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The Framework of an Optimization Model for Building Envelope

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Abstract

Building design is an iterative process from the conceptual design up to the final process, so the use of computer-based tools here is vital. The purpose of this research was to investigate the most popular tools for building design and present a framework of an optimization model for building envelope, without compromising on energy efficiency, comfort, cost, and environment. The combination of simulation tools DesignBuilder, SimaPro and the method of multiple criteria complex proportional assessment (COPRAS) were not implemented in researches yet. Following the model, we determine the values, which are usually chosen as the optimization criteria: energy demand (heating, cooling, electricity), comfort parameters (PVM, PPD values, discomfort hours, daylight), embodied, operational energy, CO_2 emission, investment and exploitation cost. As the result, the use of this optimization model does not require great experience, but improve and facilitates the building design process.

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Keywords: building design, optimization, decision making, computer - based simulation tools, DesignBuilder, SimaPro, COPRAS.

1. Introduction

The EU target to reach "nearly zero-energy buildings" up to 2020 year leads to new concepts of building design and construction: to reach high energy performance, without compromising on comfort, cost, aesthetics and environment.

Today, the construction industry is in the early stages of a revolution to reinvent the design process that was used before the advent of HVAC equipment. Design teams including both architects and engineers are formed and the building design is developed in an iterative process from the conceptual design ideas to the final detailed design [1].

The decisions made in the early stages of building design have a strong influence for building's efficiency and performance in further 50–100 year, that is why, the implication of building simulation and optimization tools/methods can make this process easier and more successful.

Five main categories of design methods and tools can be identified [1]: design process methods/tools, design strategy methods/tools, design support methods/tools, design evaluation methods/tools and simulation tools.

In literature the overview of computer-based simulation tools may be found [2–5]. Many authors try to couple building performance simulation tools with some optimization methods or tools, to reach the optimum between energy consumption and comfort [6], [7], achieve low-emission, cost – effective design solutions [8], zero-energy building design [9], or minimize the life-cycle cost for the building's operation [10].

Here, the implication of Building Information Modelling (BIM) can lead to more detailed analysis. [11] presented a methodology ThermalOpt for automated BIM-based multidisciplinary thermal simulation intended for use in multidisciplinary design optimization (MDO) environments.

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[12] used BIM in their method for applying life-cycle analysis (LCA) to early stage decision – making in order to inform designers of the relative environmental impact importance of building component materials and dimensioning choices. The wider overview about implication of BIM into early building design is discussed in [13-15].

Unfortunately most of authors focus on more narrow range of optimization criteria, or choose methods for decision making, which require knowledge and experience working on it.

The goal of this research was to develop an intelligible and clear building envelope optimization model, coupling building performance simulation tool DesignBuilder, the most widely used LCA software SimaPro and using the method of multiple criteria complex proportional assessment (COPRAS) for decision making. Following the framework, more energy efficient, cost effective and environment friendly building design can be achieved.

2. The overview of computer based simulation tools

The most popular computer – based tools (programs), for building energy simulation, life – cycle assessment and optimization are presented in Table 1.

Table 1. Computer-based simulation tools

	Program abbreviation	Features
Simulation tools	EnergyPlus, DesignBuilder, TRNSYS, eQuest, Energy-10, DOE-2, MIT Design Advisor IDA ICE	*EnergyPlus* – is a whole building energy simulation program for modelling building heating, cooling, lighting, ventilating, and other energy flows. *DesignBuilder* – simulation program for checking building energy, carbon, lighting and comfort performance. Links with all major 3-D CAD software. Includes parametric analysis. *TRNSYS*– is a transient systems simulation program with a modular structure. Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC (Heating, ventilation, air conditioning) systems, renewable energy systems, cogeneration, fuel cells *e-Quest* – easy to use, freeware building energy use analysis tool. *Energy-10* – building energy simulation program for smaller buildings, that focuses on the early stages of the architectural design process, and the integration of daylighting, passive solar design, and etc. into high performance building. *DOE-2* – hourly, whole-building energy analysis program calculating energy performance and life-cycle cost of operation. *MIT Design Advisor* – is an on-line design tool for architects and building engineers, to give preliminary estimates for the performance of building facades *IDA ICE* – a dynamic multizone simulation application for accurate study of thermal indoor climate of individual zones as well as the energy consumption of the entire building.
Life-cycle assessment	BEES, Athena GaBi SimaPro,	*BEES* – evaluates building materials and components *Athena* – evaluates whole buildings and systems; *GaBi and SimaPro* – evaluate the environmental performance of products and services in general at the material, component, and system levels, and include applications to the building industry.
Optimization tools	GenOpt, Topgui, LINGO, MCDM-23	*GenOpt* – is an optimization program for the minimization of a cost function that is evaluated by an external simulation program (EnergyPlus, TRNSYS). Has a library with local and global multi-dimensional and one-dimensional optimization algorithms, as well as algorithms for doing parametric runs. *Topgui* – is a pre-processor program for Ole Sigmund's 99 line topology optimization code. *LINGO* – a comprehensive tool designed to make building and solving Linear, Nonlinear (convex & nonconvex/Global), Quadratic, Quadratically Constrained, Second Order Cone, Stochastic, and Integer optimization models. *MCDM-23*– tool to support decision making in a design process, that requires to take esteem environment, cost, urban context and other various criteria at the same time.

Building simulation is an assistant tool in designing an energy efficient building. There is a possibility to choose from a wide range of building energy simulation tools. One of the most popular – EnergyPlus that engineers, architects use to model energy and water use in buildings, is often used in research studies [16], [17]. It can be coupled with BIM [11], optimization program GenOpt [6].

The design of buildings is a multi-criterion optimization problem, there always being a trade-off to be made between capital expenditure, operating cost, and occupant thermal comfort. Such a design process can be informed by the application of MCDM techniques. The MCDM process has two elements, the search for viable solutions, and the decision as to which solution is the most desirable [18].

MCDM-23 is the optimization tool, developed by the International Energy Agency (IEA), to support decision making in a design process of a building, for making a selection between two or more candidate design schemes. It is often mentioned as one of optimization tools or used in research studies [19], [20].

GenOpt is an optimization program, that has a library with local and global multi-dimensional and one-dimensional optimization algorithms, as well as algorithms for doing parametric runs. One of its advantage is that it can be coupled with any external energy simulation program (EnergyPlus, TRNSYS and etc.) [21], [22].

As sustainability is an increasingly important part of the building design process, it is essential to include environmental analysis in the early stage of building design. Here the most powerful are computer based tools: SimaPro, BEES, Athena, GaBi. These offer the possibility of analyzing, in detail, a wide range of environmental aspects of materials including embodied energy, gathered in most cases through life cycle inventory analysis [23–25].

3. The method

The goal of presented model is to optimize building envelope components, according the following optimization criteria: energy demand, comfort, CO_2 emission, investment and exploitation costs.

The principle of our framework is presented in Fig. 1.

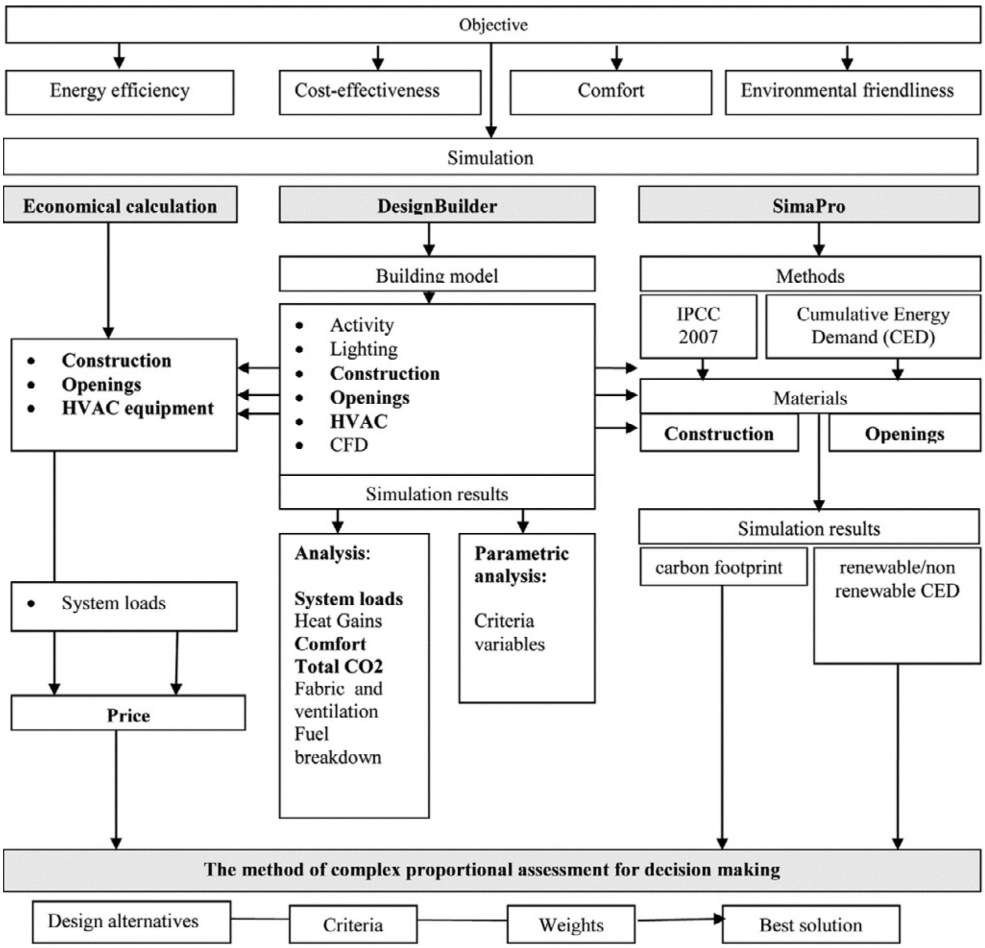


Fig. 1. A framework of a model for building envelope optimization

In the early stage of building design, the goal of architects, constructors, engineers and clients is to find a mutual decision for building design solution. Here is necessary to arrange the priorities for the criteria in decision making.

According to the presented framework, the main building design and performance simulation tool is DesignBuilder. Here a building model is created: the simulation program gives a possibility to choose proper envelope construction, HVAC parameters, activity and schedules. The simulation results show energy, comfort, environmental parameters. In order to optimize the building envelope – possible alternatives should be reiterated, or one of DesignBuilder functions –parametric study should be used.

Parametric study can help to visualize the potential of the reduction or choose the optimal solution regarding the considered criteria (if the criteria that DesignBuilder offers, are enough.)

In order to optimize building envelope from a life cycle perspective – materials of building construction, openings, HVAC equipment are analyzed in SimaPro software. The determination of carbon footprint is based on IPCC 2007 method, which contains the climate change factors of IPCC with a timeframe of 100 years. The determination of cumulative energy demand (renewable and non renewable) is based on Cumulative Energy Demand (CED) method.

The estimation of investment and exploitation costs can be done in accordance with energy simulation results (energy consumption, energy load).

The last step in this model is decision making. According to assessed criteria, building envelope alternatives are evaluated in the decision support matrix. Here a method of multiple criteria complex proportional assesment (COPRAS) is used. This method was first announced in 1994 [26].

The method COPRAS assumes direct and proportional dependence of the significance and utility degree of the investigated versions on a system of criteria adequately describing the alternatives and values and weights of the criteria [27]. The method COPRAS was applied by many authors [28–31] in their studies.

In this case the method COPRAS is advantageous because of its ability to adapt any criteria, which is essential: quantitative and qualitative ones. In this case, our requirements comply with the simulation results from DesignBuilder, SimaPro and economical calculation.

4. Case study

To show the operation of presented model framework, a simple case is considered for the optimization of building's external wall. One-zone office building (10×20×2,8 m) example for parametric analysis from the DesignBuilder library have been analyzed. The location and climate data was chosen for Lithuania, Kaunas city. The activity, HVAC schedule is common for an office building. Fig. 2 shows the view of building model.

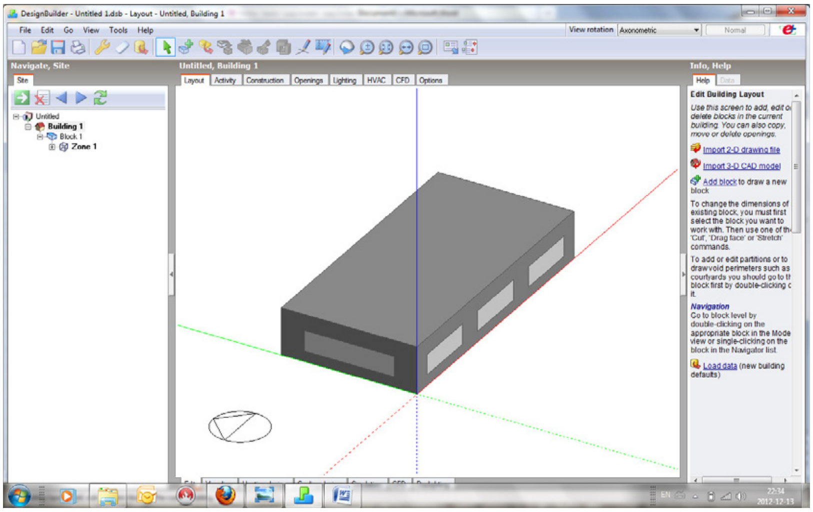
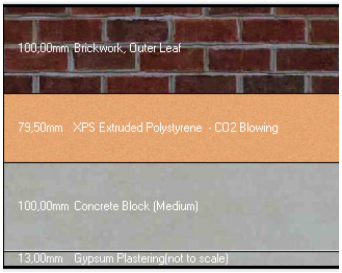
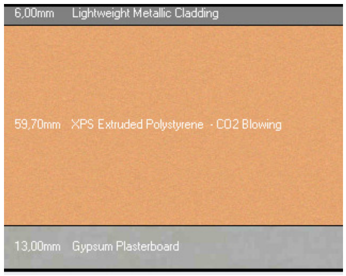


Fig. 2. Building model in DesignBuilder

To choose the best alternative of external wall, three different constructions (Alternative 1, Alternative 2, and Alternative 3) have been simulated. They are presented in Table 2.

Table 2.Alternatives of external wall construction

<table>
<tr><td></td><td>Alternative 1</td><td>Alternative 2</td><td>Alternative 3</td></tr>
<tr><td>External wall section</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td></td><td>Heat transfer coefficient:
U=0,25 W/m²K</td><td>Heat transfer coefficient:
U=0,35 W/m²K</td><td>Heat transfer coefficient:
U=0,5 W/m²K</td></tr>
</table>

Using parametric study, we found the impact of different walls construction to energy, comfort, total CO_2 emission. Using SimaPro, carbon footprint and cumulative energy demand (CED) for the materials of wall's construction were determined. Heating, cooling and total energy demand have been converted in to financial terms, according to energy price for heating and electricity from centralized networks. All these results are chosen as the criteria and presented in decision support matrix Table 3.

Table 3. Initial data for decision support matrix

Criteria	Unit		Weights	Alternative 1	Alternative 2	Alternative 3
U value	[W/(m^2 K)]	„–"	0.05	0.25	0.35	0.50
Inertia		„+"	0.05	3.15	2.97	0.60
Heating load	kWh	„–"	0.07	17621.20	17761.51	20422.73
Cooling load	kWh	„–"	0.05	3822.12	3936.82	3998.62
Total primary energy consumption	kWh	„–"	0.1	46659.69	46902.44	51008.06
Discomfort (all clo)	hr	„–"	0.1	650.50	627.00	575.00
Total CO_2		„–"	0.08	17825.67	17886.18	18692.38
Carbon footprint (1m^2 wall construction)	kgCO2eq	„–"	0.08	71.56	69.38	4.98
CED. Renewable	MJ		0.05	60.79	58.57	91.00
CED. Non-renewable	MJ	„–"	0.03	683.94	657.75	2.92
Price (for 1m² wall)	Lt	„–"	0.1	100.00	98.00	274.00
Cost for heating consumption	Lt	„–"	0.07	4792.97	4831.13	5554.98
Cost for cooling consumption	Lt	„–"	0.05	1605.29	1653.46	1679.42
Cost for total energy consumption	Lt	„–"	0.12	6398.26	6484.60	7234.40

In Table 3 the weight values for criteria have been set according to the accepted iscomfort and price (for 1m² wall), (0.08) for total CO_2, carbon footprint (1m^2 wall construction), (0.07) for heating load, cooling load, price for heating consumption, (0.05) for U value, inertia, cooling load, (CED. Renewable), (0.03) for (CED. Non-renewable). The total weights should be equal 1. The symbols „+" or „–" show the higher or lower value of criteria is more useful for us.

To get the best solution from decision support matrix, the following evaluation stages are presented [32].

The formulation of decision support matrix. The aim of this phase – to convert comparison indicators to dimensionless (normalized) values. This way all different unit measurements can be compared.

For this the following formula should be used:

$$d_{ij} = \frac{x_{ij} \cdot q_i}{\sum_{j=1}^{n} x_{ij}}, \quad i = \overline{1,m}; \quad j = \overline{1,n}, \tag{1}$$

Here : x_{ij} – value „j“ of criteria „i“ in decision value; m – number of criteria; n – the number of compared evaluations; q_i – the significance of „i“ criteria.

The significance criterion q_i value is allocated pro rata to all alternative versions a_j according to their values x_{ij}. Each criterion x_i receives dimensionless weighted values d_{ij}, which are equal to the sum of the criteria weights q_i:

$$q_i = \sum_{j=1}^{n} d_{ij}, \quad i = \overline{1,m}; \quad j = \overline{1,n}. \tag{2}$$

The summing of minimazing S_{-j} or maximazing S_{+j} normalized weighting values for option „j“, according formula:

$$S_{+j} = \sum_{i=1}^{m} d_{+ij}; \quad S_{-j} = \sum_{i=1}^{m} d_{-ij}, \quad i = \overline{1,m}; \quad j = \overline{1,n}. \tag{3}$$

The sum of S_{+j} and S_{-j} is allways equal to maximazing and minimazing criteria weighting amounts.

$$S_{+} = \sum_{j=1}^{n} S_{+j} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{+ij}, \quad S_{-} = \sum_{j=1}^{n} S_{-j} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{-ij}, \quad i = \overline{1,m}; \quad j = \overline{1,n}. \tag{4}$$

The significance of the alternatives is determined according to them describing positive S_{+j} and negative S_{-j} qualities. The relative significance Q_j of each alternative a_j is evaluated according formula:

$$Q_j = S_{+j} + \frac{S_{-\min} \cdot \sum_{j=1}^{m} S_{-j}}{S_{-j} \cdot \sum_{j=1}^{m} \frac{S_{-\min}}{S_{-j}}}, \; j = 1,2,3,...m \tag{5}$$

Calculation of the utility degree of the alternatives by the following formula:

$$N_j = \frac{Q_j}{Q_{\max}} \cdot 100 \tag{6}$$

The last stage is the determination of priority order of the alternatives.

5. Results

The calculation results for decision making of 3 different external wall constructions are presented in Table 4.

According to the priority order, the external wall construction alternatives ranges as follows: ,,Alternative 1”, ,,Alternative 2” and ,,Alternative 3”.

The assessed criteria values of ,,Alternative 1” and ,,Alternative 2“ are quite similar, that is why, the utility degree differs only 1 %. The difference between utility degree of ,,Alternative 1’’ and ,,Alternative 3’’ is only 6%, although the difference of U value is 50%. Here is important not only the criteria value, but especially the criteria weight, which can influence the arrangement of the priorities. That is why the determination of criteria weight here is fateful, and complicated. The fewer criteria are analyzed, the more objectively we can set the values.

In order to find the best combination of all building envelope components – analogically all the alternatives (window, roof etc.) should be evaluated.

Table 4. Decision support matrix for the alternatives of external wall construction

Criteria	Unit		Weight	Alternative 1	Alternative 2	Alternative 3
				The assessed dimensionless values of parameters		
U value	[W/(m K)]	„–"	0.05	0.011	0.016	0,023
Inertia		„+"	0.05	0.023	0.022	0,004
Heating load	kWh	„–"	0.07	0.022	0.022	0.026
Cooling load	kWh	„–"	0.05	0.016	0.017	0.017
Total primary energy consumption	kWh	„–"	0.1	0.032	0.032	0.035
Discomfort (all clo)	hr	„–"	0.1	0.035	0.034	0.031
Total CO_2		„–"	0.08	0.026	0.026	0.027
Carbon footprint (1m2 wall construction)	$kgCO_2eq$	„–"	0.08	0.039	0.038	0.003
CED. Renewable	MJ	„+"	0.05	0.014	0.014	0.022
CED. Non-renewable	MJ	„–"	0.03	0.015	0.015	0.000
Price (for 1m² wall)	Lt	„–"	0.1	0.021	0.021	0.058
Cost for heating consumption	Lt	„–"	0.07	0.022	0.022	0.026
Cost for cooling consumption	Lt	„–"	0.05	0.016	0.017	0.017
Cost for total energy consumption	Lt	„–"	0.12	0.038	0.039	0.043
The sum of maximizing normalized indicators ('+' S+j)			0.1	0.0379	0.0360	0.0261
The sum of maximizing normalized indicators ('–' S–j)			0.9	0.296	0.299	0.306
Significance of alternative Qj			1.00	0.34	0.34	0.32
Alternative utility degree Nj				100	99	94
The priority of wall alternatives				1	2	3

6. Discussion and conclusion

Building design is challenge for experts, who are working on the project. As the computer – based tools facilitate this process, the most widely used tools for energy simulation, optimization and LCA assessment have been presented.

The introduced framework of a model is intended to optimize the building envelope, without compromising on energy efficiency, comfort, cost, and environment. The combination of DesignBuilder, SimaPro, and the method of COPRAS was not mentioned in literature yet. The use of these tools and method does not require great experience, but facilitates the building design process.

In this case study a simple example was presented, but the optimization criteria showed only a part of all available from simulation results.

DesignBuilder and SimaPro can submit the simulation results, which are usually chosen as the optimization criteria: energy demand (heating, cooling, electricity), comfort parameters (PVM, PPD values, discomfort hours, daylight), life cycle assessment (CO_2 emission). SimaPro lets us not only model products and systems from life-cycle perspective, but also use such features as parameters and Monte Carlo analysis, or a variety of applications, like: carbon footprint calculation, environmental product declarations (EPD), environmental impact of products or services and etc.

Unfortunately, thus far the calculation results of DesignBuilder and SimaPro, can not be automatically processed, so the results should be manually extracted and placed into Excel. As well as the evaluation of investment and exploitation cost.

The biggest advantage of the method COPRAS is the ability to adapt all the criteria that have to be considered. On the other hand, the determination of significance criterion value may have some doubts, which may be solved spending more time analyzing them.

7. Further work

Our further work will focus on the early stage office building design: the optimization of the building envelope, internal comfort, integration of innovative technologies, reduction of CO_2 emission during operation and from life-cycle perspective. Here a challenge will be to implement BIM and new optimization techniques into the presented model.

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