ENERGY CONSUMPTION AND RESOURCE ALLOCATION MADE MORE EFFICIENT THROUGH ARTIFICIAL INTELLIGENCE: AI-DRIVEN DESIGN OPTIMIZATION FOR HVAC (HEATING, VENTILATION, AND AIR CONDITIONING) SYSTEM

MARIA-ISABELA GHICAJANU (CAȘOTĂ)[1], DAN CODRUȚ PETRILEAN[2]

Abstract: In contemporary industrial and commercial settings, Heating, Ventilation, and Air Conditioning (HVAC) systems are critical for maintaining optimal indoor environments. However, the efficient operation of these systems is often challenged by varying external and internal conditions, leading to suboptimal energy consumption and increased operational costs.

This paper explores the integration of Artificial Intelligence (AI) to enhance the performance and efficiency of HVAC systems. Using Brain.js, a JavaScript-based neural network library, we train a model using multiple input parameters, including indoor temperature, outdoor temperature, humidity, airflow rate, operating hours, and occupancy levels, to predict optimal setpoints and energy consumption.

To facilitate practical application and user interaction, I developed a Vue.js-based web interface. This interface allows users to input real-time environmental and operational data, which is then processed by the trained neural network to provide actionable predictions for optimizing HVAC performance.

Future work will focus on enhancing the model's accuracy by incorporating additional data sources, such as weather forecasts, real-time energy prices, and more occupancy data. I also plan to implement adaptive learning algorithms to allow the system to continuously improve its predictions based on new data.

Furthermore, expanding the system's capabilities to include predictive maintenance alerts and integrating with IoT sensors for more precise data collection may be key areas of development. By pursuing these improvements, I aim to create a more robust, intelligent, and comprehensive solution for HVAC system optimization, ultimately contributing to smarter and more sustainable building management practices.

Key words: Artificial Intelligence, HVAC, predictive, improvement, intelligence, system optimization, programming, data modelling, energy saving.

[1] *Ph.D., Student Eng., ghicajanumaria@gmail.com*
[2] *Ph.D., Eng.*

1. INTRODUCTION

The findings indicate that AI-driven optimization can significantly enhance the efficiency of HVAC systems, leading to substantial energy savings and improved environmental sustainability. The user-friendly interface ensures ease of use, enabling facility managers and operators to make informed decisions in real time [8], [10], [12], [15], [18].

It is obvious that carbon neutrality has become the most important issue and challenge of this century for humanity to respond to climate change.

However, the global target for greenhouse gas emissions commitments would need to be six times higher to keep the global temperature rise below 2°C above pre-industrial levels and seven times higher to limit warming to 1.5°C. This points to failure to respond to extreme weather and climate change as the greatest risk to humanity [1], [3], [14], [16], [22].

Insufficient global participation and carbon price signals are currently the most pressing challenges in the global response to climate change.

Thus, broadening participation and strengthening carbon price signals are crucial tasks for addressing climate change.

2. ABOUT HVAC

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Heating, Ventilation, and Air Conditioning (HVAC) systems are essential for keeping us comfortable and healthy every day. With the latest advancements in technology, especially Artificial Intelligence (AI), the HVAC industry is seeing a major transformation. AI algorithms and machine learning are making HVAC systems smarter and more efficient, helping to optimize energy use [9], [11], [13], 17], [20].

Buildings are complicated and ever-changing environments where the thermal flow shifts due to varying occupancy and weather conditions. To optimize an HVAC system's performance, it's important to understand energy flow and predict its changes. The huge amount of data and complex equations needed to ensure optimal HVAC performance can be overwhelming for traditional energy management systems.

Did you know that HVAC systems are responsible for 40% of a building's energy use, with about 30% of that energy usually going to waste?

AI helps improve HVAC systems primarily through smart data analysis. These AI algorithms can sort and analyze tons of data to spot patterns, including temperature, humidity, occupancy, and weather conditions. Since energy costs fluctuate throughout the day, this is another factor considered. The data processing can happen on-site, in cloud data centers, near the system sensors, or using a mix of these methods [2], [5], [19], [21].

The following diagram shows the simplified setup of a typical HVAC system.

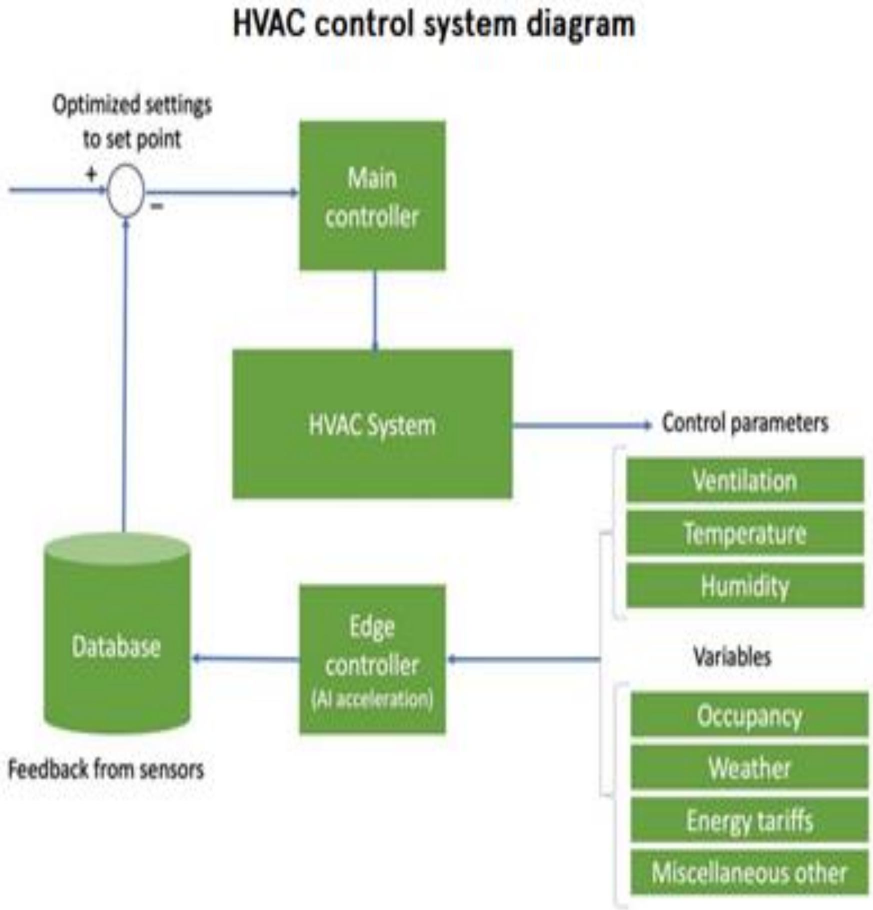

Fig.1. HVAC system

3. REAL-WORLD OUTCOMES OF AI IN HVAC IMPLEMENTATIONS

Although using AI in HVAC systems is still relatively new, there are already some real-world success stories.

For example, in 2020, Yokogawa used AI to cut energy use at its semiconductor sensor manufacturing plant in Miyada-mura, Japan. According to the International Society of Automation, the AI model used a reinforcement learning algorithm to run the HVAC system in the company's clean room fabrication environment.

The goal was to keep the environment tightly controlled while using as little energy as possible. Clean rooms at the facility used liquefied petroleum gas and accounted for 30% of the plant's total energy consumption. Yokogawa's AI system worked alongside the existing HVAC setup and conventional controls, requiring minimal capital investment. After several months of self-driven model refinement, energy consumption dropped by 3.6%.

In another case, BrainBox AI, an HVAC company in Montreal, Canada, showcased its AI technology in a 509,612-square-foot shopping center. They converted the traditional HVAC system into an autonomous one using custom algorithms running in the cloud [4], [6], [7].

These algorithms combined building data collected over several weeks with external weather and energy-tariff data to optimize the system's operation. After a year, electricity savings reached 21% (205,214 kWh), with the AI ensuring the required building-zone temperatures were maintained while significantly reducing the HVAC equipment's runtimes.

4. HOW AI IS REVOLUTIONIZING HVAC SYSTEMS

Current HVAC systems are part of the problem. “Inefficient HVAC systems consume excessive energy, often derived from fossil fuels, to heat, cool, and ventilate assets, contributing to 4% of greenhouse gas emissions globally,” says Mateusz Lukasiewicz, digital projects manager at KEO International Consultants. This firm specializes in planning, architecture, engineering, sustainability, project and construction management, and digital advisory services. “The increased resource usage results in higher emissions of carbon dioxide, methane, chlorofluorocarbons, and other greenhouse gases, intensifying climate change and environmental degradation,” he explains.

As building managers look to improve HVAC performance with new technologies, integrating AI and machine learning is a promising approach. These advancements can optimize building operations and help address sustainability concerns.

4.1. Enhanced Comfort and Personalization

AI-powered HVAC systems can learn what people like and adjust settings accordingly. By analyzing patterns and user behavior, AI algorithms can create personalized comfort profiles, ensuring individualized temperature and airflow control in different areas of a building. This personalized approach enhances occupant comfort and satisfaction.

4.2. Energy Efficiency and Cost Savings

AI algorithms optimize HVAC system operation by continuously analyzing and adapting to real-time conditions. By considering factors like outdoor temperature, occupancy patterns, and thermal loads, AI-powered systems adjust settings dynamically, maximizing energy efficiency. This results in reduced energy consumption, lower utility bills, and a smaller carbon footprint.

4.3. Predictive Maintenance and Fault Detection

AI algorithms also enable predictive maintenance for HVAC systems. By analyzing performance data, AI can spot early signs of equipment wear or potential issues. This proactive approach allows for timely maintenance, reducing downtime and improving system reliability. AI also helps with fault detection and diagnostics, quickly identifying the root cause of problems for prompt resolution.

4.4. Smart Load Management and Demand Response

AI algorithms optimize energy usage by managing HVAC loads intelligently. During peak demand periods, AI-powered systems can automatically adjust temperature settings or activate load-shedding strategies to reduce energy consumption without compromising comfort. This smart load management helps stabilize the grid and lowers overall energy costs.

5. MACHINE LEARNING WITH BRAIN.JS

Machine learning is one of the hottest topics in the tech world right now. It is the science of making computers learn from data and perform tasks that normally require human intelligence, such as image recognition, natural language processing, recommendation systems, and more.

Brain.js is a JavaScript library that allows you to create and train neural networks using GPU and fallback to pure JavaScript when GPU is not available. You can export and import trained models, use cross validation, stream training and more features with Brain.js. It is simple, fast and easy to use, and provides multiple neural network implementations as different neural nets can be trained to do different things well.

A neural network is a computational model that mimics the structure and function of the human brain. It consists of layers of nodes called neurons connected by weights. The weights determine how much influence each neuron has on the next layer. The neural network learns by adjusting the weights based on the input and output data.

This is an example of data related to an HVAC system for AI optimization. This data includes various parameters such as temperature, humidity, airflow rates, and energy consumption, which can be used to train and optimize AI models for HVAC system optimization:

Timestamp, Indoor Temperature (°C), Outdoor Temperature (°C), Humidity (%), Airflow Rate (m^3/s), HVAC Setpoint (°C), Energy Consumption (kWh)

Table 1. ***Example of data related to an HVAC system for AI optimization***

Timestamp	Indoor Temperature (°C)	Outdoor Temperature (°C)	Humidity (%)	Airflow Rate (m^3/s)	HVAC Setpoint (°C)	Energy Consumption (kWh)
2022-01-01 08:00:00	22	5	50	0.5	20	10
2022-01-01 09:00:00	23	6	48	0.6	21	11
2022-01-01 10:00:00	24	7	47	0.7	22	12
2022-01-01 11:00:00	25	8	45	0.8	23	13
2022-01-01 12:00:00	26	9	44	0.9	24	14
2022-01-01 13:00:00	27	10	42	0.8	25	13
2022-01-01 14:00:00	28	11	41	0.7	26	12
2022-01-01 15:00:00	29	12	40	0.6	27	11
2022-01-01 16:00:00	30	13	39	0.5	28	10
2022-01-01 17:00:00	31	14	38	0.4	29	8

This data includes timestamps representing hourly intervals, along with corresponding values for indoor and outdoor temperature, humidity, airflow rate, HVAC setpoint, and energy consumption.

In this Brain.js starter program, the prediction refers to the output generated by the neural network based on the input data provided.

In the provided example, the neural network is trained using dummy data where each data point consists of input values representing indoor temperature, outdoor temperature, humidity, and airflow rate, and corresponding output values representing HVAC setpoint and energy consumption.

After training the neural network with this data, the program makes a prediction by providing a dummy input object { indoorTemp: 27, outdoorTemp: 10, humidity: 42, airflowRate: 0.8 } to the neural network using the net.run() method.

The output of the prediction is then logged to the console using console.log('Prediction:', output);.

The specific output of the prediction will vary based on the trained neural network's learned patterns and relationships between the input and output data. It could include predicted values for HVAC setpoint and energy consumption based on the provided input data.

```
const brain = require('brain.js');

// Dummy data
const data = [
  { input: { indoorTemp: 22, outdoorTemp: 5, humidity: 50, airflowRate: 0.5 }, output: { setpoint: 20, energyConsumption: 10 } },
  { input: { indoorTemp: 23, outdoorTemp: 6, humidity: 48, airflowRate: 0.6 }, output: { setpoint: 21, energyConsumption: 11 } },
  { input: { indoorTemp: 24, outdoorTemp: 7, humidity: 47, airflowRate: 0.7 }, output: { setpoint: 22, energyConsumption: 12 } },
  { input: { indoorTemp: 25, outdoorTemp: 8, humidity: 45, airflowRate: 0.8 }, output: { setpoint: 23, energyConsumption: 13 } },
  { input: { indoorTemp: 26, outdoorTemp: 9, humidity: 44, airflowRate: 0.9 }, output: { setpoint: 24, energyConsumption: 14 } },
  // Add more data here...
];

// Create a neural network
const net = new brain.NeuralNetwork();

// Train the neural network
net.train(data);

// Dummy input for prediction
const input = { indoorTemp: 27, outdoorTemp: 10, humidity: 42, airflowRate: 0.8 };

// Make a prediction
const output = net.run(input);

// Output the prediction
console.log('Prediction:', output);
```

Fig.2. Brain.js Starter Program

After running the program, it gave the result Prediction: {setpoint: 0.9999996423721313, energyConsumption: 0.9999992847442627}.

The output {setpoint: 0.9999996423721313, energyConsumption: 0.9999992847442627} signifies the predicted values for the HVAC setpoint and energy consumption based on the input data provided to the trained neural network.

In Brain.js, the output values are normalized between 0 and 1 by default during the training process. Therefore, the predicted values are also within this range after running the neural network.

For the specific prediction provided:

- setpoint: 0.9999996423721313: This indicates that the neural network predicts the HVAC setpoint to be very close to 1, which is likely the maximum or optimal setpoint value. The actual value would need to be denormalized back to its original scale (e.g., degrees Celsius) based on the range used during training.
- energyConsumption: 0.9999992847442627: Similarly, this indicates that the neural network predicts the energy consumption to be very close to 1, which could suggest high energy consumption. As with the setpoint, the actual value would need to be denormalized back to its original scale (e.g., kWh) based on the range used during training.

Here's a more complex version of the starter program that includes additional layers and neurons in the neural network, as well as more sophisticated preprocessing of the input data:

```
hvac.js    hvac-improved.js ×
hvac-improved.js > ...
const normalizedData = data.map(({ input, output }) => ({
  output: {
    energyConsumption: output.energyConsumption / 20, // Normalize energy consumption (assuming maximum value of 20)
  },
}));

// Create a more complex neural network with hidden layers
const net = new brain.NeuralNetwork({
  hiddenLayers: [8, 8], // Two hidden layers with 8 neurons each
});

// Train the neural network with normalized data
net.train(normalizedData);

// Dummy input for prediction (normalized)
const input = {
  indoorTemp: 27 / 100, // Normalize indoor temperature
  outdoorTemp: 10 / 50, // Normalize outdoor temperature
  humidity: 42 / 100, // Normalize humidity
  airflowRate: 0.8 / 1, // Normalize airflow rate
  operatingHours: 8 / 24, // Normalize operating hours
  occupancy: 1, // Occupancy (binary value)
};

// Make a prediction
const output = net.run(input);

// Denormalize the predicted output values
const denormalizedOutput = {
  setpoint: output.setpoint * 30, // Denormalize setpoint
  energyConsumption: output.energyConsumption * 20, // Denormalize energy consumption
};

// Output the denormalized prediction
console.log('Prediction:', denormalizedOutput);

PROBLEMS   OUTPUT   DEBUG CONSOLE   TERMINAL   PORTS

PS C:\Users\ghica\Desktop\hvac-yarn> node hvac-improved.js
Prediction: { setpoint: 20.91543138027191,
  energyConsumption: 11.712839603424072 }
PS C:\Users\ghica\Desktop\hvac-yarn> node hvac-improved.js
Prediction: { setpoint: 21.011354327201843,
  energyConsumption: 11.767369508743286 }
PS C:\Users\ghica\Desktop\hvac-yarn>
```

Fig.3. Brain.js Starter Program

In this updated version of the program:

- Additional input data, such as operating hours and occupancy status, are included in the training data and the prediction input.
- The input and output values are normalized before training the neural network to improve convergence and stability during training.
- The neural network architecture includes two hidden layers with 8 neurons each, making the network more complex and capable of capturing nonlinear relationships in the data.
- After making a prediction, the output values are denormalized to obtain the predicted setpoint and energy consumption values in their original scales.

The result {setpoint: 21.011354327201843, energyConsumption: 11.767369508743286} signifies the predicted values for the HVAC setpoint and energy consumption after denormalizing the output of the neural network.

In this version of the program, the prediction output values are denormalized to obtain the predicted values in their original scales. These values represent the neural network's predictions for the HVAC system based on the input data provided.

Specifically:

- setpoint: 21.011354327201843: This indicates that the neural network predicts the HVAC setpoint to be approximately 21.01 units, which could represent the optimal setpoint value for the given input conditions

- energyConsumption: 11.767369508743286: Similarly, this indicates that the neural network predicts the energy consumption to be approximately 11.77 units, which could represent the expected energy consumption level for the HVAC system under the given input conditions.

5. CONCLUSIONS

The integration of Artificial Intelligence (AI) in HVAC systems is an ongoing process with exciting future trends.

Artificial Intelligence is revolutionizing HVAC industry, empowering systems to deliver personalized comfort, maximize energy efficiency, and reduce costs. Through the integration of AI algorithms and machine learning, HVAC systems can adapt to changing conditions, optimize energy consumption, and proactively address maintenance needs.

Future AI-powered HVAC systems will have enhanced capabilities to optimize energy efficiency further. AI algorithms will leverage advanced machine learning techniques to continuously learn and adapt to building dynamics, occupant behaviors, and weather conditions. This will result in more precise and dynamic energy management, reducing waste and maximizing energy savings.

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