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Method combining expert and analytical approaches towards economical energy renovation roadmaps and improved indoor comfort

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Abstract. This paper proposes a two-fold method, combining expert and analytical approaches, to develop an energy renovation roadmap for residential apartment buildings. The expert approach provides cost estimates based on energy performance certificates, considering the building's existing condition, national building tradition, and requirements. Renovation actions are limited to the most probable and required actions. The analytical approach uses computer power and various renovation action variations to identify optimal solutions for defined KPIs. As the cost efficiency of energy conservation action depends on model complexity, the expert approach considers this aspect. The analytical approach focuses on indoor comfort and energy use, as cost optimality evaluation is not possible for non-linear costs of energy conservation actions. Sensitivity analysis is used to support credible ranges for rentability of energy conservation measures and reflect on optimal solutions and indoor environmental consequences.

1. Introduction

Buildings and the building sector have the largest potential for cost-efficient emission reduction [1]. They account for 30% of final energy and global CO2 emissions, and 55% of total electricity consumption [2]. However, the annual renovation rates for deep and medium renovations are low, at 0.2% and 1.1%, respectively, despite estimates that 3% of the building stock should be renovated annually to reach environmental targets [3-4]. Renovation measures are often selected based on budget and building characteristics without considering the uncertainty of calculation and rating methods or their influence on indoor comfort [5], leading to challenges in increasing renovation rates. This paper proposes a simple, cost-effective method for evaluating renovation measures based on an indicator that links implementation cost, primary energy savings, and lifespan. This approach is preliminary to more detailed cost-optimal life cycle cost analysis that requires more assumptions [5, 6].

Model simplification choices, building performance simulation approaches, and considered retrofitting target values may also influence the credibility of the retrofitting scenarios adopted to compare different choices. Several studies demonstrated that different performance gap causes refer to the modelling phase [7], e.g. adopting steady-state models [8]. The optimisation among retrofitting scenarios generally refers to energy and cost targets, not considering additional building performance issues, such as indoor environmental KPIs, e.g. thermal comfort and indoor air quality [9], lacking in comprehensive sets of indicators. The possibility of hourly dynamic simulation tools and sensitivity analysis scenarios may help professionals study technological choices' statistical impact on different performance indicators [10] and eventually evaluate the simulation incertitude [11].

This paper presents a two-part approach to improve the credibility and optimization of building renovations. The expert approach evaluates the building's existing condition and considers possible space and market solutions to identify the most probable actions. It also considers model complexity, such as steady-state vs. dynamic and mono-zone vs. multi-zone, to address uncertainty related to modeling energy savings. The analytical approach uses sensitivity analysis to evaluate selected solutions, providing a deeper understanding of the indoor comfort consequences of renovation actions while disregarding market limitations.

2. Methodology

2.1 Expert approach

The expert approach used in this study follows the common practice of energy performance certificates (EPC) in most European certification schemes. It is based on the assessor's evaluation of the building's existing condition, national building tradition, and costs, limiting the renovation actions to the most probable and those that meet national requirements. In Denmark, the expert calculations start from the Danish EPC calculation engine Be18, with results focused on space heat demand savings and cost efficiency parameters (CEP) of energy conservation measures. This approach and results allow for a quick comparison of solutions' rentability, using costs extracted from the Danish national cost index database [12], including material and labor costs and additional expenses such as scaffolding and follow-up works. The study analyzes a limited number of energy conservation solutions related to envelop insulation and windows improvement, common measures found in EPC recommendations. The expert approach is energy and cost-oriented, and the building is modeled both as mono-zone and multi-zone using the dynamic tool EnergyPlus.

$$\text{CEP} = \frac{\text{Investment [€]}}{\text{Annual energy savings [kWh] * Lifetime of measure [years]}}$$

The CEP indicator, although not accounting for capital cost or energy price changes, is still effective for comparing actions and selecting the most cost-effective option. This simplification is largely acceptable and seldom results in incorrect decisions.

2.2 Analytical approach

The analytical approach uses a dynamic simulation platform, described in [13], that allows for massive sensitivity analysis on main design parameters. Analytical platform is linked to environmental variables like indoor comfort models, temperature levels, and energy. The platform uses EnergyPlus as the simulation engine and includes a personalised KPIs calculator module.

Table 1. Renovation actions

	Range [m] / For window: U-value/g-value/LT	Step [m]
Add external wall thermal insulation	[0.05-0.30]	0.05
Add roof thermal insulation	[0.05-0.25]	0.05
Add basement ceiling thermal insulation	[0.05-0,25]	0.05
Substitute window glazing:	0.79/0.46/0,66	#
	1.50/0.57/0.75	#
	2.71/0.70/0.78	#
	5.78/0.82/0.88	#

The platform is used to modify IDF contents and objects according to chosen actions and define variation ranges of selected values prioritizing retrofitting choices considering building energy and comfort indicators and supporting professionals. The analytical approach was tested on dynamic mono-zone and multi-zone models to study the impact of retrofit solutions on selected KPIs:

- Q_h: heating energy uses in kWh/m^2
- t_op: indoor operative temperature

Local weather data for Aalborg airport TMY was used for all simulations, while simulated retrofit actions and correlated parameter variations are presented in Table 1.

2.3 Case building presentation and modelling

A 3-story residential building in Aalborg, Denmark was constructed in 1964 and renovated in 2012. The building has 2398 m² heated floor area and is naturally ventilated. The external facades are made of cavity wall brickwork without cavity insulation. The building is connected to district heating. The thermal properties of the envelope elements before and after renovation are provided in Table 2. The basement and the unheated balcony and corridor are separated from the building zones. The building has an unconditioned basement. The insulation towards the unheated attic is initially insulated with 250 mm insulation and upgraded to 350 mm in the upgrading scenario. The external facades are made of cavity wall brickwork without cavity insulation. Building is naturally ventilated and is connected to district heating. That, in combination with a general reluctance of applying external facade insulation on brickwork, results in a decision to only evaluate cavity insulation as a possible measure for energy upgrading of the external walls. In addition, it is normally not considered economically feasible to apply external (or internal) insulation to a brick cavity wall with insulation in the cavity. This limitation is disregarded in the analytical approach. The general reluctance of applying external facade insulation on brickwork results in a decision to only evaluate cavity insulation as a possible measure for energy upgrading of the external walls. In addition, it is normally not considered economically feasible to apply external (or internal) insulation to a brick cavity wall with insulation in the cavity. This limitation is disregarded in the analytical approach. Only the apartments around one stairwell are being considered in all models, hence adiabatic faces are assumed on each side of the models.

2.4 Modeling: Steady-state monthly, dynamic mono-zone and multi-zone models

The renovation roadmap is calculated using the Danish EPC tool Be18 [14], which uses the EN ISO 13790:2008 standard to calculate heating and cooling demand. The entire building is modelled as a mono zone with the same indoor climate and solar gain distribution. The heat capacity of internal walls and floors is treated as a single node.

Figure 1. From left: a) Building from the outside, b) mono-zone model – one staircase as thermal zone, c) multi-zone model – each room as a thermal zone.

The dynamic mono-zone model treats all apartments as one zone, see Figure 1b, with the same indoor climate and even distribution of solar gains. The attic and basement are modelled as separate unheated rooms, and the heat capacity of internal walls and floors is treated as a single node.

The dynamic multi-zone model has every room as an individual zone, shown in Figure 1c. This allows internal heat capacity to be distributed to rooms where solar enters the building through windows, resulting in a more varied indoor climate than the mono-zone model. Heating needs may increase due to north-facing rooms requiring heating while south-facing rooms have surplus heat from the sun. The same energy-saving measures and costs are used as in the mono-zone model.

Table 2. The U values of the envelope before and after the expert energy upgrade suggestions. [1] The U-value for the roof includes the resistance of the attic and the roof covering.

	U value_ref (W/m²K)	U value_upg (W/m²K)
External wall	1.11	0.28
Roof[1]	0.37	0.12
Ground floor	0.30	
Basement wall	0.42	
Basement floor	0.43	0.22
Window	2.8	1.0

3. Results

In this section are presented selected results for expert and analytical approaches.

3.1 Expert renovation roadmap results

Models with higher detail levels show lower annual energy savings for glazing upgrading. CEP values for cavity wall and attic insulation are below the cost for district heating across all models, while dynamic models show higher CEP values than the stationary calculation for insulation towards the unheated basement due to the dynamic models' treatment of heat losses to the basement as a separate zone with its own temperature profile, see Figure 2.

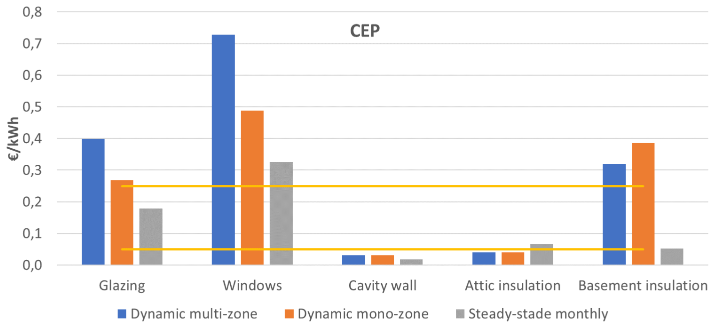

Figure 2. Cost efficiency parameter [€/kWh] for energy saving measures. Horizontal lines represent the price span for district heating in Denmark

3.2 Analytical approach results

The analytical approach is aided by graphics to help users grasp the effects of retrofit solutions on KPIs. Figure 3 reveals how insulation thickness in walls, ceilings, and basements can reduce heating energy use. External wall and roof insulations are particularly impactful, while mono-zone models may slightly underestimate space heating needs compared to multi-zone models. Figures 3a/b and 4a/b indicate that higher envelope insulation reduces winter energy needs but raises summer overheating hours requiring countermeasures, as evident from the distribution of operative temperatures relative to outdoor running mean. The platform could also explore shading systems or ventilative cooling technologies to determine whether natural means can mitigate overheating risks, balancing heating need minimization and ensuring comfort in hot weather.

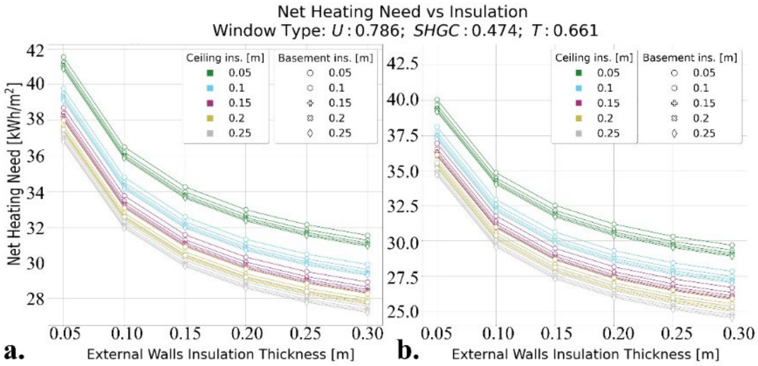

Figure 3. Heating energy needs versus insulation with triple glazing a) multi-zone model b) mono-zone model.

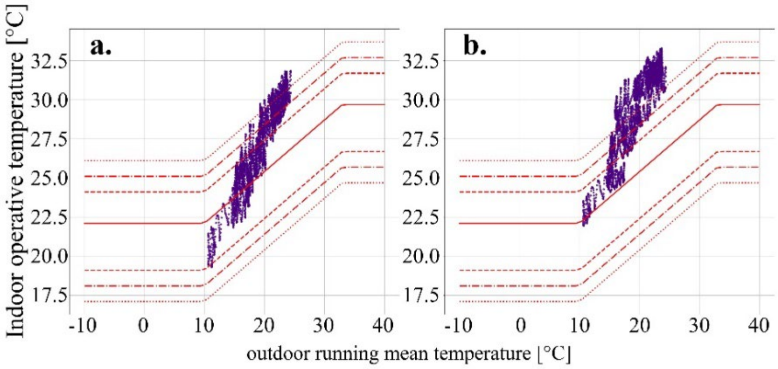

Figure 4. Adaptive comfort model points distribution considering outdoor running mean temperature in categories for multi-zone model in a) the least insulated case and (b) the most insulated case.

4. Conclusion

The expert approach for renovation roadmaps involves an expert inspecting the building and selecting measures based on available space, costs, supplemental works, building tradition, and regulations. This approach requires a limited number of calculations, which is beneficial for cost calculations that are not linear and cannot be directly applied to an analytical approach. However, the expert approach's limited calculations and focus on CEP may not ensure a holistic solution and could lead to poor indoor comfort. The analytical approach, on the other hand, can efficiently run multiple simulations of a building model and produce heatmaps to identify the statistical impact of each choice on selected KPIs. The two approaches can complement each other, with the analytical approach identifying a range of optimal solutions and the expert approach selecting the most cost-effective and compliant solution based on national building tradition and regulations. Regarding the expert approach and the calculation of energy savings for three different model detail levels (monthly single zone, mono-zone dynamic, and multi-zone dynamic), the following observations can be made:

- Cavity and attic insulation reflect similar CEP disregarding modelling approach, these interventions are cost efficient measures even for cheapest district heating in Denmark.
- Replacement of glazing and windows gives highest CEP for most detailed models and decreases towards steady-state and most simple models. The differences in CEP results are quite significant and heavily depend on modelling approach. In general replacement of only glazing gives better CEP than for whole windows.
- Additional insulation towards unheated zones (basement or attic) shows inconsistent results.

The analytical approach reveals that increasing insulation can result in a higher risk of overheating in summer, which requires verifying thermal comfort conditions and considering countermeasures. By using a wide range of input variations, the designer can conduct a sensitivity analysis to understand the impact of retrofitting choices on various KPIs, increasing their awareness of their choices.

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