An Exploratory Investigation of Social Vulnerability from the Building Resilience Perspective

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ABSTRACT

Communities and cities are becoming vulnerable due to climate change-induced disasters such as heat waves, flooding, landslides, and droughts. The severity and increased frequency of these extreme events have demanded a resilience plan in the major cities to combat extreme weather events, which requires a systematic community vulnerability assessment. However, the specific impact of extreme events such as high heat waves on community vulnerability has been difficult to measure due to the unpredictability of weather patterns and events. Further, compounding the effects of building and built environment characteristics, the social and behavioral characteristics of households can result in differing levels of vulnerability to extreme temperature events. Even though many studies have discussed social vulnerability based on community demographics, the compounding effect has not been fully explored. When it comes to thermal resilience against extreme weather events, socially vulnerable communities are more likely to be affected by extreme heat due to a lack of thermal-resilient houses. In this research, Kolmogorov-Smirnov (KS-2 test) test was used to extend the relationship between building features data and the social vulnerability index of the city of Philadelphia. The outcome of this research strengthens our understanding of how social vulnerability and building resilience are correlated, also in the future to build community prototypes that integrate building features and social vulnerability to simulate community response against extreme weather events.

KEYWORDS: Social Vulnerability; Building Resilience; Energy Sustainability; Data Analysis

INTRODUCTION

Due to extreme weather and weather-induced events, resilience is getting significant attention among practitioners, scholars, and policymakers. Communities are becoming vulnerable due to climate-induced unpredictable extreme weather making some cities unlivable (Salimi and Al-Ghamdi 2020), which can add strain to the current energy infrastructures and critical urban infrastructure that should be resilient to extreme weather; the probability of extreme weather event occurrences is increasing due to climate change in recent years. The climate projections coupled with social vulnerability should be a consideration for the infrastructure designs because households with low economic, minorities, and households with younger residents are likely to be impacted differently (Coleman et al. 2020). The equitable resilience approach in infrastructure systems is needed in order to prioritize investments and reduce the risk of disparity of vulnerable populations' service disruptions caused by extreme weather (Chen et al. 2022). The growing threat of climate change and extreme weather events have forced the community to have a resilience plan. At the same time, populations are not uniformly vulnerable to climate change because vulnerability is largely social and economic, not merely a matter of different exposure to climate-related hazards (Thomas et al. 2019). Two communities even if they are geographically close can experience vastly different impacts based on their socio economic structures. In addition, access to resources is one critical factor that shapes communities' ability to plan for and respond to the impacts of climate change. Often, it's the socially vulnerable communities already grappling with economic constraints, that lack the resources to effectively plan for resilience.

The U.S. Department of Energy (DOE) defines resilience as "the ability of the system to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents" – resilience metrics are more useful for capturing the impacts of singular, infrequent large-scale events, like hurricanes, earthquakes, and terrorist attacks, that result in long-term electricity outages (Maguire, 2021). Further, US Federal Emergency Management Agency Defines social vulnerability as "the susceptibility of social groups to the adverse impacts of natural hazards, including disproportionate death, injury, or loss, or disruption of livelihood" (National Risk Index, 2023.). Drawing from these definitions, it is evident that while individual vulnerabilities might be influenced by various socio-economic and physical factors, bolstering resilience can act as a protective barrier, mitigating the harshest impacts of such unforeseen events.

Various factors such as building features, and the social and behavior of households can influence their vulnerability to such extreme events (He et al. 2022). However, enhancing the resilience of individuals can alleviate the adverse effects of these events (Ulrichs et al. 2019).

Socially vulnerable communities are more likely to be affected by extreme events such as heat waves due to the lack of disposable resources and services, such as buildings, that can cope with unpredictable scenarios. So, socially vulnerable communities need strategic policies in response to extreme events such as heat waves (Guardaro et al. 2022). Policies and practices that aim to enhance energy systems and promote the adoption of sustainable technologies can play a critical role in building resilience and reducing the impact of extreme events on socially vulnerable communities (Balogun et al. 2020). The promotion of passive homes with proper insulation can lead to better thermal performance of the buildings to respond to heat and cold stress (Omrany et al. 2016). Similarly, leaky envelopes may negatively influence a building's resilience. Building resilience can contribute to positive social outcomes, such as improved health and well-being, increased access to education and economic opportunities, and enhanced community cohesion. The misalignment in the planning of resilience can lead to increased health risks and the likelihood of economic, social, and physical disruption. So, studying the integration of social resilience and building resilience should get more attention. There are still gaps in our understanding of the relationship between social and building resilience, such as the question about how the built environmental characteristics and social vulnerability indexes are correlated. This relationship can forge to further identify effective strategies for building resilience in different contexts and communities. Further, more strategic attention is needed to the social implications of different resilience strategies.

METHOD

The objective of this study is to explore whether building characteristics in communities with different social vulnerability levels have significant differences. To achieve this, the data analysis technique KS test is employed. The data analyzed in this research are obtained from the Centers for Disease Control and Prevention (CDC) and Zillow- a real estate marketplace company. Philadelphia County is selected for this study due to the overall high level of vulnerability as per the CDC interactive map. The authors obtained building features data from Zillow and social vulnerability index data from the CDC.

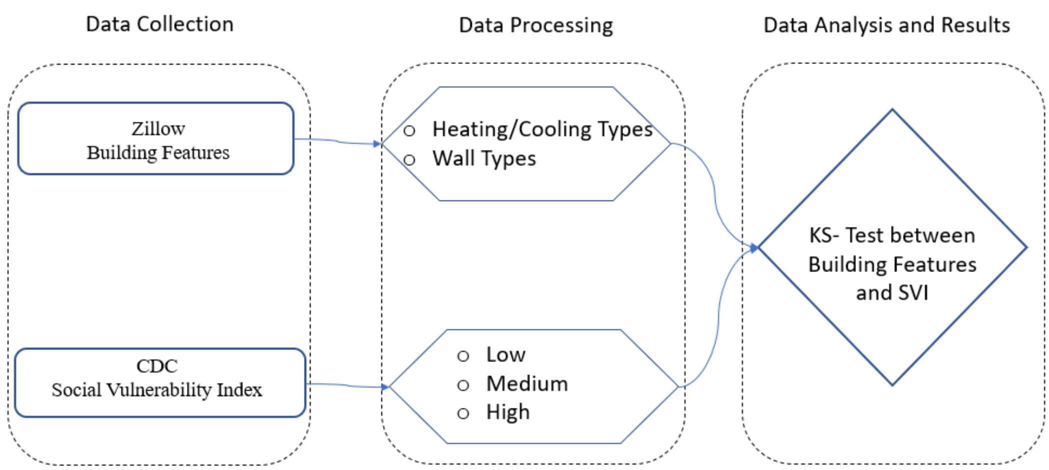

Figure 1: Methodological Framework Used to Explore Building Characteristics and Social Vulnerability

Data obtained from Zillow is sorted per the census tract, then the number of key building characteristics such as stories, rooms, areas, heating/cooling types, and building envelopes per the census tracts are counted. The FIPS code 42101 with a total census tract of 363 regions is studied. Based on the Zillow data, the county has 400446 households (Zillow, 2020). Then, we further processed to identify the number of key building block features. Heating/cooling system and building envelope building features data are sorted into a few distinctive categories using their functional attributes as shown in Table 1 and Table 2. These features intrinsically represent building characteristics that have a significant impact on indoor thermal comfort. In addition, areas are grouped into three categories below 1000 sq ft, between 1000 and 1500 sq ft, and above 1500 sq ft; then the number of each category as per the census tracts is recorded. In addition, heating/cooling types are grouped as central, zonal, etc., and wall types as brick, and concrete respectively as described in Tables 1 and 2. This grouping helps to characterize building features into the community scale rather than individual households.

For the Social vulnerability index, only RPL_Themes (overall percentile ranking of SVI data) is considered as it ranks the overall vulnerability. The RPL_Themes obtained from the CDC dataset combines percentile ranking of each themes such as socioeconomic status, household characteristics, racial and ethnic group, housing type, and transportation. The vulnerability group of low, medium, and high are divided based on the percentile of RPL_Themes as shown in Table 3.

Table 1: Heating/Cooling Types Obtained from Zillow Data

Heating/Cooling Systems	Description
Central type (HVAC_CT)	Central, Forced Air, Forced Wall, Vent, FA/FL
Zonal HVAC (HVAC_ZN)	Zone, Baseboard, Partial, Space/Suspended, Radiant, Convection, Stream Heating, Wood Burning

Table 2: Wall Types Obtained from the Zillow Data

<table>
<tr><td colspan="2" rowspan="2">Wall Types</td><td colspan="2">General Thermal Properties</td></tr>
<tr><td>Thermal insulation</td><td>Thermal mass</td></tr>
<tr><td>Wall_BR</td><td>Brick, Brick Veneer</td><td rowspan="2">Brick walls are normally combined with insulation layers. Comparatively, concrete walls generally have a lower thermal resistance</td><td rowspan="2">Both brick and concrete materials have high specific heat capacity, while the overall thermal mass of concrete walls is relatively higher because of the thickness and density used in concrete construction.</td></tr>
<tr><td>Wall_CT</td><td>Concrete Block, Concrete</td></tr>
</table>

Table 3: Overall Tract Percentile SVI Ranking Obtained from CDC Data

Social Vulnerability	RPL_Themes based on Percentile Ranking
Low	0 – 0.33
Moderate	0.34 – 0.66
High	0.67 -1.0

The Kolmogorov-Smirnov (KS) test was selected. KS test is a non-parametric statistical test that compares two probability distributions to determine if they are significantly different from each other (Kolmogorov–Smirnov Test, 2008). The KS-2 sample test is a version of the KS test that is used to compare two samples to determine if they are significantly different from each other. In addition, the KS test does not make any assumptions about the underlying distribution of the data, and it does not require that the data be normally distributed or that the variances be equal. The test statistic for the KS-2 test is also the maximum distance between the two empirical distribution functions (ECDF) of the two datasets ECDFs, and the p-value is determined by comparing this statistic to a critical value from a reference distribution. The KS-2 test is conducted for building features obtained from Zillow data on a county scale but not by individual buildings.

RESULTS AND DISCUSSION

Building Characteristics Description. Prominent building features such as building envelope, heating and cooling systems, areas, stories, etc collectively define the building characteristics. As for building envelopes, more than 92% of households have a brick or similar thermal conductance material in their building envelope in the Philadelphia region, as shown in Figure 2. Furthermore, based on the Zillow data, only less than 1% of homes don't have any type of heating system. Most of the houses have some type of heating/cooling system as shown in Figure 3.

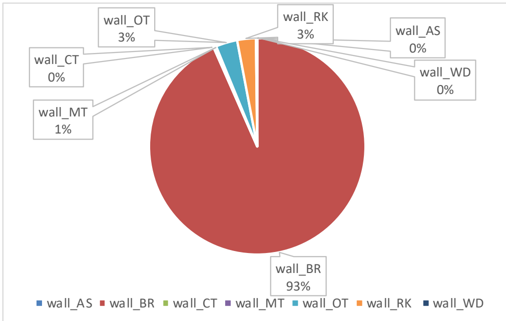

Figure 2: Types of Wall Distribution Obtained from Zillow Data

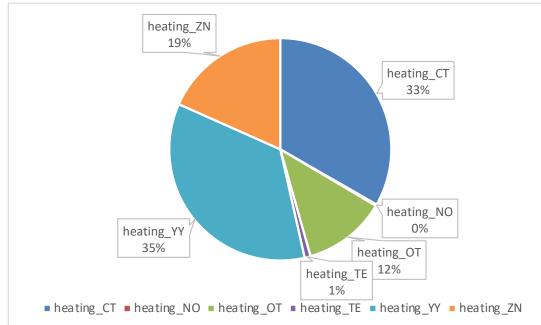

Figure 3: - Heating Types Distribution Obtained from Zillow Data

Other key attributes considered for the analysis are the years in which buildings were constructed originally. The clustering distribution is for the 10-year range except for the year_1979 and year_2010. For example, Year_1989 represents houses constructed between the years 1979 and 1989 representing 10 years of timeframe. In addition, Year_1979 and Year_2010 represent all the dwellings constructed before 1979 and after 2010 respectively. The distribution of the number of dwellings constructed in years is shown in Figure 4 based on the low, moderate, and high vulnerability index. Low, medium, and high in the below figures represent the number of dwellings in the respective SVI group.

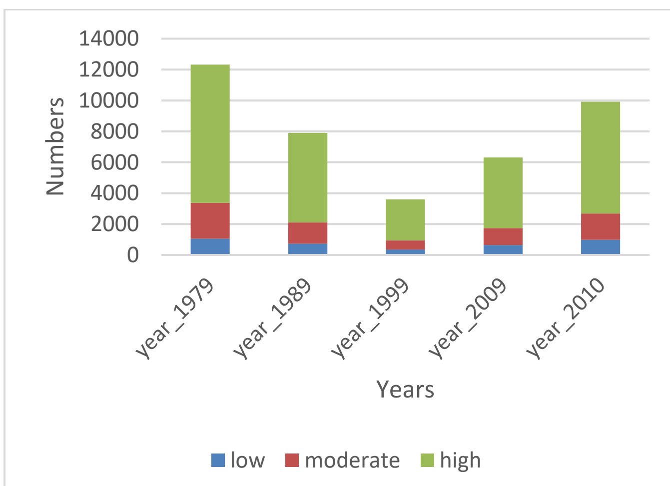

Figure 4: Number of Homes Constructed Based on The 10-Year Range Distribution.

Socially vulnerable index distribution

Philadelphia County is selected for this research. For Philadelphia county, SVI themes of 11% of low, 17% of medium, and 72% of high vulnerable groups are represented based on the

CDC data. Furthermore, for this study, the individual index such as unemployment, poverty below 150%, age, etc. are not individually analyzed with building features rather the overall themes index is used to classify census tracts information into the low, medium, high vulnerable group to derive a relation between building features and social vulnerability index.

The Kolmogorov-Smirnov (KS-2) Test. The KS-2 test is selected to derive a relationship between building features and the socially vulnerable index. The value of the statistic obtained from the KS-2 sample test indicates the maximum vertical distance between the two cumulative distribution functions (CDFs) being compared. In general, the larger the statistical value, the more different the two CDFs are. A small p-value (typically less than 0.05) indicates strong evidence against the null hypothesis and suggests that the observed difference in distributions is not due to chance and is statistically significant as shown in Figures 5 to 9. In contrast, a large p-value (typically greater than 0.05) indicates weak evidence against the null hypothesis and suggests that the observed difference in distributions is due to chance and is not statistically significant. The results discussed in below Figures 5 to 9 don't encapsulate all the results but carefully selected results to demonstrate the KS-2 test significance between building features and the social vulnerability index. Building features such as stories, rooms, areas, heating/cooling systems, and building envelope characteristics and their correlations/significance with respect to social vulnerability are discussed below.

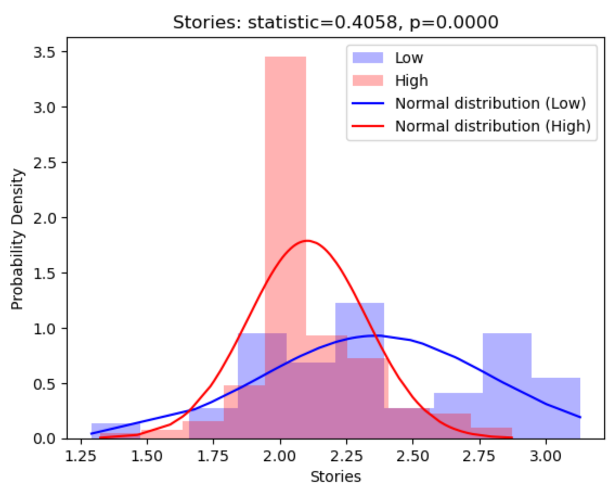

Figure 5: KS-2 Sample test of Stories between low and high-vulnerable group

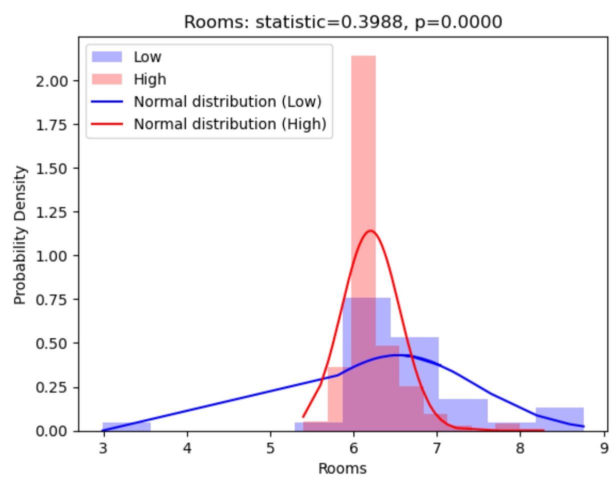

Figure 6: KS-2 Sample test of Rooms between low and high-vulnerable group

Figure 5 shows that low-risk areas have significantly (p-value < 0.005) high stories compared with high-risk areas whereas the higher vulnerable group had less number of rooms in their homes compared with the group with low vulnerability. In addition, Figure 6 reveals a (p-value < 0.005) relationship between rooms and vulnerability where the number of rooms decreases with an increase in vulnerability. In Figure 7, p-value < 0.05 signifies high vulnerable group has less square footage of the building, specifically less than 1500 sq ft compared to the low vulnerable group.

A whole house heating and cooling system can improve a building's resilience to extreme weather. For instance, by maintaining a comfortable indoor temperature, a central heating system can make a building habitable even during harsh winter conditions. This is particularly critical in buildings housing vulnerable individuals, such as the elderly or those with certain health conditions. Figure 8 clearly illustrates a marked difference (p-value < 0.05) in the usage of central HVAC systems between groups with high and low vulnerability, particularly in regions with lower system utilization rates. Areas with high vulnerability are associated with significantly less frequent use of central HVAC systems compared to their low-vulnerability counterparts.

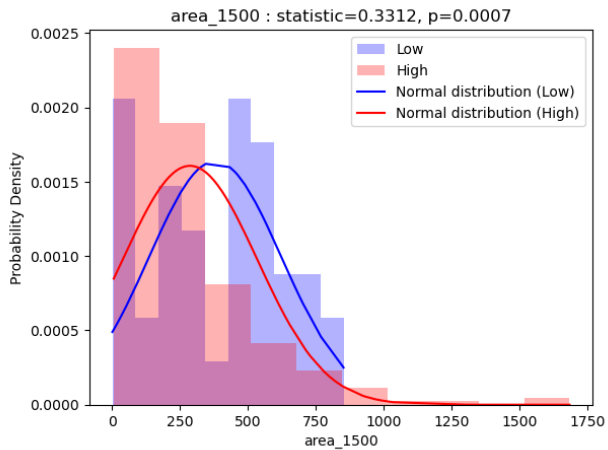

Figure 7: KS-2 Sample test of areas of residential units larger than 1500 sq ft between low and high-vulnerable group

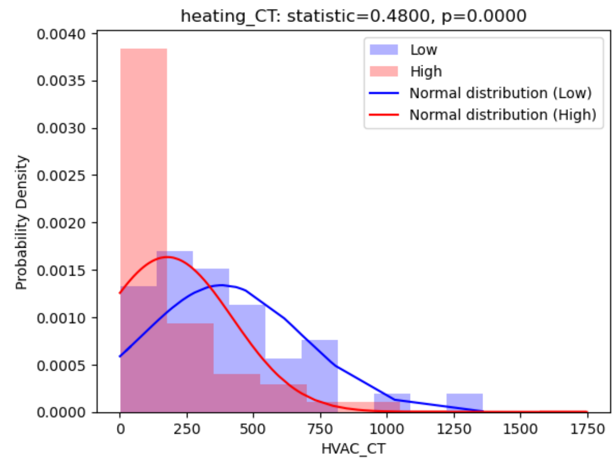

Figure 8: KS-2 Sample test of HVAC_CT between low and high-vulnerable group

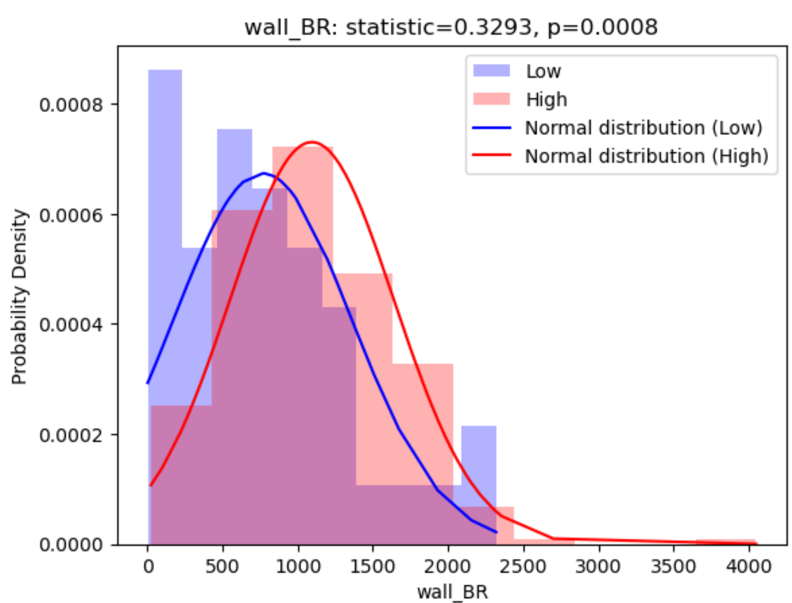

Figure 9: KS-2 Sample test of wall_BR between low and high-vulnerable group

Table 2 above demonstrates that brick walls are typically built with substantial insulating layers. These layers potentially enhance a building's thermal resilience to external weather conditions and alleviate the risk of overburdening indoor HVAC systems during extreme temperature events. Figure 9 reveals a statistically significant difference (p-value < 0.05) in the usage of brick wall construction between high and low-vulnerability groups. In comparison, groups with high vulnerability tend to have fewer instances of brick-wall construction.

Based on the KS-2 test, the relationship between SVI and building features such as rooms, stories, areas, heating types, and wall types is significant. Furthermore, the low-vulnerability group tends to follow the larger rooms/home size, and thermally resilient homes with better-performing heating/cooling types and wall types compared to high-vulnerable groups that have smaller room sizes/areas, and less resilient homes and cooling systems.

CONCLUSION

With the increasing frequency and magnitude of extreme heat waves, it is critical to systematically assess community vulnerability for effective resource allocations and preparations to improve community resilience. Even though many studies have discussed how building social vulnerability and building features are related, few studies have discussed the compounding effect. Further, the vulnerable group located in thermally good or poor conditions buildings can cause significantly different outcomes during extreme weather conditions. To fill the existing gap with the compounding effect, this paper collected Zillow data representing building characteristics and CDC data representing social vulnerability index in the Philadelphia region to analyze the compounding effect by employing the KS-2 test to analyze whether building characteristics have significant differences in different SVI levels. We found that building areas, building stories, number of rooms, heating types, and external wall types all have a significant difference in low-risk and high-risk areas, while the difference between low and medium-risk areas, and the difference between medium and high-risk areas are not significant. The findings of this research help to bridge the gap in our understanding of how social vulnerability and building resilience are correlated, the outcome of this research can be used in the future to build community prototypes that integrate social and physical features (building) to simulate community response against extreme weather events. Based on the simulation results, policymakers can develop a comprehensive and integrated approach that takes into account the interrelated factors that contribute to vulnerability and resilience to forge synergy between building and social resilience. A few limitations still exist in this paper. First, we only analyzed the Philadelphia region, the generalization of the outcome needs further justification. Second, the quality of data obtained from Zillow may or may not represent the current state of buildings in the region. Further, the vulnerability index term used in the paper only repress the social vulnerability but not other types such as vulnerability to the her events.

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Data provided by Zillow through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at http://www.zillow.com/ztrax. The results and opinions are those of the author(s) and do not reflect the position of Zillow Group

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