World Academy of Science, Engineering and Technology
International Journal of Structural and Construction Engineering
Vol:17, No:11, 2023

Degradation of Heating, Ventilation, and Air Conditioning Components across Locations

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Abstract**—**Materials degrade at different rates in different environments depending on factors such as temperature, aridity, salinity, and solar radiation. Therefore, predicting asset longevity depends, in part, on the environmental conditions to which the asset is exposed. Heating, ventilation, and air conditioning (HVAC) systems are critical to building operations yet are responsible for a significant proportion of their energy consumption. HVAC energy use increases substantially with slight operational inefficiencies. Understanding the environmental influences on HVAC degradation in detail will inform maintenance schedules and capital investment, reduce energy use, and increase lifecycle management efficiency. HVAC inspection records spanning 14 years from 21 locations across the United States were compiled and associated with the climate conditions to which they were exposed. Three environmental features were explored in this study: average high temperature, average low temperature, and annual precipitation, as well as four non-environmental features. Initial insights showed no correlations between individual features and the rate of HVAC component degradation. Using neighborhood component analysis, however, the most critical features related to degradation were identified. Two models were considered, and results varied between them. However, longitude and latitude emerged as potentially the best predictors of average HVAC component degradation. Further research is needed to evaluate additional environmental features, increase the resolution of the environmental data, and develop more robust models to achieve more conclusive results.

Keywords**—**Climate, infrastructure degradation, HVAC, neighborhood component analysis.

I. Introduction

THIS paper explores the degradation of HVAC components of buildings due to environmental and other factors. The motivation behind this study is the protection, resilience, and security of US critical infrastructure, one of the key themes of the National Security Strategy [1]. With the value of all Department of the Air Force (DAF) facilities and utilities topping $359 billion [2], Air Force infrastructure can be costly to maintain, yet is a valuable resource to military missions.

HVAC systems are of the more critical infrastructure components to US Air Force and Space Force missions due to the strict temperature and humidity requirements of several key mission assets, specifically those supporting cyber, space and remotely piloted aircraft missions. Consistent maintenance on frequently failing assets within the HVAC systems have been shown to not only allow them to run longer but also to be more energy efficient [3]. Anecdotal stories from across the US Air Force civil engineering enterprise revealed several instances of mission impacts due to degrading infrastructure, particularly HVAC systems. With further investigation, it is hoped to gain knowledge on how environmental conditions may contribute to HVAC component failure, and then use this knowledge to better manage critical infrastructure across the DAF portfolio.

II. Literature Review

Prior to focusing on HVAC systems, a broad literature review was conducted to identify environmental factors that affect various common building materials. In concrete, freeze-thaw cycles [4] and dry climates [5] cause degradation. In masonry, weathering processes such as wind and rain [6] as well as freeze-thaw cycles [7] contribute most to degradation. For paint, temperature [8] and humidity [9] cause deterioration. In steel, temperature [10], salinity, wet-dry, and freeze-thaw cycles [11] are the most common causes of degradation. Finally in timber, temperature [12] and precipitation [13] contribute most to degradation. With several overlapping environmental factors causing degradation between common building materials, the literature review advanced to reviewing work about various infrastructure systems.

The planning, design, construction, and maintenance of airfield and road pavements heavily consider climate due to its direct impact on deterioration. One study on airfield pavements concluded that temperature, precipitation, subsurface moisture, and freeze-that cycles cause the most harmful environmental effects on pavement performance and lifespan [14]. Another study involving 14 different US Air Force Bases indicated that flexible pavements performed worse in colder regions due to the presence of freeze thaw-cycles, whereas in more arid and warm conditions, pavement degraded less quickly [15]. Analysis determined that aircraft passing only contributed to 14% of airfield degradation while environmental conditions account for the remainder [15].

In a study on roofing systems across 61 locations involving five diverse types of systems, infrastructure condition assessment data were used to construct a roof degradation model. Environmental factors such as high temperature, solar radiance, and hail damage were determined as significant contributors to the degradation of roofing systems [16].

Within HVAC systems, ultraviolet light (UVC) used to kill microbes and maintain clean air flow has been shown to degrade surrounding materials due to poor shielding or improper layering of the HVAC system [17]. Because the UVC

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wavelength used for HVAC disinfection is also emitted by the sun, it is posited that solar irradiation is likely to cause HVAC systems to degrade and lose performance efficiency. There has been little research on environmental factors that cause degradation of HVAC components or systems. Based on the susceptibility of other infrastructure systems, it is likely that several environmental factors could play a role in HVAC degradation when HVAC components are exposed to the environment.

A. Background

The US Department of Defense (DoD) uses a building asset management system called Sustainment Management System BUILDER as its repository of infrastructure condition across its portfolio. The DoD implemented BUILDER in 2010, and mandated its use in September of 2013 [18]. Each US military base inspects and assesses the condition of individual infrastructure components at least once every four years. Inspection reports are then stored in BUILDER, a non-public data repository, for reference and analysis.

During an inspection, inspectors follow a predetermined checklist to rate an infrastructure component, resulting in an asset condition assessment rating between 0 and 100, called a condition index (CI). The CI is a "value that is objective, repeatable, and clearly communicates the general physical health of the asset" [19]. Based on the current condition, a model showing how the CI degrades over time is then assumed for each infrastructure component (e.g., Fig. 1). CI is a maximum of 100 at initial construction and approaches the minimum of 0 as it degrades non-linearly. Routine maintenance is assumed to be completed throughout the asset's service life within the degradation model. When repairs are conducted, the CI may increase at the next inspection. Likewise, if there is a major degradation event, CI may be lower than anticipated at the next inspection.

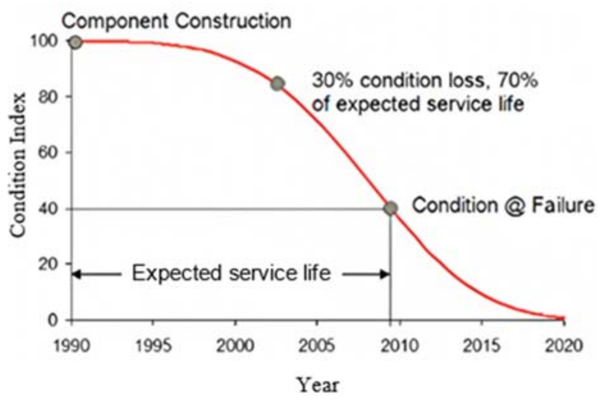

Fig. 1 Typical lifecycle condition degradation curve of an asset constructed in 1990 with no repairs over its lifetime, adapted from [19]

The degradation model of an infrastructure component may be adjusted slightly based on the CI determined at subsequent inspections. Tracking the CI of an infrastructure component over time is helpful to those charged with prioritizing and financing repair and recapitalization projects. Currently, the degradation model for each component does not vary between types of HVAC components and does not vary with geographic location.

B. Purpose

This paper will explore how HVAC component degradation varies across the US. Several environmental features and non-environmental features that could affect the degradation of HVAC components are explored. The rate of degradation over time for HVAC components will be compared between different geographic locations with different climatic conditions. Average degradation trends will be discussed as well as observed correlations to climate variables. The aim is to begin to understand how differing environmental conditions could affect the degradation of HVAC components across multiple locations.

III. Methods

A. Data Acquisition

Inspection reports from 21 Air Force and Space Force bases in the continental US were accessed from BUILDER in November and December 2022. The reports contained data dating from early 2009 through late 2022. The inspection reports used in this study were developed by hundreds of different inspectors following visual inspections of the condition of HVAC components at each location and at each point in time, however use of the standard inspection checklist was expected to maintain sufficient levels of consistency across reports.

The data were filtered to only include HVAC components reasonably expected to be installed outside or exposed to the elements such as chillers, condensers, package units, and exhaust systems. Next, the data were further filtered by the CI at the time of their most recent inspection. Data in this study only included HVAC components with a most recent CI between 40 and 70. The slope of the degradation curve is almost perfectly linear between condition indices of 40 and 70 (see Fig. 1), therefore the expected rate of degradation per unit time is near constant in this region. A constant expected rate of degradation across a range of CIs creates suitable conditions to make comparisons across the dataset.

Once the dataset of HVAC components exposed to the elements with a current CI between 40 and 70 was assembled, the duration of time between each inspection was calculated for each individual HVAC component. Similarly, the change in CI between inspections was computed. While repair work is critical to maintaining effective HVAC systems, the purpose of this study is to observe degradation, and data that involved repair would skew the findings. In an effort to exclude inspection data for components which had repair work take place between inspections, data were excluded if CI increased between inspections. Using (1), *average degradation* was computed and used to compare HVAC components across the 21 locations. Average degradation was calculated as change in CI divided by the change in time between inspections in months and multiplied by 30 days to establish a rate of degradation per month in units of points per month.

$$Average\ degradation = \left[\frac{\Delta\ condition\ index}{\#\ days\ between\ inspections}\right] \times 30\ days/month \quad (1)$$

If HVAC components degrade at a constant rate, the computed average degradation for each observation would be identical. Differences in degradation between inspections would yield different values of average degradation. Average degradation values for each of the observations in the dataset were either zero, indicating no change in inspection score between inspections, or negative, indicating the asset's condition decreased between inspections.

To begin to attribute environmental features to HVAC component degradation, climate data were collected from the National Oceanic and Atmospheric Administration [20]. The average high temperature, average low temperature, and annual precipitation between 1991-2020 for each of the 21 locations were acquired. As an example, a visual representation of annual precipitation is shown in Fig. 2 with the 21 locations represented by the circular icons.

Fig. 2 Map of annual precipitation (darker = greater precipitation)

TABLE I
DATA FEATURES AND SOURCES

Feature	Source
area code	[21]
latitude	[22]
longitude	[22]
average high temperature	[20]
average low temperature	[20]
annual precipitation	[20]
age	BUILDER

Other non-environmental features such as latitude, longitude, and component age at the time of the inspection were included in the dataset as well. Lastly, the telephone area code of the location of each HVAC component was also added as a control feature and was not expected to impact average degradation. The final dataset consisted of 11,773 observations from seven different types of HVAC components across 21 locations, each with seven features (Table I). Note, the values of six of the seven features were identical for all HVAC components at a given location, save age of the component.

B. Neighborhood Component Analysis

Neighborhood Component Analysis (NCA) [23] was employed using the commercially available software, MATLAB [24] and its *fsrnca* function in an attempt to identify the most important features related to average degradation. The values of each of the seven features were scaled to a mean of zero and standard deviation of 1.0. 70% of the data was used as the training set and 30% as the test set. Five-fold cross-validation was used to tune the regularization parameter against the selected loss function. Two different loss functions were explored in this study: mean absolute error (MAE) and ε-insensitive, resulting in two different models. Both models minimized their respective loss functions when compared to the predictor variable, which was average degradation for each of the 11,733 observations. MAE is a generalized loss function valid for some applications, and the ε-insensitive loss function can be more robust for real-world applications involving "noisy" data [25]. The outputs from each model were feature weights corresponding to the relative importance of each feature in predicting the average degradation of an HVAC component as well as predicted values of average degradation for each observation.

IV. RESULTS AND DISCUSSION

A. Statistical Analysis

The mean average degradation across all HVAC components at each location was calculated. Values varied widely between the 21 locations from -0.74 points per month at Dover Air Force Base (AFB) in Delaware to -0.12 points per month at Eglin AFB in Florida (Fig. 3). Delaware is located near a coastline and experiences cold conditions, whereas Florida is also along a coast, but is much further south and has a warmer climate. While some difference in average degradation was expected, this drastic difference between locations was a surprising find, and motivated a further look into statistical correlations of individual features.

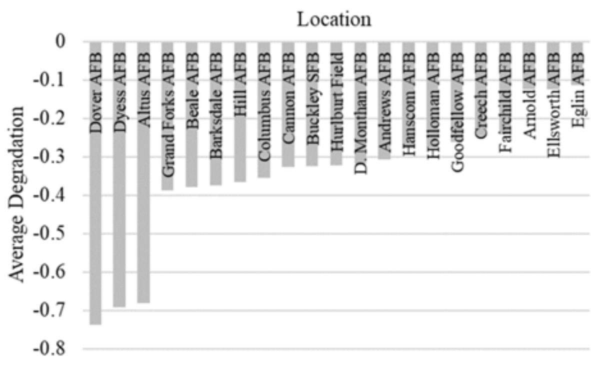

Fig. 3 Mean average degradation by location

When comparing the features individually to the average degradation, no significant correlation was observed (Fig. 4). The highest correlation to average degradation was with area code at 0.0758 and the lowest correlation was with longitude at

0.00248 (Figs. 4 (a) and (c), respectively). This finding of no significant correlation to any one variable was expected given most of the features used were constant for all observations within a given location. The implication of this finding is that no individual feature used in this study is a viable predictor of HVAC component degradation.

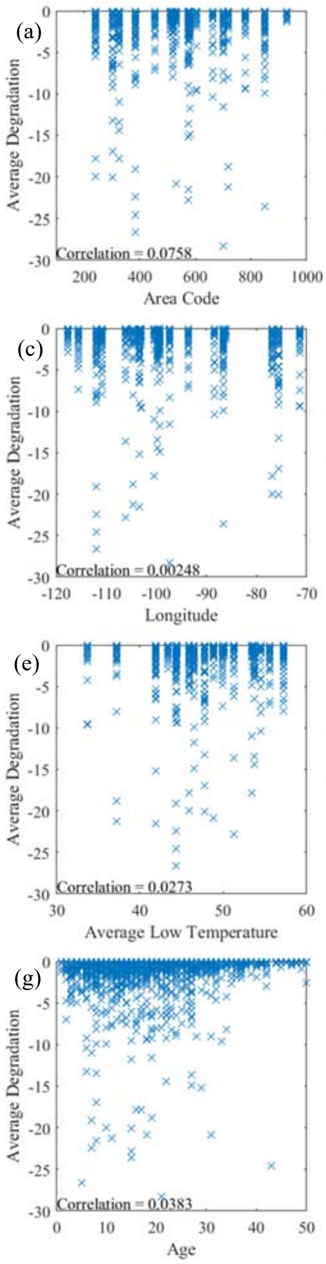

Fig. 4 Correlations between average degradation and (a) area code, (b) latitude, (c) longitude, (d) average high temperature, (e) average low temperature, (f) annual precipitation, and (g) age

B. Feature Weights

When NCA was employed, results varied depending on the selected loss function. The model employing the MAE loss function concluded that the most relevant feature was latitude, followed closely by average high temperature, age, and then annual precipitation (Fig. 5 (a)). NCA assigned non-zero feature weights to all seven features in this model indicating it was not able to reduce the feature space based on the noise in the dataset and the MAE loss function. The NCA model tuned with the ε-insensitive loss function produced a more decisive result. Results show feature weights equal to zero for six of seven features, with the most relevant feature towards predicting HVAC component degradation as longitude (Fig. 5 (b)).

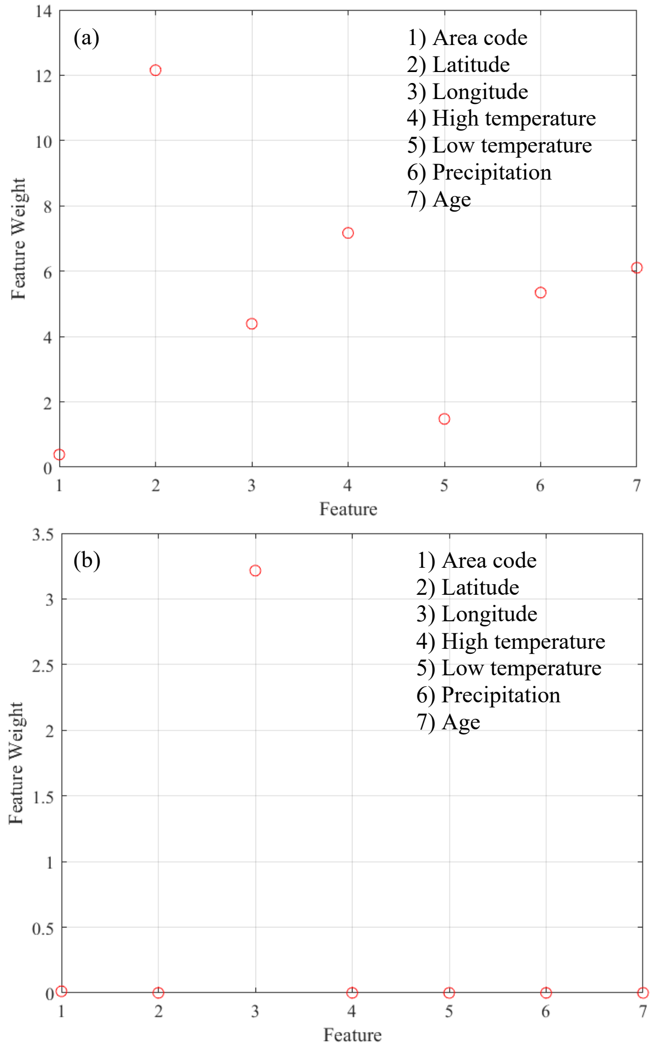

Fig. 5 Feature weights for each of the seven features using the model with (a) MAE loss function and (b) ε-insensitive loss function

As expected, neither model showed area code as an important predictor of average degradation. Age was the third leading predictor in the MAE model. While age may already be a consideration into maintenance, repair, and replacement decisions, results herein show that other factors should be considered as well. The leading feature relating to average degradation between the two models differed, but both are both related to geographic location. Given the literature review indicating various forms of environmentally-caused building material and infrastructure system deterioration, we expected that an environmental feature would have the highest feature weight, revealing it as the most important predictor of average degradation. However, it is hypothesized that latitude is related to other features not addressed in the study, such as freeze-thaw cycles, which were found to be key degradation factors in our literature review [3]. Similarly, longitude could be related to aridity, salinity, or other features not addressed in this study.

C. Model Predictions

The NCA model employing MAE attempted to fit all the datapoints, even the outliers, which resulted in overfitting (Fig. 6 (a)). The points in Figs. 6 (a) and (b) represent the actual average degradation for each observation and the lines represent the model's predicted average degradation. The NCA model employing the ε-insensitive loss function did not overfit but produced more consistent average degradation predictions across the dataset and missed variations in average degradation between observations (Fig. 6 (b)). Higher resolution datasets are required with more robust feature values to further investigate the models and ultimately tune and select the most appropriate one.

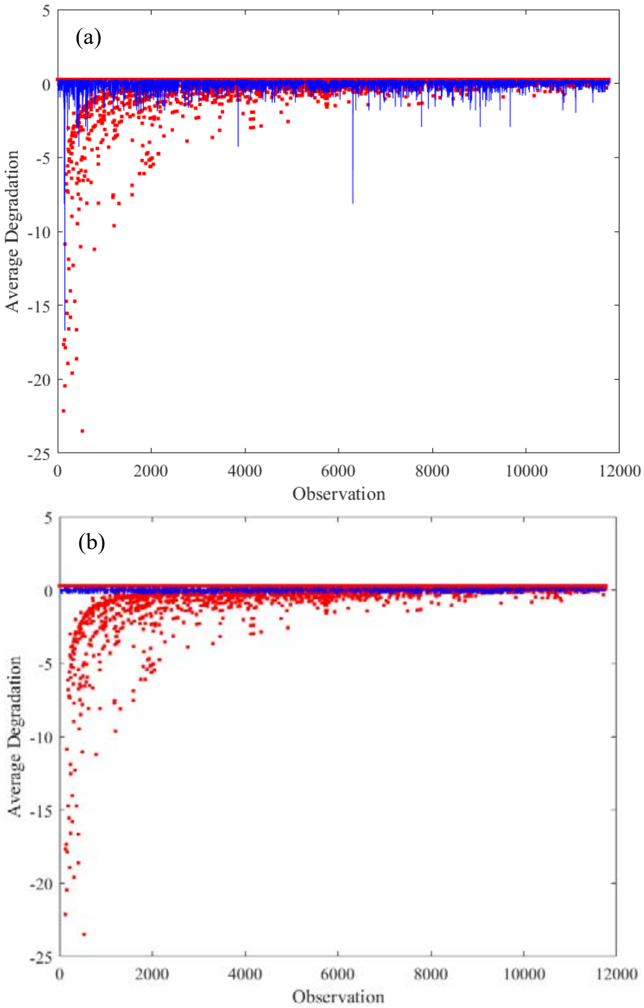

Fig. 6 Predicted average degradation for each observation using the model with (a) MAE loss function and (b) ε-insensitive loss function

V. Conclusion

Because HVAC systems are critical to Air Force and Space Force missions, causes of degradation are important to understand. This study utilized inspection data from seven types of HVAC components across 21 locations in the United States combined with seven features. Environmental-related features were average annual high temperature, average annual low temperature, and annual precipitation, while the four other features were not directly related to environmental conditions. No strong correlations between individual features and average degradation were found.

Two models employing NCA were built. One concluded that the most relevant features to HVAC degradation were latitude, average high temperature, age, and annual precipitation, while the other model reported longitude was the most relevant feature. Additional investigation into modeling techniques will be employed in future work to increase confidence in identification of the most relevant features that contribute to HVAC component degradation.

This work could be further expanded to include all HVAC components and other types of infrastructure systems using the same methodology. This study only considered exterior HVAC components exposed to the elements, but sheltered components could still be affected indirectly by environmental conditions such as high temperatures, where the HVAC system may run for longer durations causing an increase in degradation.

The preliminary results reported herein provide insights into the factors that cause HVAC degradation and motivate interest for more refined research. Future work will utilize additional environmental features. More importantly, instead of using average climate data over a 30-year range for each location, future work will incorporate actual weather data associated with the timeframe between infrastructure inspections. This increased resolution and feature space should yield much more actionable insights.

Disclaimer

The views expressed in this paper are those of the authors and not necessarily reflect those of the United States Air Force Academy, the Air Force, the Department of Defense, or the U.S. Government.

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