Developing a Complex Decision-Making Framework for Evaluating the Energy-Efficiency of Residential Property Investments

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Abstract: Currently, energy efficiency and energy security are among the most important energy issues that face Hungary and the European Union. Since households are responsible for one third of the primary energy consumption, we believe that significant results can be achieved in this area. According to our research, the typical design methods currently utilized are not entirely suitable to achieve the stated energy goals, since the goal of these methods is not to search and design an energetically optimal solution, but rather to comply with target values stipulated by law. Therefore, in order to increase the energy efficiency of the design of the buildings, we have developed a complex decision support model that enables in the conceptual design phase to effectively evaluate the emerging alternatives, taking into consideration both convenience and economy, as well as various subjective elements. This article presents a methodology developed through examples of four typical family homes in Hungary.

Keywords: analytic hierarchy process; energy; households; property investments; net present value

1 Introduction

Currently, one of the main areas of research in the European Union is focused on reducing the energy consumption of households and making them more energy efficient, given that households are responsible for one third of the primary energy consumed. However, this topic requires a complex, systematic approach, whereas nowadays the general construction energy strategy is mostly limited to the technical parameters, which could lead in erroneous directions. In the course of my research, I have found that the consumption habits and lifestyles of consumers influence household energy consumption, at least as much as the technical solutions applied. In addition, existing rules in different countries can have a decisive impact on the amount of energy consumed, as well as on the energy efficiency of the building. It is essential that we make consumers (owners and renters) interested in the implementation/construction of energy-conscious designs by delivering an optimal, or at least adequate, solution for them from the point of view of aesthetics and comfort, including finances. This objective requires designers to adopt new and unconventional attitudes and methods.

During the application of current building design practices, designers rely on their experience of energy-conscious methodologies as they try to meet legal regulations and requirements valid at the given location and time. In recent years, these technical requirements have become considerably stricter, and they are expected to become stricter still in the coming years, as starting from 2020 only those buildings can be constructed in the EU whose energy consumption is near zero. [1] As it was already mentioned, this fact alone may not be enough for the EU to achieve the energy efficiency targets it has set, so it is also necessary to examine the design phase of construction projects, in particular the energy-efficiency criteria.

Looking at the design process, we can see that the decisions made in the early, conceptual stages of the design process can significantly influence the future energy consumption of the building. Therefore, in the course of our research, we developed a decision support model that can efficiently solve the ranking of the various options arising in the conceptual design phase. The decision support model and the possibilities of its application will be described in the following paragraphs. Other decisive factors that can significantly affect the energy consumption of a building or household are the habits of the consumers and the factors associated with their living conditions. Therefore, a model was developed to help to manage the uncertainties arising from such factors, as well as to determine the future energy consumption of the building in the early design phase accurately and personalized. During the creation of the methodology, financial investment considerations and the reduction of greenhouse gas emissions were considered.

2 The Key Factors of Households Energy Consumption

In order to estimate the energy consumption of a building, or the change in efficiency due to a change in it or its parts, as well as to achieve the savings impact desired, it is necessary to understand the factors affecting the energy consumption of the household or building. In both Hungary and the rest of the European Union, a mix of general primary energy sources (e.g. wood, gas) and secondary energy sources (e.g. electricity) are used to satisfy the various energy needs of buildings, which can be grouped accordingly [2] [4]:

- Energy needed to ensure comfortable air space in living areas (e.g. heating, cooling, ventilation)
- Energy needed to produce domestic hot water
- Energy needed to operate lighting and electrical appliances (e.g. refrigerators, cooking appliances, etc.)

According to G. Swan et al. [2], the energy needed to ensure adequate air comfort depends on the technical characteristics and solutions of the building as well as on climatic conditions of the area; thus the relevant energy use can be calculated utilizing technical and meteorological data. However, as for the other two factors, Swan [2] shows that demographic factors, the number of household members, consumer behavior, and the energy efficiency of the appliances also influence the level of energy consumption. Therefore, in order to determine the energy use for hot water, appliances and lighting, he recommends the use of statistical data [2]. Professionals should not rely exclusively on technical and other data for determining energy use for these factors, independently from considering the user, since even if the building is nearly a zero-energy building assuming an average consumer, it will not achieve near zero energy use if the consumer does not use the building according to the principles of energy efficiency. In case of residential buildings, it is very difficult to influence consumer behavior by way of technical solutions. Residents generally have the need for what is usually expressed as "manual control", and thus intervene in the operation of the building; one need only think of such a simple thing as opening the windows to let in some air, for example. Consequently, energy efficiency cannot be guaranteed even though the best available technologies are used during the design and the construction of the building.

In order to take into consideration the issues cited above, the proposed decision support model consists of two major parts. One part deals with the uncertainties resulting from consumer behavior, tailoring the projected energy consumption of a household to a specified consumer, in order to eliminate inaccuracies resulting from projections based on the average consumer. The other part of the model considers technical factors that are independent from consumer habits, as it ranks the alternatives arising during the conceptual design and estimates the consumption of the building, or part of the building, based on the consumption rate of the specific household, which had been calculated with the first part of the model.

3 The Design of the Complete Decision Support System

As explained in the previous paragraph, in order to estimate accurately the energy consumption of a household, it is extremely important to consider the effects of consumer habits and living conditions. Towards this end, an artificial neural network based interference system was created that allows us to determine the average annual primary energy consumption of a household in accordance with the relevant statistical data. These factors, according to Aydinalp et al. [3] and supplemented with considerations of domestic peculiarities, are the following [4]:

- Size of the settlement
- Type of housing arrangement (owner, renter)
- Number of people living in the household
- Number of children living in the household
- Number of household members actively employed
- Highest education level of the head of the household
- Household income decile
- Size of the actual living space of the property
- Type of housing (house, flat)

To train the artificial neural network a starting database was needed, which was created based on the 2011 Census and the income and consumption statistics of the same year. [4] One benefit of the developed system is that the database can be expanded and modified, so the neural network model can be retrained with the up-to-date data in the future, thereby increasing the accuracy of the conclusions. To prepare and train the neural network based model, the Matlab software package, "Neural Network Fitting Tool" was used.

For the other part of the model an AHP (Analytic Hierarchy Process) based model similar to the models traditionally used in multi-criterion decision problems was created, which allows us to rank the alternatives emerging in the early planning stages. A complete evaluation is essential, as the owner or tenant, or in some cases the investor, will only be satisfied with the investment if it meets his/her needs on all points, since no matter how energy efficient a specific concept is, if it is unacceptable from the point of view of aesthetics or comfort, then that particular version will not be built. Accordingly, the main criteria of the AHP system are as follows [5]:

- Conceptual efficiency
- The performance of the building structures

- The energy efficiency of the equipment
- Architectural value, design
- Interior comfort
- Lifetime and reliability

The complete AHP hierarchy with the criteria and the sub-criteria along with their relationships are shown in Figure 1. During the evaluation, the classic AHP method was applied with the use of the basic Saaty scale and the eigenvector method. [5]

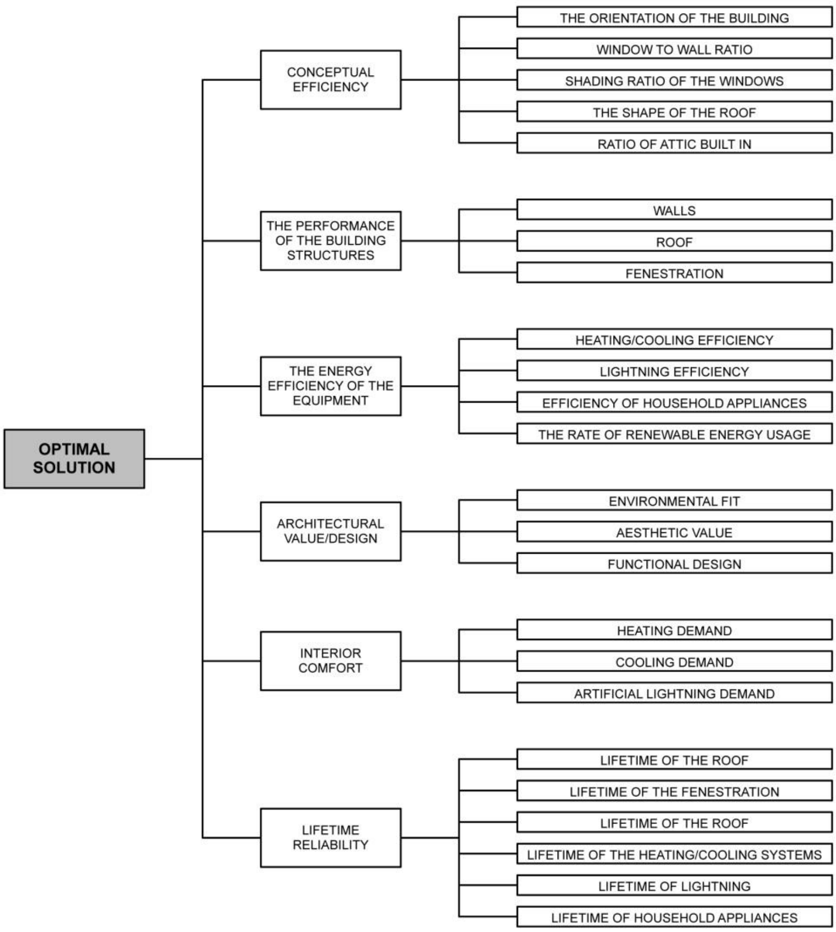

Figure 1

The AHP system with main- and sub-criteria [5]

Based on studies conducted during the research, it was observed that the use of the traditional AHP system is a relatively labor-intensive system. [5] Therefore, an improvement of the model was made as a Hybrid Fuzzy AHP system. This can significantly reduce labor-intensity and evaluation time. [5] The substance of the applied fuzzy AHP system is that instead of the paired comparison matrixes, we use fuzzy inference systems on the input side, which define the adequate SPIs (Site Performance Indexes) for specific factors and alternatives. [5] With the help of the SPIs, the evaluation continues within the established AHP structure, but by this point, the main and sub-criteria have already undergone a preliminary and generalized evaluation and received their assigned weights, which also accelerates the ranking process. [5] To prepare the model, the Matlab software package "Simulink" module was used. As discussed above, some economic calculation will be needed in order to complete the developed decision support system. The flowchart of the whole decision method along with the new modules is shown on Figure 2. It contains three major parts related to the economic investigation:

- Energy consumption estimate system
- Cost estimate system
- Return of investment calculation

The above listed systems and the results obtained with the completed method on the four fictional family houses will be described in the following paragraphs.

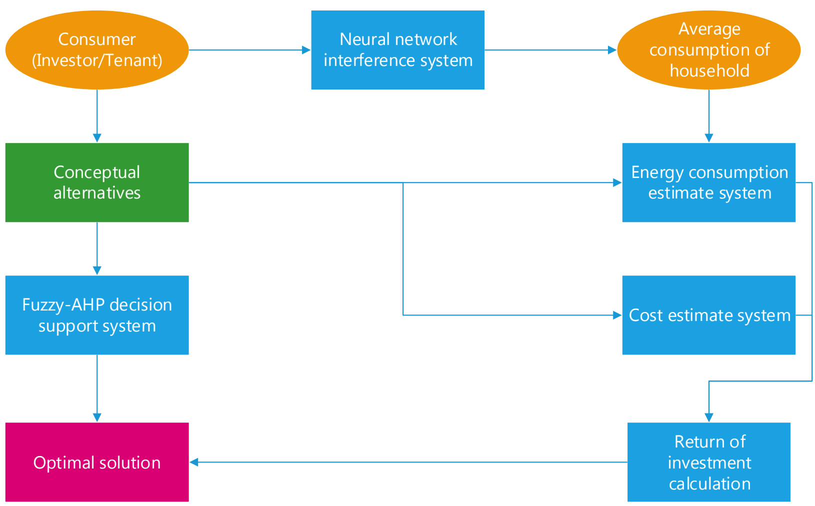

Figure 2
The flowchart of the developed decision method

4 Estimating Investment Costs

For a complex analysis of energy efficient investments, it is essential to examine the economics of the investments as well. However, in the studied design phase, it is difficult to determine the cost of the investment, since certain issues that can significantly affect the costs have not been definitively decided, at this point. In addition, the designer cannot be expected to write up a detailed budget for all the incurred alternatives, since this would require much more detailed plans than the conceptual design, which in turn would make the work economically unfeasible for the designer. To overcome this problem, a fuzzy inference based investment cost estimate system was developed and harmonized with the AHP based decision support models, which enables estimation for the cost of a building (or part of a building) by knowing some basic data. The reason for a system separate from the AHP model, is the extremely high price sensitivity of the investors/occupants; since in the AHP system the price has an unrealistically high weight, it would distort the results. In the future it would clearly be worth examining various financing structures, as they significantly affect the profitability of an investment, but that analysis is beyond the scope of this paper.

The backbone of the developed cost estimate system is made from the criteria and sub-criteria set in the AHP model, omitting those that do not at all or do not significantly affect the cost of the investment. During the development of the system, the key factor was matching the input data structure to the decision support models described above in order to ensure interoperability between the AHP based decision support model and the cost estimate system. The model was prepared in the "Simulink" module of the Matlab software package. The structure of the model is shown in Figure 3. Due to the design of the system and the variables used, the system can be fully integrated into the system already described and also systems made with the "Simulink" package.

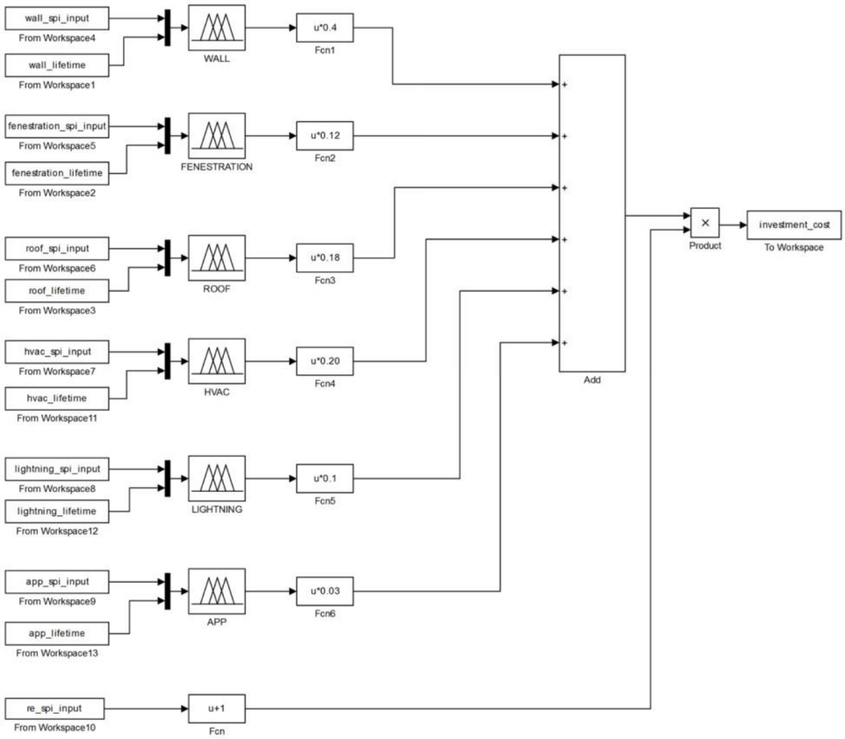

Figure 3
The structure of the cost estimate system in Matlab

To determine the cost of the structures and equipment, fuzzy controllers were used, with two input variables and one output variable. The fuzzy controller determines the relevant cost factor of the associated device or equipment by its performance and lifetime. In the event that the exact input values are unknown, with the help of the fuzzy controllers, linguistic variables [6, 7] could be used, which in the case of performance, for example, may be as follows: available worst, below average, average, above average, the best available. The membership functions of a particular fuzzy controller and its controlling surface is shown in Figure 4.

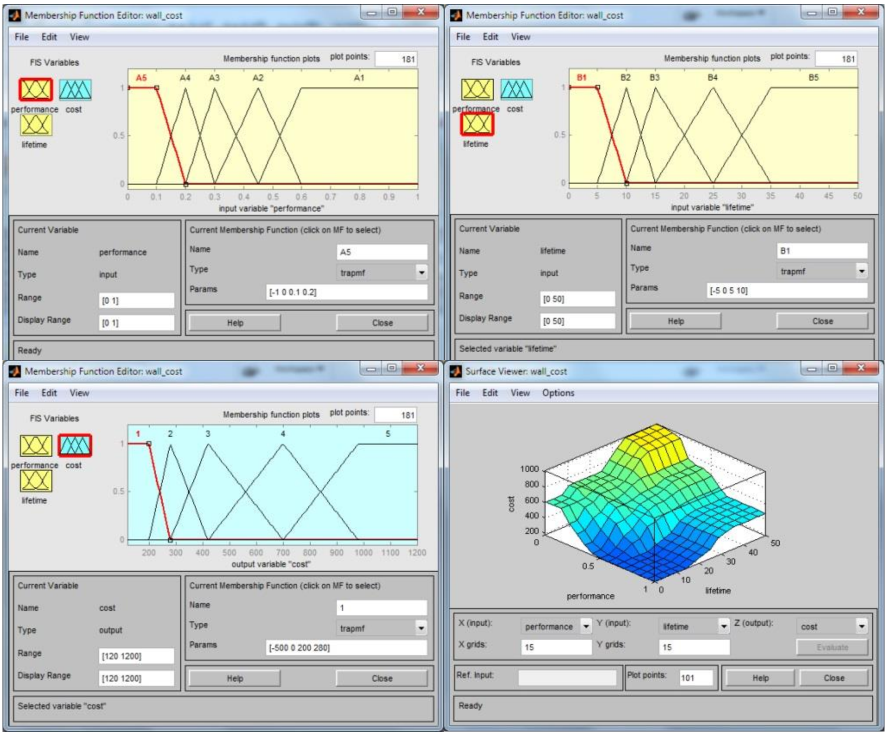

Figure 4

The membership functions of the wall-cost fuzzy controller and its controlling surface

For the calculation, the costs of different structures and equipment based on current construction statistics in Hungary were used. Obviously, the data that not yet known in the early design phase are not taken into account, so the actual investment cost may vary from the estimates; however, it is still possible to compare the alternatives that arise, particularly for the demonstration of differences in the quality of energy-conscious investments.

5 Determining the Costs of Operation

The determination of the operating costs is worth a more detailed investigation than the estimation of the investment cost. Based on our research, the expenses occurring over the lifetime of a building or a household can be divided into two independent groups, which would be the following:

- The cost of energy use
- The cost of replacement investments, due to the known lifetime of structures and equipment

The starting point for the calculation of the costs of energy use is the previously developed artificial neural network based inference system, based upon which we know the average annual primary energy consumption for a particular customer (household). In the case of a particular household, to evaluate the effects of different energy efficient investments, a high number of simulations with hypothetical reference buildings and households are required. Using these results, we developed a system to estimate the energy savings, which helps to compare the alternatives that arise during the conceptual design phase. It needs to be emphasized that the system does not replace the simulation methods, since a specific building has several parameters that are not known, or only approximately known; therefore it is not possible to calculate the precise energy consumption, which is required at later stages of the design. But the basic objective, the ranking of different versions by energy consumption, had been achieved. For the simulations needed to create the system, the Open Studio software system from NREL (the National Renewable Energy Laboratory) was used.

The model for estimating energy savings is also designed to be interoperable with the AHP based decision support system, as well as based on design variables already introduced. The system consists of fuzzy controllers that can help to estimate the impact of an investment on energy consumption utilizing the same factors that are used in the AHP system. This module was also prepared in the "Simulink" module of the Matlab software package, as was the above-described models. The schematic diagram of the model is shown in Figure 5.

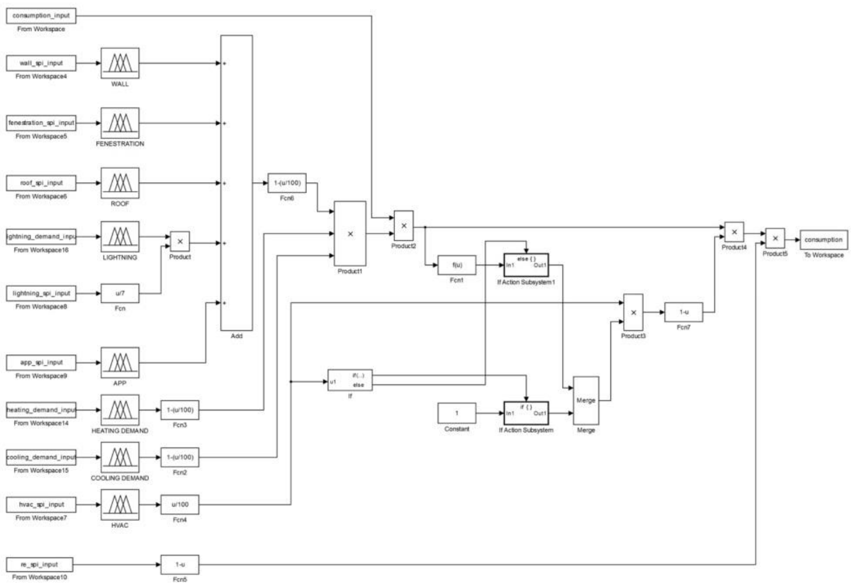

Figure 5

The schematic diagram of the energy consumption estimate system

The costs of the replacement investments occurring over the lifetime of the building or household were considered along with the useful life of the structures and equipment used in the investment. During the research, the design longevity was set at 50 years, while the replacement investments are cyclically repeating, according to the lifetime of the structure or equipment.

6 Results

The developed system was tested with 4 typical family houses in Hungary. In order to have an objective comparison, the four selected buildings have the same floor space and replaceable design. The reference household was a private "owned" urban household. There were four inhabitants, two of which are children. Of the four, 1 person is working and has finished secondary school, and they belong to the 6th decile income group. During the evaluation, I determined the average annual energy consumption of the reference household, ranked the alternatives with the developed fuzzy AHP hybrid model, with the estimating module I determined their investment cost and estimated their energy consumption and the reduction of resulting greenhouse gas emissions. Based on the results of all 4 versions, I made net present value calculations for the design longevity and calculated the internal rate of return for the initial investment. For verification, I made a detailed energy simulation of each alternative; however, in our previous researches we have already established that with the developed AHP and Fuzzy AHP based model, the energy ranking of the alternatives is solvable with adequate accuracy in the early design phase. [5] The design data of the selected 4 variants is in Table 1.

Table 1
The data of the alternatives

	Alternatives				
Criteria	**A1**	**A2**	**A3**	**A4**	
Conceptual efficiency					
The orientation of the building	90	90	90	90	*[°] N - 0°*
Window to wall ratio	0.18	0.18	0.25	0.43	
Shading ratio of the windows	0.00	0.00	0.52	1.00	
The shape of the roof	38.83	38.83	30.00	5.00	*[°]*
The ratio attic building in	0.00	0.00	0.00	0.00	
The performance of the building structures	**A1**	**A2**	**A3**	**A4**	
Performance of the walls	1.79	0.39	0.24	0.14	*[W/m²K]*
Performance of the fenestration	2.20	1.60	1.60	0.80	*[W/m²K]*
Performance of the roof	1.69	1.69	0.74	0.12	*[W/m²K]*

The energy efficiency of the equipment	**A1**	**A2**	**A3**	**A4**	
Heating/cooling efficiency	0.80	0.80	1.00	1.50	
Lighting efficiency	10.50	10.50	7.00	5.25	*[W/m^2]*
Efficiency of household appliances	3.45	3.45	2.30	1.80	*[W/m^2]*
The rate of renewable energy usage	0.00	0.00	0.10	0.20	
Architectural value/design	**A1**	**A2**	**A3**	**A4**	
Environmental fit	0.20	0.20	0.50	1.00	
Aesthetic value	0.20	0.20	0.30	0.80	
Functional design	0.50	0.50	0.40	0.60	
Interior comfort	**A1**	**A2**	**A3**	**A4**	
Heating demand	22	21	20	21	*[°]*
Cooling demand	-	-	25	24	*[°]*
Artificial lighting demand	13	13	11	8	*[hour]*

Lifetime/reliability	**A1**	**A2**	**A3**	**A4**	
Lifetime of the walls	20	20	25	50	*[year]*
Lifetime of the fenestration	10	10	20	25	*[year]*
Lifetime of the roof	10	20	20	25	*[year]*
Lifetime of the heating/cooling system	5	10	10	20	*[year]*
Lifetime of lighting	5	10	10	10	*[year]*
Lifetime of household appliances	5	10	10	10	*[year]*

For the calculations of investment profitability, I set up different scenarios with varying energy prices, since considering the 50-year longevity, it is difficult to rely only on one data series. Accordingly, I relied on both domestic and international literature as well as my estimates, with regards to expected energy prices in the next 50 years. The 4 different scenarios are shown in the following charts.

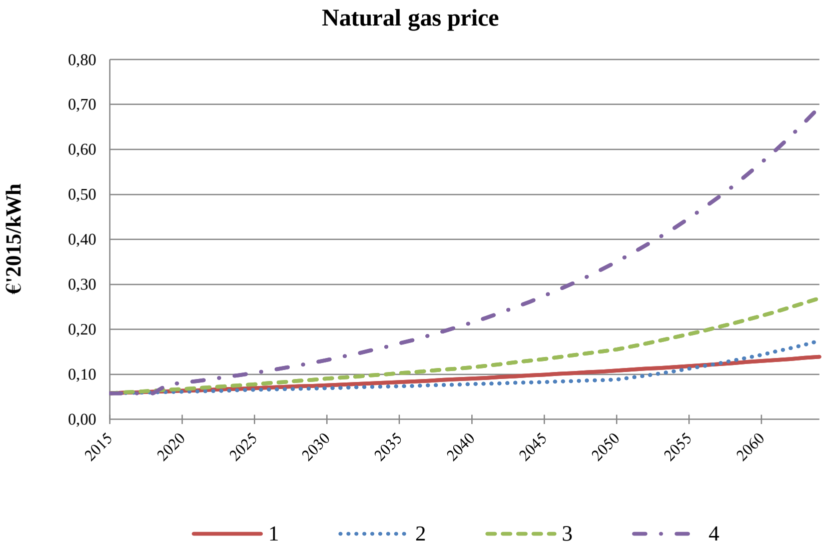

Figure 6
Price of natural gas based on the 4 scenarios

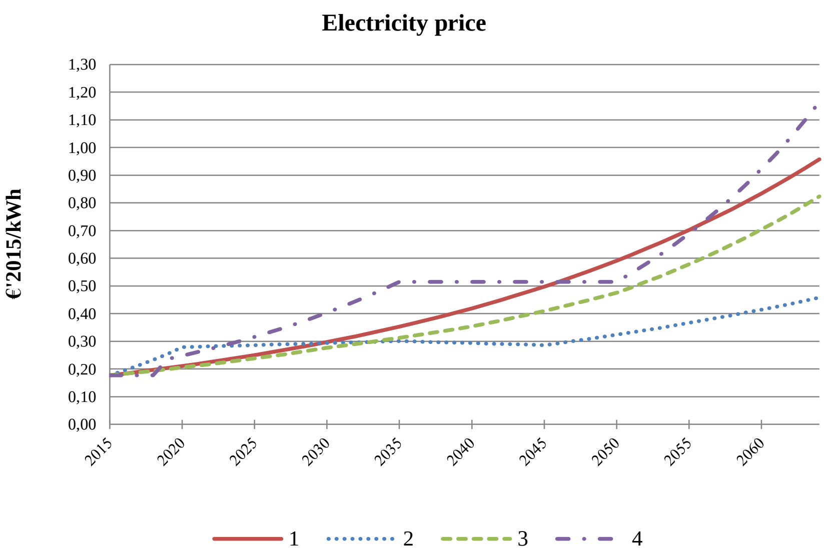

Figure 7
Price of electricity based on the 4 scenarios

The first scenario was based on research by the Hungarian Energy Club, according to which energy prices are expected to increase with relatively stability, meaning a gas price increase at an average annual rate of 4.3%, and an electricity price increase of an average of 5%. [8] In the second scenario, which is based on the European Commission's forecast, gas prices steadily rise at a slightly lower rate compared to the previous scenario until 2050, after which it will rise at a higher rate. However, electricity prices will increase considerably until 2020, and then stagnate until 2035, followed by a moderate increase. [9] The intermittent rise and stagnation in electricity prices is a consequence of the life cycle of investments made at different times in the electricity sector. In the third version, which was prepared according to the forecast of the European Renewable Energy Council, the rise in energy prices is moderate until 2030, higher until 2040, and even higher after 2040. [10] According to my own estimates, which is the fourth version, in 2018, a sharp correction in energy prices will be felt, resulting in an immediate 33% increase compared to the period of stagnation before. In the subsequent period, gas prices will steadily rise with an average annual rate of 5%, while electricity prices increase fractionally, similarly to the third scenario. To perform the economic calculations, a supposed 2.5% cost of capital, during the entire life cycle, and the funds for the investment are considered as available. It would require a separate analysis to forecast the various economic indicators, which is beyond the scope of our research; however, the model provides the opportunity to the change the capital cost as well as to consider other forms of financing. The results of the economic calculation of the 4 selected family houses are in Table 2.

Table 2
The results

	Alternatives				
Decision support system	**A1**	**A2**	**A3**	**A4**	
Fuzzy-AHP results	0.40	0.52	0.62	0.83	*[0-1 point]*
Costs	**A1**	**A2**	**A3**	**A4**	
Net square footage	85	85	85	85	*[m^2]*
Cost per square footage	816	1603	2203	3735	*[€/m^2]*
Investment cost	69371	136274	187274	317516	*[€]*
Energy consumption	**A1**	**A2**	**A3**	**A4**	
Simulation results	509	368	294	170	*[kWh/m^2*year]*
Estimated results	494	332	263	159	*[kWh/m^2*year]*
Deviation	3.07	10.96	11.71	6.86	*[%]*
GHG emission	10.54	7.09	5.61	3.39	*[t/year]*
GHG emission reduction	-	32.79	46.76	67.81	*[%]*
Not appropriate comfortable	1845	2336	1229	437	*[h]*
Economical results	**A1**	**A2**	**A3**	**A4**	
Scenario 1					
Lifetime net present value	438877	379374	389999	427334	*[€]*

NPV - deviation from A1	-	59503	48878	11543	*[€]*
Internal rate of return	-	6.07	4.30	2.72	*[%]*
Scenario 2					
Lifetime net present value	394193	349343	366210	412952	*[€]*
NPV - deviation from A1	-	44849	27983	-18759	*[€]*
Internal rate of return	-	5.70	3.84	2.25	*[%]*
Scenario 3					
Lifetime net present value	492655	415516	418630	444643	*[€]*
NPV - deviation from A1	-	77138	74025	48012	*[€]*
Internal rate of return	-	6.45	4.75	3.19	*[%]*
Scenario 4					
Lifetime net present value	711682	562717	535237	515139	*[€]*
NPV - deviation from A1	-	148965	176444	196542	*[€]*
Internal rate of return	-	7.71	6.16	4.58	*[%]*

*based on 310 HUF/€ exchange rate

Conclusions

Looking at the results, it can be observed that the fuzzy inference system developed to estimate the energy savings estimated the energy consumption of a particular investment with a margin of error under 15%. This is sufficiently accurate for the examined planning stage, especially considering my main goal was to rank the alternatives and to select the best version for further development. The ranking made by the fuzzy AHP system harmonizes well with the energy results, but as to the point of comfort, it leads to disparity. In this respect, the A2 version performs even worse than the A1 alternative, even though it is the favored solution considering energy consumption, due to a simple and/or poorly executed energy refurbishment. We can see many examples of the above these days, e.g. different air condition problems such as mold, too low or too high humidity and discomfort in isolated parts of the building.

In the results of the economic calculations, it can be seen that, apart from scenario 2, in virtually every case, the A1 variant had the highest expenses, calculated for longevity. Consequently, we can conclude that, in almost all cases, the energy-conscious investments should be implemented, since if we look at the whole life cycle, in most cases they are economically worthwhile as well. This fact could impact the perspective of the consumer, because if the investor sells the property, or if for some reason it comes under another person's use, then the investor does not realize these economic benefits. Nevertheless, the social and environmental impacts of the project are not negligible. Considering the complex evaluation, it can be concluded that the fuzzy AHP system herein, established an adequate ranking via the economic criteria as well, since if we look at the evaluation of the A2 and A3 versions, it shows that the expenses for the entire lifespan are similar, but the A3 alternative performs better as regards both energy and comfort.

With regard to greenhouse gas emissions, obviously, the lowest-energy building achieves the best results. If we take this fact into consideration, the nearly 3% internal rate of return is not a bad result, since the amount of the emitted gases decreases by 2/3. However, the future social and environmental impacts of this cannot be measured objectively via economic indicators. In the view of the Author, however, taking a long-term perspective, the issue of greenhouse gas emissions is a more important factor than different economic factors, especially with regard to fulfilling the objectives set by the EU. Based on these results, the developed method is suitable for evaluating the alternatives available in the early stages of planning and for choosing the best alternatives for future plans. However, concerning economic issues, it needs to be mentioned, that a significantly better return on the investment can be achieved with adequate incentive and/or funding programs.

Acknowledgement

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