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Energy modeling and predictive control of environmental quality for building energy management using machine learning

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Highlights

- Energy consumption of HVAC systems contribute significantly towards overall energy usage of a building and carbon footprint.

- A predictive model for HVAC temperature forecasting using Machine Learning (ML) algorithms is presented.
- A comparison of Transformer Neural Networks and CNN-LSTM on multiple forecasting horizons has been performed.
- The transformer model yielded energy savings and reduced energy consumption by up to 50%.
- Optimization of energy efficiency while ensuring thermal comfort in building energy management systems was achieved.

Abstract

Heating, Ventilation, and Air Conditioning (HVAC) systems play a vital role in building energy management by controlling the indoor temperature and ensuring the occupant's comfort. However, the energy consumption of HVACs contributes significantly towards overall energy usage of a building and carbon footprint. To address this challenge, this research proposes the development of a predictive model for HVAC temperature forecasting using Machine Learning (ML) algorithms to optimize energy efficiency while maintaining thermal comfort in buildings. The study focuses on comparing the performance of Transformer Neural Networks and CNN-LSTM, a seq2seq model combining Convolutional Neural Networks (CNN) and Long-Short Term Memory (LSTM) on multiple forecasting horizons using data obtained from multiple devices deployed in a room verified by feedback survey forms filled by occupants. The transformer model outperformed, achieving an R^2 score of 0.936 at a 1-minute forecasting horizon, surpassing the performance of CNN-LSTM model at all tested forecasting horizons. The transformer model yielded significant energy savings thereby reducing energy consumption by almost 50% compared to the non-AI conventional methods, particularly at forecasting horizons of 1 min and 60 min, while the occupant survey also favoured a 60-minute forecasting horizon. The performance of transformer model particularly with a 60-minute forecasting horizon underscores its potential to optimize energy efficiency while ensuring thermal comfort in building energy management systems.

Introduction

HVAC (heating, ventilation, and air conditioning) systems utilise considerable amount of energy globally while being the major contributor of greenhouse gases. As reported by Longo et al. (Longo et al., 2021), 38% of all energy consumption is used by HVAC systems, including 32% from residential sources and 47% from tertiary industries. The use of HVAC systems has become even more widespread to combat the rising temperatures as the global mean surface temperature has risen by 1.1 °C since the industrial revolution (Romanello et al., 2022). In addition to man-made climate change, HVAC systems are releasing dangerous particulate matter and other pollutants into the air. HVAC systems emit greenhouse gases like carbon dioxide and toxic refrigerants that deplete the ozone layer, wreaking havoc on the ecosystem. As, people spend 90% of their time indoors and like to breathe clean air and a have suitable indoor temperature, it is essential to develop precise forecasting models for widely utilized HVAC systems, and carefully assess outcomes to use energy wisely (Indoor air pollution: An introduction for health professionals | US EPA." https://www.epa.gov/indoor-air-quality-iaq/indoor-air-pollution-introduction-health-professionals (accessed Dec. 24, 2002, n.d.) Accurately estimating indoor temperature is crucial in ensuring people's comfort while simultaneously improving the efficiency and reducing the energy consumption of HVAC systems (Jiang et al., 2022-a).

Currently Physical knowledge-based, data-driven, and hybrid models are the three types of models used most frequently to predict energy consumption and temperature (Dong et al., 2016; Foucquier et al., 2013). White-box models, also known as the physical knowledge-based models are employed in the development of prediction models using mathematical representations of the principles of physics (Enescu, 2017). The primary drawback to this approach is that it demands extensive knowledge with the building or area that one is attempting to model. Moreover, the equations in the model typically contain assumptions that may not always correspond to actual behaviour (Amara et al., 2015). Gray-box models are hybrid models that narrow the gap between White-box models and actual building conditions. This model uses white-box techniques with actual data instead of assumptions. Gray-box models' drawbacks include the need for substantial prior information and mathematical presumptions in order to obtain accuracy (Homod, 2013). Machine Learning (ML) and other data-driven black-box techniques have demonstrated superior performance over other methods. Black-box modeling based on data can simulate thermal dynamics without the requirement to explicitly identify zone-specific characteristics like heat capacity and size (Elmaz et al., 2021).

Various machine learning techniques have also been used for indoor temperature forecasting including support vector machines (SVM) (Chen & Tan, 2017; Vrablecová et al., 2018), Random forests (Moon et al., 2018), and Extreme Gradient Boosting (XGBoost) (Seo et al., 2022; Wang et al., 2020), and Artificial Neural Networks (ANNs) (Kamel et al., 2020). An Artificial Neural Network is a nonlinear statistical technique that has three basic parts: an input layer, a hidden layer, and an output layer. Nevertheless, these models lack adequate techniques for processing time series data and fail to take into consideration the temporal connections between the input and output data. These issues are frequently addressed using time correlation and the Recurrent Neural Network (RNN) (Rahman et al., 2018). LSTM (Long Short-Term Memory), an improved version of RNN algorithm is also being extensively utilized for time-series forecasting as it resolves the exploding or vanishing gradients problem of the former. Xu, et al. (Xu et al., 2019) used LSTM for the prediction of the indoor temperature with forecast horizon of 5 min. It was compared to Support Vector Machines (SVM) and Back Propagation Neural Networks (BPNN). The results indicated that the

LSTM outperformed the other models, with an R-squared of 0.79. In another study conducted by Mtibaa et al. (Mtibaa et al., 2020) the MAPE (Mean Absolute Percentage Error) and MAE (Mean Absolute Error) scores are highest for the NNARX (Neural Network-based Autoregressive Model with Exogenous Inputs) for 6-h prediction model but took time due to slower execution. In contrast, LSTM completed a 4-hour prediction in <15 s, whereas NNARX takes >5 min while the results were same for both models. Additionally, it was also observed that while NNARX's standard deviation of error is slightly larger than LSTM's, it is still lower than NNARX's at 0.45 °C. Moreover, in a study conducted by Fang et al. (Fang et al., 2021) a seq2seq LSTM model that includes LSTM-Dense, LSTM-LSTM and LSTM-Dense-LSTM to predict the indoor temperature of various building zones was presented. The primary idea of this research was that an encoder takes critical elements from the input sequence and passes them to the decoder, which uses them for forecasting. Out of these three architectures, LSTM-Dense out-performed with RMSE of 0.458. Another seq2seq model used convolutional neural networks (CNN) to do feature extraction on the input data and then an LSTM to predict the interior temperature fluctuation for the following 120 min with a high R-squared value of above 0.9 (Elmaz et al., 2021). Attention-LSTM, another seq2seq model was used by Jiang et al. (Jiang et al., 2022-b) to predict the indoor temperature. It was found out that the attention-LSTM performed better than the GRU (Gated Recurrent Units) and LSTM when horizon was 30 min or greater. However, one of the disadvantages of LSTM-based models includes the challenge of training on long sequences since LSTM networks have trouble capturing long-term dependencies in data, especially if the sequences are quite long. Additionally, because LSTM networks do not involve parallel processing, they may take longer to train as they process input sequences one timestep at a time. When compared to RNN-based techniques lower prediction errors are achieved by using transformer-based approaches since they are more capable of recognizing long-term latent patterns in all the past data (Liu, n.d.). This is because transformers may consider all timesteps at once because they process input sequences using self-attention processes rather than repetition. This makes transformers particularly well-suited for tasks that involve long sequences.

The focus of this study is to explore the effectiveness of transformers in forecasting energy usage data obtained from multiple devices and surveys. The Transformer model for time-series modeling in indoor temperature forecasting has rarely been explored in the literature specifically for HVAC temperature forecasting. Four different forecasting horizons i.e. 1, 15, 30 and 60 min were considered, and the models were trained using the collected data. A specially designed infrared sensor was utilized to track the HVAC system in real-time in order to assess the models' forecasts' accuracy. The energy usage data was collected, and the results were compared at different forecasting horizons. In addition, surveys were conducted to gather information about the occupant's thermal comfort inside the room. The primary significance of this work is in improving power optimization and enhancing occupant comfort, which can be achieved by utilizing the trained model to optimize HVAC systems in similar setups with sensors and data recording devices, thus indicating wider applicability of the study's results. The findings of this study can shed light on the viability of using transformers in energy forecasting and their prospective use in the creation of energy-efficient buildings.

Section snippets

Data Acquisition

Fig. 1 shows framework of the proposed methodology illustrating the data acquisition process into cloud storage that is utilized by a deep learning model for generating temperature predictions to control HVAC. The dataset comprises information obtained from an air quality analyser, power quality analyser, and surveys. The data was collected with sampling rate set at 1 min. The data collected was divided into 5 classes i.e., anthropometric measurements, air quality, power quality, indoor …

Subjects

The study aimed to assess thermal comfort levels in relation to the temperature forecasting of HVAC. This research is carried on 4–6 occupants who participated in experiments conducted in a room to evaluate the thermal comfort within an indoor environment. Participants chosen for the study fell within the age range of 24 to 30 years and had a weight varying between 55 and 80 kg. Prior to the commencement of the study, consent was obtained from each participant. Whereas, confidentially of data …

Results and discussions

The present study evaluates the effectiveness of a deep learning model in predicting HVAC setting to optimize energy efficiency while maintaining thermal comfort in buildings by utilizing dataset obtained from sensors. The machine learning algorithms were trained for this purpose using various time step predictions on the collected dataset for assessing the accuracy of the model's predictions. The energy consumption data collected from the resulting prediction outcomes were compared with the …

Conclusion

This study implements a predictive model based on machine learning to forecast HVAC temperature while optimizing energy consumption and thermal comfort. To achieve our objective, transformers and CNN-LSTM were trained at forecasting horizons of 1, 15, 30 and 60min on a comprehensive dataset that included air quality, power quality, and thermal comfort parameters gathered through multiple devices and surveys. The models' performance was evaluated using standard evaluation metrics, including …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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