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Original research article

Predictive Modelling of Building Airtightness for Life Cycle-Based Assessment of Energy Performance

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ABSTRACT

This paper presents a data-driven approach for assessing building airtightness and infiltration-related energy effects using a predictive mathematical model based on artificial neural networks and preliminary evaluation against blower door measurements. The model enables preliminary estimation of airtightness parameters (e.g., n50) during early design stages, supporting building performance assessment without relying exclusively on costly on-site testing. The research further conceptually integrates predicted infiltration-related energy effects into Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) frameworks, supporting sustainable decision-making. Results indicate that predictive approaches may support energy performance evaluation and contribute to improved building envelope design in early design stages.

Key words: *airtightness, blower door, Life Cycle Assessment, energy performance*

1. INTRODUCTION

Rising energy prices and global climate change are the main reasons for reconsidering energy consumption habits. Research worldwide consistently shows that buildings are a major driver of energy use and a significant source of global environmental pollution [1, 2]. A similar trend is observed in Croatia, where the 2024 Energy in Croatia report shows that buildings account for 42% of total national energy use [3]. Considering the long lifespan of buildings, it is important to acknowledge their lasting environmental impact [4]. Studies have shown that improving the energy efficiency of buildings is one of the most effective ways to reduce harmful emissions and energy costs [5]. Proper energy management and the adoption of energy-saving measures reduce greenhouse gas emissions, lower costs, and help protect the environment [2]. Therefore, airtightness is an important factor in both energy consumption and savings [6]. It is quantified in various ways, which are generally grouped under the common term “air leakage.” The resistance of the building envelope to air leakage is referred to as airtightness [7]. This property is important from multiple perspectives, most of which relate to the fact that airtightness is a fundamental building characteristic influencing infiltration [8]. To determine the level of air leakage, the building envelope must undergo pressurization testing [9]. Such testing is costly, especially for large buildings, and for new buildings it cannot be carried out until the later stages of the construction process [10]. These limitations have led to research aimed at developing suitable computational models to support preliminary airtightness assessment during the design phase [10]. Such models enable more affordable assessments of air leakage in existing buildings and allow for preliminary estimation of airtightness-related performance in new buildings during the design phase, before construction begins.

There are two main types of models used to predict air leakage: mathematical and statistical [11, 12]. In general, larger datasets lead to more reliable models [13]. However, mathematical models require extensive building data, making statistical models more practical [10].

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This study presents a mathematical model developed by Krstić et al. [14] which uses neural networks and a database based on 58 residential units from Osijek-Baranya county area to predict building envelope characteristics and airtightness. The ANN model and correction factors applied in this study were originally developed and calibrated in previous research involving 58 residential units [14].

The present study does not aim to develop a new ANN model, but rather to demonstrate its preliminary application and conceptual integration within a lifecycle-based assessment framework through evaluation on six measured cases. It relies on key input parameters describing the characteristics of the building envelope, its composition, and exposure conditions. These parameters are available early in the design phase and should be considered when evaluating energy efficiency and lifecycle costs [15-18] and they are also important for upgrading existing buildings to improve performance and estimate cost savings over their lifespan.

This study conceptually links predicted infiltration-related energy effects with Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) frameworks, enabling a more comprehensive evaluation of environmental and economic impacts. This integration supports sustainable decision-making by establishing a relationship between airtightness performance and long-term energy consumption, associated emissions, and operational costs. The proposed framework suggests that predictive models can support early-stage building performance evaluation and contribute to improved building envelope design. In addition, the approach may support future renovation strategies aimed at improving energy performance and thermal comfort. By identifying the influence of envelope airtightness on energy-related performance indicators, the framework provides a basis for prioritizing retrofit measures and improving the overall sustainability of the building stock.

Although numerous studies have addressed airtightness prediction and building energy performance, there is still a lack of approaches that explicitly integrate early-stage airtightness estimation into life cycle-based decision-making. In particular, the potential of predictive models to support life cycle cost (LCC) and environmental impact (LCA) assessments remains underexplored. Since airtightness significantly influences infiltration heat losses and, consequently, operational energy demand over the building lifespan, its preliminary estimation during the design phase represents an important step toward more informed decision-making. This study therefore aims not only to evaluate the applicability of neural networks for predicting airtightness, but also to demonstrate their relevance as a supporting tool in life cycle-based assessment of building energy performance. The framework is intentionally conceptual and serves as a methodological basis for future quantitative implementation.

2. METHODOLOGY

2.1 Experimental data collection

Air leakage measurements presented in this research were conducted on six individual cases located in the Osijek-Baranja County area, including three residential units and three classrooms within one public building (an elementary school). A "blower door" device [19] was used to measure air leakage in accordance with the HRN EN ISO 9972:2015 [20].

All conditions required by the standard for conducting the test were fulfilled. The testing procedure was carried out in accordance with the manufacturer's instructions and the prescribed methodology. Upon completion of the testing, the measurement results were obtained in the form of a "blower door" test report, which includes the following values:

- v50 – airflow rate at 50 Pa (m^3/h),
- n50 – air change rate per hour (1/h),
- w50 – airflow rate at 50 Pa per unit floor area ($m^3/(h \cdot m^2)$),
- q50 – airflow rate at 50 Pa per unit envelope area ($m^3/(h \cdot m^2)$),
- equivalent leakage area (EqLA),
- effective leakage area (ELA),
- air flow coefficient (Cenv),
- air leakage coefficient (CL),
- flow exponent (n),
- correlation coefficient.

The measured values for the six analysed buildings are presented in Table 1. The six analysed cases were used exclusively for preliminary evaluation of the previously developed ANN model and for demonstrating its integration within the proposed conceptual framework. The present study does not aim to establish a statistically representative validation dataset.

2.2 Dataset and input parameters

To evaluate the applicability of neural networks for preliminary estimation of the airtightness of residential buildings measured using the blower door method, a set of input parameters was defined based on variables identified in previous research [14] as having a significant influence on air leakage. The input data used for the previously developed neural network model were grouped into four categories: (1) quality of opaque envelope elements, (2) quality of transparent envelope elements, (3) proportion of transparent elements relative to the total envelope area, and (4) degree of envelope exposure to external air.

The first two parameters incorporate material and construction characteristics through empirically derived correction factors previously established in [14]. The opaque envelope parameter accounts for wall and floor/ceiling properties (e.g., thickness, material, and thermal insulation), weighted by their share in the total envelope area, while the transparent envelope parameter is obtained as the product of correction factors related to window quality, maintenance, frame material, and glazing type. The remaining two parameters are determined from the geometric and layout characteristics of the buildings. All correction factors were previously established based on empirical data and prior studies presented in [14], while the necessary input data required for the present study were collected through on-site surveys conducted during the testing process. The four parameters presented in Table 2 therefore represent simplified normalized input variables used by the previously developed ANN model for preliminary airtightness estimation.

Table 1 – *Results of "Blower Door" Tests for the six analysed buildings*

Building no.	V_{50} (m^3/h)	n_{50} (1/h)	w_{50} (m^3/(h·m^2))	q_{50} (m^3/(h·m^2))	EqLA (cm^2)	ELA (cm^2)	Cenv	CL	C	n
1	1205	8.43	21.91	6.06	521.3	293.1	119.2	120.4	0.99925	0.589
2	641	5.34	13.94	11.66	283.5	161.4	66.9	67.6	0.99946	0.575
3	356	7.11	15.46	5.23	144.6	78.5	30.8	30.6	0.99870	0.627
4	1112	6.86	19.85	5.50	446.5	240.7	92.7	92.7	0.99753	0.635
5	1782	10.61	31.83	8.82	731.4	399.2	156.8	156.6	0.98795	0.622
6	1513	9.34	27.01	7.49	650.6	364.6	149.2	149.0	0.99845	0.593

2.3 Preliminary prediction of building airtightness and infiltration-related energy demand

A predictive model based on artificial neural networks (ANN) was previously developed in [14] and applied to estimate building airtightness (n_{50}) using the input parameters described in the previous section. The model enables preliminary estimation of airtightness based on early-stage design information, reducing reliance on physical testing. The predicted airtightness is subsequently used to derive air infiltration rates, which represent an important mechanism of heat transfer through the building envelope. These infiltration rates are conceptually associated with ventilation-related heat losses and gains, which may influence the overall energy performance of buildings. This step conceptually establishes the link between geometric envelope characteristics and energy-related performance indicators, forming the basis for further lifecycle-based assessment.

2.4 Conceptual integration with Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) frameworks

The overall conceptual methodological framework used in this study is presented in Fig- 1. It illustrates the proposed conceptual framework for linking building envelope characteristics with environmental and economic performance indicators. Input parameters describing the envelope configuration, including opaque envelope elements, transparent elements, their proportion in the total envelope area, and the degree of envelope exposure, may be processed by means of a predictive model based on artificial neural networks to estimate the airtightness indicator (n_{50}).

The predicted airtightness may subsequently be translated into indicative air infiltration rates, which represent a key component of ventilation-related heat losses and gains. These infiltration-related effects are conceptually linked to variations in operational energy demand for space heating and cooling, thereby conceptually establishing a relationship between envelope performance and building energy behaviour. The estimated energy demand may then be considered a potential input for Life Cycle Assessment (LCA), enabling the conceptual evaluation of operational environmental impacts, such as greenhouse gas emissions, and for Life Cycle Costing (LCC), supporting the conceptual assessment of long-term economic performance through energy-related costs.

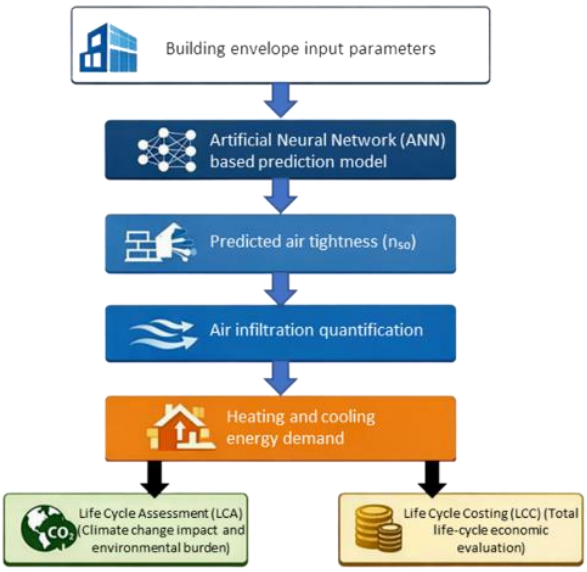

Fig. 1 *Conceptual framework linking predicted airtightness with LCA and LCC analysis*

Although no explicit numerical calculations are performed in this study, the proposed framework conceptually outlines a clear methodological pathway for incorporating airtightness-related effects into lifecycle-based assessment tools. By integrating predictive modelling with LCA and LCC frameworks at a conceptual level, the proposed approach facilitates informed decision-making in early design stages, while reducing reliance on post-construction measurements. In this way, it supports more informed consideration of building envelope design with respect to both environmental and economic performance objectives. The proposed framework should therefore be interpreted as a preliminary conceptual approach intended to support future quantitative implementation and validation.

3. PRELIMINARY APPLICATION OF THE PREDICTIVE MODEL

3.1 Predicted values

Based on the four input parameters entered into Microsoft Excel - quality of opaque envelope elements, quality of transparent envelope elements, proportion of transparent elements, and degree of envelope exposure, the air leakage of individual buildings was preliminarily estimated. The previously developed neural network model was implemented using the NeuroShell2 software, which provided preliminary predicted air leakage values. The results, where AC n50 represents the measured air leakage and PC n50 the preliminary predicted air leakage, are presented in Table 2.

3.2 Comparison of measured and preliminarily predicted values

The results obtained using the blower door method were compared with the preliminary results obtained from the previously developed neural network model. Table 3 shows that deviations between measured and preliminarily predicted values remain within an acceptable range for preliminary assessment purposes.

The mean absolute error (MAE) between measured and predicted n50 values was 1.04 h^{-1}, while the mean absolute percentage error (MAPE) was 12.98%. These results indicate that the model “may provide acceptable preliminary estimates for early-stage design applications where simplified input data are used, particularly considering the limited number of analysed cases and the preliminary nature of the evaluation.

Table 2 – *Preliminary predicted air leakage values obtained using the previously developed mathematical model*

Building no.	Parameter 1	Parameter 2	Parameter 3	Parameter 4	AC n_{50}	PC n_{50}
1	0.6408	0.0576	0.0465	0.1473	8.43	9.6522
2	0.9023	0.3840	0.0389	0.1836	5.34	4.4507
3	0.6584	0.0864	0.0136	0.4332	7.11	7.1702
4	0.7324	0.2304	0.1050	0.2257	6.86	7.8968
5	0.7324	0.3072	0.1050	0.2257	10.61	9.0762
6	0.7332	0.2304	0.1336	0.1336	9.34	7.8186

Table 3 – *Comparison of measured and preliminarily predicted air leakage values obtained using the mathematical model*

Building no.	Measured value n_{50} AC	Predicted value n_{50} PC	Absolute error	Percentage error [%]
1	8.43	9.65	1.22	14.50
2	5.34	4.45	0.89	16.65
3	7.11	7.17	0.06	0.85
4	6.86	7.89	1.04	15.11
5	10.61	9.08	1.53	14.46
6	9.34	7.82	1.52	16.29
Mean	-	-	1.04	12.98

4. IMPLICATIONS FOR LIFE CYCLE-BASED ASSESSMENT

Airtightness is a key parameter influencing the energy performance of buildings through its direct impact on air infiltration and associated heat losses. Higher air leakage rates result in increased heating and cooling demand, which significantly affects operational energy consumption over the building’s lifespan [6, 16, 17]. Consequently, even relatively small deviations in airtightness levels can lead to considerable differences in cumulative energy use, greenhouse gas emissions, and life cycle costs [15, 18].

The results presented in this study indicate that the previously developed neural network model may provide preliminary estimates of airtightness values that are reasonably consistent when compared to measured data obtained using the blower door method. The deviations between measured (AC n50) and predicted (PC n50) values are relatively small and do not indicate a clear systematic bias, suggesting potential applicability of the model for early-stage assessments.

The practical significance of this lies in the possibility of integrating airtightness prediction into the design phase, where key decisions regarding building envelope configuration are made. Unlike experimental measurements, which are typically conducted after construction or in its final stages, predictive models enable designers to evaluate different design alternatives before implementation [10, 12]. This allows airtightness to be considered as a relevant parameter within multi-criteria building performance assessment frameworks [15]. From a life cycle perspective, improved airtightness may contribute to reduced operational energy demand, which is often a significant share of total life cycle energy use in buildings [4, 15].

In addition, lower energy consumption results in reduced CO_2 emissions and operational costs over time [2, 18]. When combined with LCC and LCA methodologies, predictive airtightness models can therefore support more comprehensive assessments of building performance [15, 18]. Furthermore, the use of such models is particularly relevant in the context of large-scale building stock renovation, where direct measurement of airtightness for each building is often impractical due to cost and time constraints [10].

Predictive approaches may provide a cost-effective supplementary tool, enabling the prioritization of interventions and estimation of potential energy savings at the portfolio level. Overall, preliminary prediction of airtightness during the early design phase represents a valuable tool for enhancing the integration of energy performance considerations into life cycle-based assessment approaches and supports the development of more sustainable and energy-efficient buildings. Therefore, the presented results should be interpreted primarily as an initial proof of concept.

5. DISCUSSION

The proposed study introduces a conceptual framework that links building envelope characteristics with airtightness estimation and subsequent environmental and economic performance assessment through Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Although no numerical simulations were performed, the proposed methodology conceptually outlines a pathway for integrating predictive modelling into lifecycle-based decision-making processes.

The results highlight the potential applicability of artificial neural network (ANN) models to estimate building airtightness (n_{50}) based on early-stage design parameters. This is particularly relevant because airtightness is traditionally evaluated through on-site measurements conducted at advanced construction stages, when design modifications are limited or economically impractical. By shifting the preliminary airtightness assessment to the design phase, the proposed approach may support earlier identification of envelope-related performance issues and contribute to more informed design decisions.

A key contribution of this work lies in establishing the link between predicted airtightness and infiltration-related energy effects. Air infiltration is a critical yet often simplified component in building energy analysis, despite its significant influence on heating and cooling demand. By explicitly positioning airtightness as an intermediate variable between envelope configuration and energy performance, the framework contributes to the conceptual understanding of how design parameters may influence energy and lifecycle impacts. Furthermore, the integration with LCA and LCC frameworks extends the applicability of the proposed model beyond energy prediction. Although the study does not include quantitative environmental or economic calculations, the conceptual mapping demonstrates how airtightness-related energy variations can be systematically incorporated into sustainability assessment tools. In practice, this may support interpretation of how design decisions influence long-term implications in terms of greenhouse gas emissions and operational costs.

The findings also support the broader transition towards data-driven and predictive approaches in building performance assessment. In comparison with traditional deterministic or measurement-based methods, the proposed framework may offer greater flexibility in early design stages, where limited information is available but decisions have long-term consequences. This is particularly important in the context of nearly zero-energy buildings (nZEB), where envelope performance plays an important role in achieving regulatory and sustainability targets. However, several limitations should be acknowledged. The framework is currently conceptual and has not been validated through full-scale LCA or LCC numerical implementation.

In addition, the predictive model is based on a relatively limited dataset, which may affect its generalizability to different building typologies and climatic conditions. Future research should therefore focus on expanding the dataset, validating the ANN model on broader building samples, and implementing the proposed framework in fully quantitative LCA and LCC analyses. Despite these limitations, the study provides a preliminary methodological foundation for integrating machine learning-based predictions with lifecycle assessment tools. The proposed approach may contribute to the development of more comprehensive decision-support systems that consider not only energy performance but also environmental and economic impacts throughout the building life cycle.

6. CONCLUSION

This study presented a conceptual framework for integrating preliminarily estimated building airtightness into Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analyses through a predictive modelling approach based on artificial neural networks. The framework links building envelope characteristics to airtightness (n_{50}), air infiltration, and subsequently to operational energy demand for space heating and cooling, thereby conceptually establishing a methodological pathway from design parameters to lifecycle performance indicators.

The main contribution of the study lies in demonstrating how airtightness, as a key but often indirectly treated envelope property, may be considered within early-stage building performance evaluation. By using a predictive model, reliance on time-consuming and costly in-situ measurements may be reduced during initial design phases, while still supporting a structured assessment of its potential implications on energy performance. Although no numerical LCA or LCC calculations were performed, the proposed framework provides a transparent conceptual basis for linking building physics with environmental and economic assessment tools.

This may support a more holistic understanding of how envelope design decisions influence long-term greenhouse gas emissions and operational costs. The study also highlights the potential applicability of combining data-driven predictive methods with lifecycle-based evaluation frameworks to support more informed decision-making in sustainable building design. This is particularly relevant in the context of nearly zero-energy buildings (nZEB), where envelope performance plays a an important role in achieving regulatory and sustainability targets. Future research should focus on extending the proposed framework through full quantitative implementation, including validation on larger and more diverse datasets, as well as coupling the predictive model with detailed LCA and LCC calculations. This could enable a more precise quantification of environmental and economic impacts and further support evaluation of the approach in real-world design and decision-making processes.

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