Using Sensor Data and ML to

Estimate Room Occupancy

Literature Review, Data Description

and Project Approach

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# Abstract

## Problem

To provide comfort for occupants, commercial buildings rely on heating, ventilation, and air conditioning (HVAC) systems and lighting systems. Large amounts of energy are wasted, especially during non-working hours (Masoso and Grobler, 2010).

To optimize these systems, a research paper (Singh et al., 2018) described an experiment for accurately estimating the number of occupants in a room using “non-intrusive” environment sensors and machine learning (ML) models. Multiple sensor nodes were placed throughout a 6m by 4.6m test room in a wireless sensor network (WSN). Low-cost sensors were deployed at each of the four desks to measure temperature, light, and sound. A carbon dioxide (CO2) sensor was deployed in the middle of the room to provide the most accurate reading. Additional motion detection sensors were deployed on the ceiling, above the door and large window. Because of privacy concerns, video-based systems are not considered appropriate for detecting occupancy.

Previous research focused on using occupancy detection (i.e., determining whether a room is occupied or not) to save energy. On the other hand, the goal of ML occupancy estimation research is to design adaptive systems that can detect the exact number of occupants, resulting in additional energy savings and improved comfort for occupants.

## Themes and Research Questions

For my project, I have chosen the theme of Classification for building predictive models.

To reduce energy consumption in buildings, I will investigate research questions such as:

* Which of the implemented supervised learning techniques perform the best in predicting occupancy?
* Which types of sensor data show the most promising results? Are there limitations in using certain types of sensor data such as light?
* Based on the research, what alternative techniques could be used for ML-based occupancy estimation?

## Data

For my project, I will be using the Room Occupancy Estimation dataset, available from the [UC Irvine Machine Learning Repository](https://archive.ics.uci.edu/). The Room Occupancy Estimation dataset can be downloaded from <https://archive.ics.uci.edu/dataset/864/room+occupancy+estimation>.

The dataset contains over 10000 data points and 16 features. Each feature represents data (temperature, light, sound, motion, or CO2) from a particular sensor. Measurements were recorded over several days in 30 second intervals. The actual occupancy was established by having participants register and record the exact time each time they entered or left the room. At any given time, up to three participants were in the room at the same time. In about 80% of the data points, the room was unoccupied.

## Techniques and Tools

To solve the stated problem, I propose to implement supervised learning algorithms such as random forests and support-vector machines (SVM). In addition, I plan to investigate how an unsupervised learning algorithm such as Principal Component Analysis (PCA) can be used for dimensionality reduction.

For this project, I plan to use R for the initial data analysis and Python for implementing the machine learning algorithms. All the supervised and unsupervised learning algorithms can be implemented using the scikit-learn open-source library. To evaluate the models, I will use multiple performance metrics including accuracy and F1 score.

# Literature Review

At least six pages answering the questions listed earlier in the introduction section:

* What do you already know about the topic?
* What do you have to say critically about what is already known?
* Has anyone else done anything that is exactly the same?
* Has anyone else done anything that is related?
* How does your work fit in with what has gone before?
* Why is your research worth doing in the light of what has already been done?

If you choose to replicate an existing study, you may need to highlight the similarities and differences between the replicated research and your analyses. For example, suppose you decided to replicate study X. In that case, you need to stress whether you will be applying the same set of research questions, using a different time frame of the datasets, following the same approach, or conducting similar analyses. Nevertheless, you might need to compare your outcome with the actual results of the replicated research.

Ceni: While you are writing your literature reviews, write a summary of the related papers that you reviewed.  Write it in your own words and don’t use something from the paper that you don’t understand. A short paragraph about each paper you reviewed should be sufficient.

A literature review is not a review of general machine-learning techniques. You should focus on your research question and similar research questions as well as your dataset and similar datasets. You should be talking about previous approaches that relate to your current project.

By literature, we mean research papers, conference papers, journal papers, books, etc.

## Introduction

## Previous Studies on Occupancy Detection

Some previous studies focused on using occupancy detection to save energy. The goal of occupancy detection is to determine whether a room is occupied or not. Unlike occupancy estimation, occupancy detection does not try to determine the actual number of occupants in a room at any one time.

In one study (Hailemariam et al., 2011), the authors deployed multiple low-cost sensors within an office cubicle to measure light, sound, CO2, power use, and motion. After collecting data for a week, the authors used the Decision Tree classification method to predict whether the cubicle was occupied at any one time. In their study, features related to motion performed the best in predicting the presence of a worker. Light features, on the other hand, performed the worst. Combining features had mixed results. Notably, none of the feature combinations outperformed the features derived from using motion sensors alone. The study did not explore classification methods other than Decision Tree.

In (Candanedo & Feldheim, 2016), the authors used data from light, temperature, humidity, and CO2 sensors to predict whether an office room was occupied. The classification models were tested under two data sets, depending on whether the office door was closed. The authors noted that including timestamps in the models led to better results in most cases. Accuracies of 97% or higher were achieved using Linear Discriminant Analysis (LDA) with two predictors (e.g., temperature and light) and Classification and Regression Trees (CART) with light as the top node.

This table summarizes these occupancy detection studies:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Study | Sensor Data | Classification Methods | Data | Evaluation Metrics | Best Results |
| [[3]](#_References) | Light, sound, CO2, power use, motion | Decision Tree | 7 days | Accuracy | Motion features (98.4%) |
| [[4]](#_References) | Light, temperature, humidity, CO2 | CART  Random Forest  GBM  LDA | 2 days | Accuracy | LDA with two predictors (97%)  CART with light as the top node (97% or higher) |

## Previous Studies on Occupancy Estimation

The goal of occupancy estimation research is to design systems that can determine the actual number of occupants in a room at any one time. As previously mentioned, demand-driven HVAC and lighting systems can result in additional energy savings and improved comfort for occupants.

In (Dong et al., 2010), three sensor networks were deployed in an open-plan office building:

* Gas detection sensor network to measure pollutants such as CO2
* Wireless ambient sensor network to measure lighting, temperature, humidity, motion, and sound
* Independent CO2 sensor network

During feature selection, the authors determined that the CO2 features had the largest information gain. As a result, these features were used as inputs to the classification models: Hidden Markov Model (HMM), Artificial Neural Network (ANN), and Support Vector Machine (SVN). The authors concluded that HMM performed the best overall with an accuracy of 75%.

In (Yang et al., 2012), the authors used data from temperature, humidity, CO2, light, sound, and motion sensors to estimate the number of occupants in two shared lab spaces. After collecting data from 20 days, the authors used radial basis function (RBF) neural network for classification. They reported an average detection rate of 87.62% for self-estimation (model is trained and tested using the same lab) and 64.83% for cross-estimation (model is trained and tested using different labs). To account for rounding errors produced by the model, a tolerance of 1 was used. For example, if the model predicted 2.8 occupants, an error was not reported if the actual number of occupants was 2 or 3.

This table summarizes these occupancy estimation studies:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Study | Sensor Data | Classification Methods | Data | Evaluation Metrics | Best Results |
| [[5]](#_References) | CO2, light, temperature, humidity, motion, sound, | HMM  ANN  SVN | 14 days | Accuracy | HMM with CO2 features as input (75%) |
| [[6]](#_References) | Temperature, humidity, CO2, light, sound, motion | RBF neural network | 20 days | Accuracy (tolerance = 1) | Self-estimation (87.62%) |

## Recent Studies on Occupation Detection and Estimation

Since the Singh et al. research paper that is the focus of this project was published in 2018, more recent studies into occupancy detection and estimation have been carried out.

In (Wang et al., 2021), the authors proposed a cost-effective, non-intrusive occupancy detection system that they said could be easily installed in residential buildings. Installed in a living lab, the system used four temperature and one motion sensors to detect human activities (such as opening the front door or running water) over 54 days. Data on the human activities was then used to train and test four classification models: Random Forest, Decision Tree, K-Nearest Neighbor, and Support Vector Machine. The authors concluded that Random Forest performed the best overall, with an accuracy and F1-score of 98% or higher.

In (Kim et al., 2023), the authors used Internet of Things (IoT) sensors to estimate the number of occupants in a living lab over 55 days. Overnight and weekend data were excluded as no occupants were in the lab at that time. Random Forest and Artificial Neural Network (ANN) classification models were used, with data from CO2 concentration, differential pressure (air flow), and the ventilation system state used as inputs. For predicting occupancy, the authors concluded that the Random Forest model had the lowest root mean square error (RMSE) when the ventilation system state data was added to CO2 concentration as input values. Conversely, including differential pressure data tended to decrease accuracy and increase RMSE in the models.

In (Mao et al., 2023), the authors adapted a predictive framework for room occupancy using the same [dataset](#_Descriptive_Statistics_of) that is the focus of this project. Several classification methods were used: Logistic Regression, Linear Discriminant Analysis (LDA), Support Vector Machine (SVM), Multi-layer Perceptron (MLP), LightGMB, XGBoost, and Random Forest. The models were evaluated using balanced accuracy, F1-score, and Area Under ROC Curve (AUC). Among the methods, Random Forest performed the best in all three metrics. In the Random Forest model, the light values from sensor 1 and sensor 2 had the largest impact in predicting room occupancy. The results, the authors claimed, improved on the performance of the original paper.

In (Banihashemi et al., 2024), the authors deployed IoT sensors in two rooms of an office building over multiple months. The sensors collected CO2, temperature, relative humidity, indoor air quality, sound pressure level, and light data. The authors then trained Random Forest, XGBoost, and dense feedforward neural network (DFNN) on the dataset to determine the best features. The best features were then used to reduce dimensionality of sequential models. For occupancy detection, the authors concluded that using six days of sound pressure level, CO2, and light data could achieve an accuracy above 95% and an F1-score above 93%.

This table summarizes these occupancy estimation studies:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Study | Sensor Data | Classification Methods | Data | Evaluation Metrics | Best Results |
| [[7]](#_References) | Temperature, Motion | Random Forest  Decision Tree  K-Nearest Neighbor  SVN | 54 days | Accuracy  F1-score | Random Forest (98% or higher for both) |
| [[8]](#_References) | CO2 concentration, differential pressure, ventilation system state | Random Forest  ANN | 55 days | Accuracy  RMSE | Random Forest with ventilation system state added to CO2 concentration (RMSE = 1.462) |
| [[9]](#_References) | Temperature, Light, Sound, CO2, motion | Logistic Regression  LDA  SVM  MLP  LightGBM  XGBoost  Random Forest | 7 days | Balanced Accuracy  F1-score  AUC | Random Forest |
| [[10]](#_References) | CO2, temperature, humidity, air quality, sound, light | Random Forest  XGBoost  DFNN | 80 days, 20 days | Accuracy, F1-score | Accuracy (>95%)  F1-score (>93%) |

## Additional Studies

The research papers cited in this review present specific studies that use sensor data and machine learning techniques to detect or estimate room occupancy in a test environment. Other studies take a broader perspective.

In (Tao et al., 2024), the authors reviewed the development of data collection methods and predictive algorithms. To enhance data collection, the authors advocated using new Internet of Things (IoT) technology including Bluetooth signals, Wi-Fi, camera images, and GPS data. To increase prediction accuracy, they advocated for further research into hybrid machine learning models. The authors noted that interest in occupancy prediction research has increased since 2012, except during the COVID-19 pandemic.

In (Khan et al., 2024), the authors reviewed the advantages and limitations of alternative IoT technologies for occupancy detection, estimation and prediction. These technologies include UWB radar, Bluetooth low energy (BLE), WiFi, cameras, and electric meters. For example, UWB radar technology has high precision and can be used to detect the movements of people; limitations include their high cost and potential for privacy issues. The authors also discussed how combining data from different types of sensors into a unified system can increase prediction accuracy.

## Conclusion

# Descriptive Statistics of the Selected Dataset

The data set contains 10129 data points and 16 features. Each feature represents data (temperature, light, sound, motion, or CO2) from a particular sensor. Measurements were recorded over several days in 30 second intervals. There were actual occupants on three of those days.

There are no missing values in the dataset.

## Univariate Analysis

### Data Dictionary

This table describes the variables in the Room Occupancy Estimation data set:

|  |  |  |
| --- | --- | --- |
| Field Name | Data Type | Description |
| Date | Date | Date of observation in YYYY/MM/DD |
| Time | Date | Time of observation in HH:MM:SS |
| S1\_Temp | Continuous | Temperature reading from sensor 1 in degrees Celsius |
| S2\_Temp | Continuous | Temperature reading from sensor 2 in degrees Celsius |
| S3\_Temp | Continuous | Temperature reading from sensor 3 in degrees Celsius |
| S4\_Temp | Continuous | Temperature reading from sensor 4 in degrees Celsius |
| S1\_Light | Integer | Light reading from sensor 1 in lux |
| S2\_Light | Integer | Light reading from sensor 2 in lux |
| S3\_Light | Integer | Light reading from sensor 3 in lux |
| S4\_Light | Integer | Light reading from sensor 4 in lux |
| S1\_Sound | Continuous | Sound reading from sensor 1 in volts (amplifier output read by ADC) |
| S2\_Sound | Continuous | Sound reading from sensor 2 in volts (amplifier output read by ADC) |
| S3\_Sound | Continuous | Sound reading from sensor 3 in volts (amplifier output read by ADC) |
| S4\_Sound | Continuous | Sound reading from sensor 4 in volts (amplifier output read by ADC) |
| S5\_CO2 | Integer | CO2 reading from sensor 5 in ppm |
| S5\_CO2\_Slope | Continuous | Derived slope of C02 values taken in a sliding window  **Note:** This was calculated by fitting a linear regression in a window of 25 points at each instance and calculating the slope of the line. The factor of 25 was chosen by trial and error with respect to the classification accuracy metric. |
| S6\_PIR | Binary | Binary value conveying motion detection from passive infrared (PIR) sensor 6:  **0:** No motion events detected in 30 second frame  **1:** At least one motion event detected in 30 second frame |
| S7\_PIR | Binary | Binary value conveying motion detection from passive infrared (PIR) sensor 7:  **0:** No motion events detected in 30 second frame  **1:** At least one motion event detected in 30 second frame |
| Room\_Occupancy\_Count | Integer | Number of occupants in the room at one time (ground truth) |

### Dependent (target) Variable

The dependent (target) variable is Room\_Occupancy\_Count.

### 5 Number Summary

This table shows the 5 number summary of the numeric attributes in the data set:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable | Minimum | Q1 | Median | Q3 | Maximum |
| S1\_Temp | 24.94 | 25.19 | 25.38 | 25.63 | 26.38 |
| S2\_Temp | 24.75 | 25.19 | 25.38 | 25.63 | 29.00 |
| S3\_Temp | 24.44 | 24.69 | 24.94 | 25.38 | 26.19 |
| S4\_Temp | 24.94 | 25.44 | 25.75 | 26.00 | 26.56 |
| S1\_Light | 0.00 | 0.00 | 0.00 | 12.00 | 165.00 |
| S2\_Light | 0.00 | 0.00 | 0.00 | 14.00 | 258.00 |
| S3\_Light | 0.00 | 0.00 | 0.00 | 50.00 | 280.00 |
| S4\_Light | 0.00 | 0.00 | 0.00 | 22.00 | 74.00 |
| S1\_Sound | 0.0600 | 0.0700 | 0.0800 | 0.0800 | 3.8800 |
| S2\_Sound | 0.0400 | 0.0500 | 0.0500 | 0.0600 | 3.4400 |
| S3\_Sound | 0.0400 | 0.0600 | 0.0600 | 0.0700 | 3.6700 |
| S4\_Sound | 0.0500 | 0.0600 | 0.0800 | 0.1000 | 3.4000 |
| S5\_CO2 | 345.0 | 355.0 | 360.0 | 465.0 | 1270.0 |
| S5\_CO2\_Slope | -6.29615 | -0.04615 | 0.00000 | 0.00000 | 8.98077 |

This chart shows the boxplot of the temperature variables by sensor:

A graph showing different colored squares

Description automatically generated

The temperature values are quite high, indicating that the room was in a hot climate without air conditioning.

This chart shows the boxplot of the light variables by sensor:

A graph of a boxplot of light values

Description automatically generated

The median values of 0 suggests that the lights were turned off most of the time. This chart shows the same boxplot, except that days without occupants have been excluded:

A graph of different colored squares

Description automatically generated

Similarly, most of the time no sound or little sound was detected. This chart shows the boxplot of the sound variables by sensor on days with occupants:

A graph of different colored lines

Description automatically generated

This chart shows the boxplot of the CO2 variables on days with occupants:

A graph of co2 values

Description automatically generated

### Frequency of Categorical Variables

This bar chart shows the frequency of the S6\_PIR variable used to detect motion:

A graph with a bar and a number of squares

Description automatically generated with medium confidence

This chart shows the frequency of the Room\_Occupancy\_Count (target) variable:

A graph with blue squares

Description automatically generated

In about 80% of the data points, the room was unoccupied. This chart shows the same bar chart, except that days without occupants have been excluded:

A graph of a bar graph

Description automatically generated with medium confidence

## Bivariate Analysis

### Pairwise Visualizations

This chart shows the scatter plot matrix of the temperature (S1), light (S1), sound (S1), and CO2 (S5) values:

A collage of images

Description automatically generated

There appears to be a linear relationship between temperature and CO2 values.

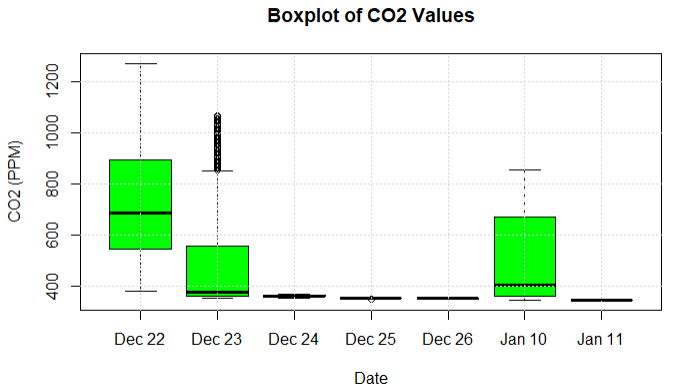
This boxplot shows the distribution of room occupancy for each day:

A graph with green and black squares

Description automatically generated

There were occupants only on December 22, December 23, and January 10.

This boxplot shows the distribution of CO2 values for each day:



Significant CO2 values were only detected on days with occupants.

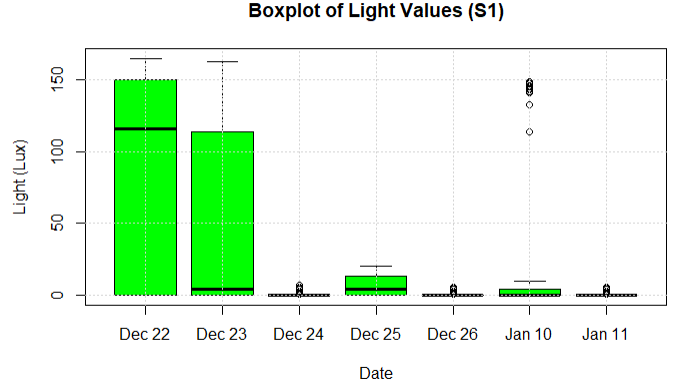
This boxplot shows the distribution of temperature values (sensor 1) for each day:

A graph with green and black squares

Description automatically generated

The highest temperatures occurred on the days with occupants.

This boxplot shows the distribution of light values (sensor 1) for each day:



The highest light values occurred on days with occupants. Notably, light was detected on Christmas, indicating that lights were turned on during part of that day.

This boxplot shows the distribution of sound values (sensor 1) for each day:

A graph of a box plot

Description automatically generated

As expected, the highest sound values occurred on days with occupants.

### Correlation Analysis

In this analysis, Spearman analysis was used as the features are not normally distributed, which was apparent from the boxplots and and confirmed by the Shapiro test.

This chart shows the correlation matrix between room occupancy and temperature variables:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Room Occupancy | S1\_Temp | S2\_Temp | S3\_Temp | S4\_Temp |
| Room Occupancy | 1.00 | 0.59 | 0.55 | 0.56 | 0.53 |
| S1\_Temp | 0.59 | 1.00 | 0.97 | 0.95 | 0.87 |
| S2\_Temp | 0.55 | 0.97 | 1.00 | 0.93 | 0.84 |
| S3\_Temp | 0.56 | 0.95 | 0.93 | 1.00 | 0.90 |
| S4\_Temp | 0.53 | 0.87 | 0.84 | 0.90 | 1.00 |

There is a moderate correlation between room occupancy and temperature variables. As expected, there is a strong correlation of temperature values between sensors.

This chart shows the correlation matrix between room occupancy and light variables:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Room Occupancy | S1\_Light | S2\_Light | S3\_Light | S4\_Light |
| Room Occupancy | 1.00 | 0.72 | 0.71 | 0.66 | 0.50 |
| S1\_Light | 0.72 | 1.00 | 0.998 | 0.97 | 0.93 |
| S2\_Light | 0.71 | 0.998 | 1.00 | 0.97 | 0.93 |
| S3\_Light | 0.66 | 0.97 | 0.97 | 1.00 | 0.94 |
| S4\_Light | 0.50 | 0.93 | 0.93 | 0.94 | 1.00 |

There is a moderate correlation between room occupancy and light variables. As expected, there is a strong correlation of light values between sensors.

This chart shows the correlation matrix between room occupancy and sound variables:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Room Occupancy | S1\_Sound | S2\_Sound | S3\_Sound | S4\_Sound |
| Room Occupancy | 1.00 | 0.64 | 0.67 | 0.65 | 0.36 |
| S1\_Sound | 0.64 | 1.00 | 0.53 | 0.51 | 0.47 |
| S2\_Sound | 0.67 | 0.53 | 1.00 | 0.60 | 0.31 |
| S3\_Sound | 0.65 | 0.51 | 0.60 | 1.00 | 0.28 |
| S4\_Sound | 0.36 | 0.47 | 0.31 | 0.28 | 1.00 |

There is a moderate correlation between room occupancy and sound variables, except for sensor 4. Notably, there is a relatively weak correlation of sound values between sensors.

This chart shows the correlation matrix between room occupancy and the CO2 and motion variables:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Room Occupancy | S5\_CO2 | CO2 Slope | S6\_PIR | S7\_PIR |
| Room Occupancy | 1.00 | 0.58 | 0.54 | 0.65 | 0.64 |
| S5\_CO2 | 0.58 | 1.00 | 0.01 | 0.38 | 0.39 |
| CO2 Sound | 0.54 | 0.01 | 1.00 | 0.35 | 0.37 |
| S6\_PIR | 0.65 | 0.38 | 0.35 | 1.00 | 0.57 |
| S7\_PIR | 0.64 | 0.39 | 0.37 | 0.57 | 1.00 |

There is a moderate correlation between room occupancy and CO2 variables and between room occupancy and motion variables. There is no correlation between CO2 and the derived CO2 slope values.

This chart shows a plot of the correlation matrix:

A screenshot of a computer generated image

Description automatically generated

# GitHub Repository

For this project, I’m using the following repository in GitHub:

<https://github.com/jeffreyfitzpatrick/Big-Data-Analytics-Capstone-Project>

# Overall Methodology

A graph showing the tentative overall methodology

Ceni: I'd like to share with you a few tips on the graph you need to prepare for your tentative overall methodology. I suggest you prepare a flowchart for that purpose. A flowchart is a type of diagram that represents a workflow or process. The flowchart shows the steps as boxes of various kinds, and their order by connecting the boxes with arrows.  This diagrammatic representation will illustrate your tentative methodology for your research problem. You should also provide a brief explanation of this flowchart to clarify the purpose of each step and how they contribute to your overall research methodology.

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