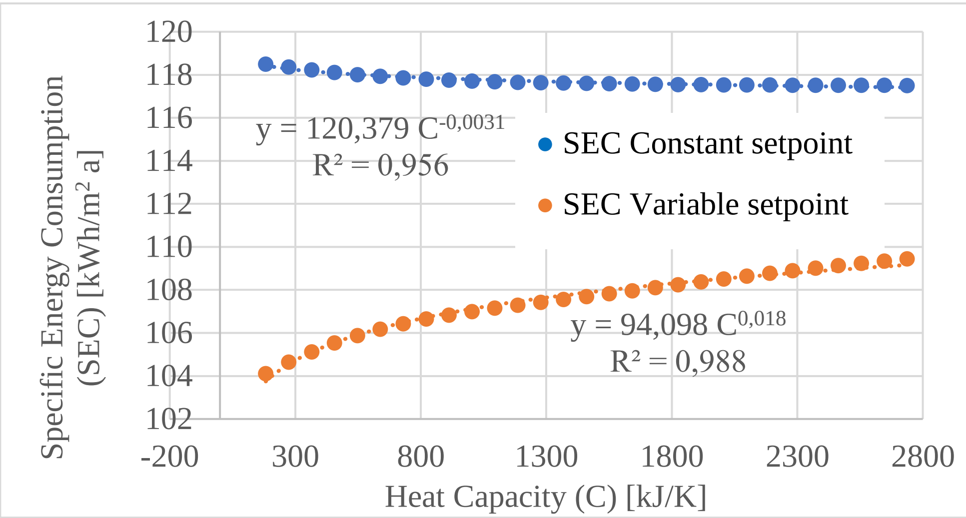
5.1. Fig. Residential buildings (A=100-170 m², U_R= 0,32-0,987 W/m²K, A/V=0,59-1,1 m²/m³) Specific Annual Savings

4. Thesis

I conclude that there is a relationship between the specific heating energy consumption of residential buildings and the heat capacity (C) of buildings structures that can be described by a power function. It has a decreasing tendency in the case of fixed setpoint heating, and an increasing tendency in the case of a time-varying setpoint. Based on these, as the heat capacity of building structures increases, the difference between the annual specific heating energy savings decreases.

In the case of Hungarian residential buildings with a floor area of 100-170 m^2, U_R= 0.32-0.987 W/m^{2}K, A/V = 0.59-1.1 m^2/m^3, the descriptive equations describing the heat capacity of wall structures in the range of 182.5-2737 kJ/K are:

Constant setpoint	**$SEC = 120{,}379 \cdot C^{-0{,}0031}$**	**$R^2 = 0{,}956$**
Variable setpoint	**$SEC = 94{,}098 \cdot C^{0{,}018}$**	**$R^2 = 0{,}988$**



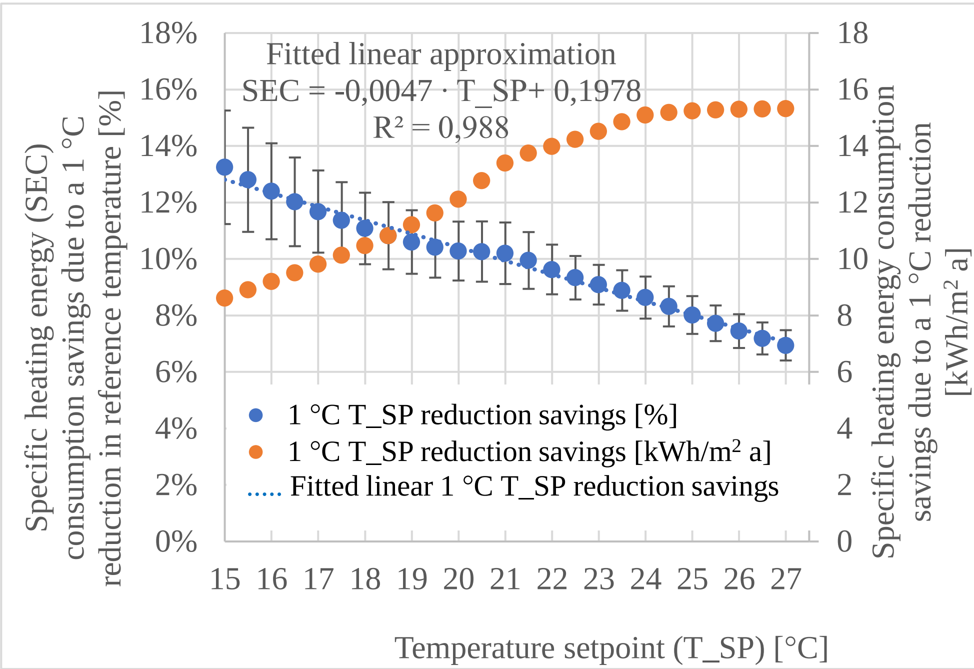
5.2. Fig. Residential buildings (A=100-170 m^2, U_R= 0,32-0,987 W/m^{2}K, A/V=0,59-1,1[m^2/m^3]) specific annual heating energy consumption is a constant and variable setpoint, depending on heat capacity

Based on the knowledge of the relationships, based on the heat capacity of the structures of buildings, the expected specific heating energy demand can be determined, with a constant setpoint and a variable setpoint. The heat capacity of the structures of the buildings under consideration covers the building materials used. The above statement confirms the phenomena known from practice, that lightweight buildings can be heated faster, but are more prone to temperature fluctuations, while heavy-structure buildings cool down more slowly due to their sluggish reaction and have a more uniform internal *temperature. It can also be seen that in the case of normal building materials, the two curves do not intersect, i.e. heating with variable setpoints requires less energy.*

5. Thesis

Based on simulation results, I proved that there is a linear relationship between the given temperature setpoint and the percentage heating energy savings that can be achieved by reducing by 1 °C, the coefficient of determination of the descriptive equation is R^2=0.988. I conclude that the percentage savings that can be achieved are between 7-13%, if the temperature is changed between 15-28 °C by 1 °C, for residential buildings with a floor area of 100-170 m^2, U_R= 0.32-0.987 W/m^{2}K, A/V = 0.59-1.1 m^2/m^3 in Hungary.

The descriptive equation is: $\Delta SEC_{\%} = -0{,}0047 \cdot T\_SP + 0{,}1978$



5.3. Fig. Residential buildings (A=100-170 m^2, U_R= 0,32-0,987 W/m^{2}K, A/V = 0,59-1,1 m^2/m^3) % and absolute savings of specific annual heating energy in case of 1°C temperature setpoint reduction

Based on the simulations, it can be concluded that lowering the temperature setpoint by 1 °C results in greater percentage savings at lower temperatures than at higher temperatures. In absolute terms, the value of savings decreases, but results proportionally in a higher percentage in the range under consideration.

6. Thesis

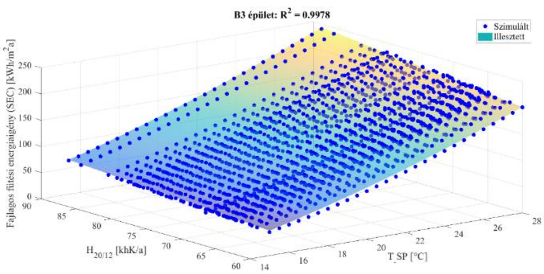
Based on simulation results, I created a simplified five-parameter quadratic function, which determines the specific heating energy consumption of residential buildings with a determination factor R^2>0.99 using the descriptive equation:

$$SEC\,(T\_SP, H_{20/12}, U_R, nf_{house}, q_b) = a \cdot T\_SP^2 + b \cdot H_{20/12} + d \cdot T\_SP \cdot H_{20/12} + c \cdot U_R + e \cdot nf_{house} + f \cdot q_b$$

The variables of the approximate function for a residential building are:

T_SP – internal temperature setpoint [°C]
$H_{20/12}$ – Temperature Bridge [khK/ a]
U_R – resultant heat transfer coefficient [W/m^{2}K]
nf_{house} - filtration factor [l/h]
q_b - internal heat source [W/m^2]
For county seats, temperature bridge calculated in the years 2020-2023 H20/12 = 60-88.8 khK/a and 15-28 °C internal temperature setpoint, the parameters are: a=0.212; b=0.183; c=113.621; d=0.045; e=169.401; f=50.193

The simulation studies cover four years between 2020 and 2023 for county seats, Gödöllő and Zabar, using data from NASA's database to set an internal temperature of 15-28 °C using a simulation model verified with data from five residential buildings. The approximate equation is used to calculate the heating temperature bridge, internal temperature setpoint, internal specific heat gain and the resulting heat transfer factor for the given year and geographical location. The procedure is much faster, more accurate and simpler than previous solutions. For example, a simplified and detailed method described in the Energy Performance of Buildings Act or methods requiring detailed data entry through simulation. The model can be easily expanded with additional buildings and geographical locations, which allows for further expansion.



5.4. Fig. B3 building simulated and matched specific annual heating energy consumption at different temperature bridges and temperature setpoint

6. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

1. **Páger Sz.**, Földi L., Géczi G. (2023): Comparative temperature and consumption data measurement of model buildings with different thermal time constants, Thermal Science. Online first: 0354-98362300228P, 13 p. https://doi.org/10.2298/TSCI230604228P, ISSN 2334-7163
2. **Páger Sz.**, Földi L., Géczi G. (2022): Creation and validation of simplified mathematical model for residential building energy analysis in matlab environment. Mechanical Engineering Letters: R and D: Research and Development, Vol. 22, pp. 26-41., 16 p., ISSN 2060-3789
3. **Páger Sz.**, Veres A., Géczi, G, Földi L. (2021): Energy Simulation Based on a Mathematical Model of a Residential Building, Scientific Bulletin Series C: Fascicle Mechanics, Tribology, Machine Manufacturing Technology Vol. 35 pp. 67-70., 4 p., ISSN: 1224-3264
4. **Páger Sz.,** Földi L., Géczi G., (befogadva, lektorálás alatt 2024): Increasing heat capacity – in temperature-controlled accommodation - increases energy use, Thermal Science.

Referred articles in Hungarian language

5. **Páger Sz.**, Földi L., Géczi G. (2022): Matematikai modell fejlesztése és validálása lakóépületek energiaigényét befolyásoló hidraulikai kapcsolások vizsgálatára, Magyar Energetika 29: 3 pp. 14-21., 8 p., ISSN 1216-8599
6. **Páger Sz.**, Géczi G., Földi L. (2023) Energiahatékonyság igazolása lakóépület fűtési rendszer szabályozási módjának a függvényében, MATLAB SIMULINK környezetben modellezve, Journal of Central European Green Innovation 11: 2 pp. 49-58. Paper: 4850, 10 p., ISSN 2064-3004
7. **Páger Sz**., Géczi G., Földi L. (2024): A szakaszos fűtési üzem hatása az energiamegtakarításra különböző időszakban épült családi házak esetén, Magyar Épületgépészet LXXIII: 3 pp. 9-17. Paper: LXXIII. évfolyam, 2024/3. number, 9 p. ISSN 1215 9913

International conference abstracts

8. **Páger Sz.**, Géczi G., Földi L. (2021): Modelling of buildings with a mathematical approach, 27th Workshop on Energy and Environment, December 9-10, 2021, Gödöllő, Hungary: Book of Abstracts 38, pp., 30 p, 1p.: Gödöllő, Magyarország: Hungarian University of Agriculture and Life Sciences, ISBN 978-963-269-972-1
9. **Páger Sz.**, Földi L., Veres A., Géczi G. (2021): Family house energy balance modeling, Efficiency, solar and thermal energy for the human comfort, Book of Abstracts 47 p. pp. 41-42., 2 p.: Gödöllő, Magyarország: Hungarian University of Agriculture and Life Sciences, 978-963-269-958-5