Cost-Effective Detection of Multi-Family Housing-Related Health and Safety Standards

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WHEDco
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Executive Summary

This HUD-funded study on advancing the basis for cost-effective detection of multi-family housing-related health and safety hazards took place between October 2013 and January 2017. Its primary objective was to test the efficacy of integrated laser scanning and thermal imaging for assessing housing-related health and safety hazards. Secondary objectives included comparing this new method to conventional approaches and identifying adoption pathways. We explored minimally intrusive strategies for incorporating this cost-effective method into conventional practices for managing building-related health hazards, through consultation with an industry advisory group and as informed by comparison to conventional facility condition assessment.

This research was conducted by a multidisciplinary team of researchers from Rutgers University blending knowledge of (1) building environment health concerns and decision-making behavior, with (2) the evolving science of air quality hazards, and (3) technological systems toward cost-effective identification and mitigation of health and safety threats to affordable housing occupants. Clint Andrews is an engineer and urban planner with deep knowledge of green buildings and building system innovation. Gediminas Mainelis is an expert in aerosols and in assessing exposure to indoor air pollutants. Jie Gong contributes expertise in building science and technology, particularly in the areas of Building Information Modeling (BIM), structural forensics, remote sensing, data fusion and visualization, and pattern recognition. Other team members include Jennifer Senick, an expert in green building including in property management, and building codes and standards; MaryAnn Sorensen Allacci, a specialist in community-based collaborative research, affordable and sustainable housing design; Deborah Plotnik, a trained architect working in communities that have experienced community and building structural disruptions as a result of natural disasters. Additionally, several graduate students across three disciplines made substantial contributions to this project, while our housing development partner, WHEDco (Women's Housing and Economic Development Corporation), provided important contextual information, site access and a reality-check as to the suitability of our research design and its implementation.

This study was designed and implemented as a multiple site case study participatory evaluation of building-based health and safety hazards. The majority of data collection took place in and around two buildings in the Bronx Borough of NYC owned and operated by WHEDco. A period of laboratory calibration and validation at other (university-owned) sites preceded fieldwork at the selected study sites.

Our main finding concerns the relationship between missing insulation and particle penetration from outdoors to indoors. We found a clear and significant correlation between the concentration of airborne particles and the indoor/outdoor ratio of those particles, meaning that higher (I/O) rations were found in apartments with higher percentages of missing insulation. Additionally in apartments were residents reported mold, higher amounts of insulation were missing. Because the measured concentrations of airborne particles proved to be significantly correlated with residents' asthma reports, we conclude that building defects such as missing insulation have a direct effect on the residents' well-being.

This field study demonstrates that the proposed method for low-cost detection of housing hazards is able to generate systematic measures to gauge the performance of the building and individual apartments and that the rapid scanning of building performance via infrared thermography and laser scans correlate with other data streams such as indoor air quality data and questionnaires. The integration of the different data streams allows developing a more complete picture of building performance and residents' health.

Our main report is accompanied by the following Appendices:

Appendix A contains the BIM models of the two study buildings.
Appendix B is the reports by the building condition assessment consultant for the two study buildings.
Appendix C contains the building resident interview questionnaire.
Appendix D includes detailed findings and analysis of the data from three data streams: questionnaires, indoor air quality measurements and thermal imaging.
Appendix E includes data attributes for thermal imaging and laser scanning
Appendix F includes drafts of publications resulting from this project.

Study Need, Aims and Objectives

Study Need

This project addresses the need for the development of low-cost test methods and protocols for identification and assessment of housing-related hazards. It develops an approach that applies to the analysis of existing data and the generation of new data to improve knowledge regarding the prevalence and severity of specific hazards in low-income housing. The project also pursues more cost-effective means of informing efforts at integrated pest management, mold and moisture control, and indoor air quality including infiltration of ambient air pollution.

It is estimated that millions of home occupants in the United States are exposed to moderate or even severe health and safety hazards such as roofing and other structural problems, heating and plumbing deficiencies, leaks, and pest problems that are associated with a wide range of health issues from injuries to respiratory illnesses (Joint Center for Housing Studies of Harvard University 2016). Housing-related environmental health hazards may exist in the full range of housing quality conditions, from those structures that are new and / or well-constructed and maintained, to those buildings that lack substantially in many of the basic protections for health and safety. Several types of housing deficiencies can pose both overt and subtle health hazards, particularly in urban communities, where the lowest-income residents living in areas of disinvestment have few options for quality housing and building owners may have limited resources. The structural integrity of buildings, for example, can affect habitability and housing stability and therefore residents' opportunities to establish a "home base" from which they may raise healthy families, provide for adequate nutrition and education, and participate in health and social networks that help link people to physical and psychological well-being. Other physical deficiencies related to health hazards include inadequate heat and ventilation, concentrations of toxic chemicals in indoor air, and biological agents such as mold conditions, rodents, and roaches that have been linked to asthma exacerbations and other respiratory and cardiac conditions (Jacobs 2011, Reponen, Lockey et al. 2012).

Current Practices for Identifying and Mitigating Housing-Related Hazards

The U.S. Department of Housing and Urban Development (HUD), the White House Council on Environmental Quality (CEQ), the Environmental Protection Agency (EPA), the Surgeon General, and the Department of Energy have introduced, in 2013, a collaborative initiative entitled Advancing Healthy Housing—a Strategy for Action (HUD 2013). The program prompts federal agencies to support "pre-emptive actions" for reducing the number of US homes with health and safety hazards through five goals: 1) establishing recommendations for healthy homes; 2) encouraging adoption of such recommendations; 3) supporting workforce development to address health and safety hazards in housing; 4) educating the public about healthy homes; and 5) supporting research to inform and advance cost-effective measures toward healthy housing.
A few examples of resources that support this approach include HUD's Healthy Homes program, US EPA's Tips for Housing Managers and the NJ Department of Health Indoor Environments Program. A collaborative example, Integrated Pest Management in Multi-Family Housing, was developed by seven entities. In sum, guidance related to maintaining a healthier interior environment in a multifamily housing typically includes basic steps related to preventative maintenance and cleaning procedures.

With our previous HUD grant, we added to this body of best practices for multi-family building design and operation through a number of interventions to improve apartment-level Indoor Air Quality (IAQ) along with interventions to improve apartment-level energy efficiency. These best practices, when followed, are powerful tools for mitigating health-related hazards in residential structures. However, procedures for *identifying* and *characterizing* these hazards remain labor-intensive, time-consuming, and expensive. Standard practices depend heavily on residents to identify problems and bring them to the attention of building management professionals, who then must correlate complaints with likely sources and pathways before taking remedial actions. The need for improved characterization of sources and pathways of residents' exposures to environmental hazards within buildings and communities is especially widely noted (Jacobs 2011). Needed are tools and/or methods to assist in diagnostic tasks and in the planning of more effective interventions.

Building Diagnostics

There is an opportunity emerging as a side benefit from the recent focus on energy efficient buildings. That effort has spurred much research into the development of better energy simulation models. In particular, to better simulate the energy performance of existing buildings for identifying retrofitting strategies, many studies have looked into the integration of infrared thermography with 3D imaging methods such as terrestrial laser scanning or photogrammetric methods (Lagüela, Martínez et al. 2011, Wang, Cho et al. 2012). The integration of infrared thermography with terrestrial laser scanning produces three-dimensional thermography. However, current integration efforts are limited to superimposing infrared data on laser scanning data for energy efficiency applications. The integrated data still requires manual interpretation. We have recognized that the integration of terrestrial laser scanning and infrared thermography brings new opportunities for identifying and diagnosing various housing-related health and safety hazards; many of these hazards are interrelated or interacting threats to healthy living. However, the use of such an integrated approach to detect and control key housing-related health and safety hazards has not been studied to its full potential, while associated opportunities in reasoning, fusing, storing, and tracking housing-related hazard data with building information models (BIM) have not been explored. Also needed are visual pattern recognition methods for automated processing of 3D thermography data. Together, laser scanning, BIM, and infrared thermography can be deployed as part of a larger effort to improve existing methods for detecting and controlling key housing-related health and safety hazards and to inform decision-making as to how to address them.

Despite best efforts to comprehensively address housing deficiency factors that have been associated with poor health outcomes for low-income residents there remain important gaps in knowledge about how to mitigate some of the more intractable conditions while relying on relatively low budgets. Integrated pest management, considered safer than conventional methods that employ highly toxic pesticides, can be a time consuming and expensive undertaking as it requires thorough and careful inspection of virtually all exterior and interior building surfaces to detect openings or harborages where vermin might gain access to human residences. Similarly, building envelope, plumbing, or HVAC system faults can result in moisture accumulation in areas that are not generally visible to inspection and can result in harmful mold. Mitigation of the problem can require an extensive search to pinpoint the source sometimes associated with unnecessary tearing out of partitions or ceilings that can be disruptive and expensive. The methodology defined for this project seeks to substantially reduce the guess-work associated with identifying the locus of the problem and improve targeting for remediation.

Study Objectives and Tasks

The main objective of the Cost-Effective Detection of Multi-Family Housing Health and Safety Hazards study was to assess whether an integrated application of laser scanning and infrared thermography can improve identification of building related hazards and inform remediation in a cost-effective and non-intrusive manner. Our vision for using integrated laser scanning, BIM, and infrared thermography to overcome challenges in cost-effectively detecting and treating health and safety hazards in housing is that this approach: generates new data to assist in better understanding housing-related health and safety hazards; offers distinctions among the presence and behavior of hazards in various contexts or classes of housing; facilitates a comparison of the results of these technologies in assessing the hazards to more labor-intensive approaches; produces a new BIM-based database framework for recording, updating, and managing housing-related health and safety hazards; and informs best practices with regard to hazard assessment and control.

Main tasks of this research study included:

- Engaging a community-based partner in the Bronx, NYC to provide access to two high-rise multifamily low-income residential buildings for data collection.
- Developing participatory relationships with resident and professional advisory committees.
- Collecting sufficient quality building scans, indoor air quality samples and building resident interview data to validate integrated BIM, scanning, and infrared technology for detection of building related hazards and safety concerns.
- Validating scanning technology with conventional inspection methods and obtaining feedback and support by the professional advisory committee on the capabilities of our detection methods and to advance applications in the industry.
- Presenting results to study partners including the funder (HUD), at conferences and via peer-reviewed articles.

Execution of Project

Study Design

To meet the above-noted data objectives, the study was designed as a multiple site case study participatory evaluation of building-based health and safety hazards. A period of laboratory calibration and validation preceded fieldwork at the selected study sites. Data methods were intended to provide a systematic approach to collection and analysis of quantitative and qualitative parameters at two research sites. As with the previous HUD Healthy Homes grant, we partnered with WHEDco (Women's Housing and Economic Development Corporation) to access two of their high-rise affordable housing buildings as study sites: Intervale Green located in Crotona Park East of the South Bronx and Urban Horizons, formerly the abandoned Morrisania Hospital, located in the Bronx. Both buildings house low-income and otherwise vulnerable populations who are predominantly African American or Hispanic or Latino. Intervale Green was built in 2009 and contains 127 apartments. Urban Horizons was built in the 1920s and retrofitted in 2006 and contains 131 apartments. Further description of the buildings is located in Data and Findings. The BIM models for these buildings created during this study are located in Appendix A.

Research Methods

In order to develop an integrated housing-related hazard detection approach, we first developed a plan for integrating interview, scan & infrared images, IAQ, and also building archival data (building system plans and reports as available) as depicted in Figure 1. These combined data allowed the research team to (1) validate the accuracy of information through triangulation of methods, (2) identify areas requiring additional data collection, and (3) modify existing data collection methods to more effectively capture valid, reliable, and context-relevant information over the course of the project.

Specifically, laser and infrared scanning were used to collect infrared thermography and 3D point cloud data on existing buildings. 3D point cloud data was used to create BIM models for providing a systems view of a building facility to facilitate hazard identification. The integration of 3D point cloud data and infrared thermography data gives rise to spatially-resolved infrared thermography. We then developed an intelligent computing layer, consisting of visual pattern recognition methods, for facilitating the interpretation of 3D point cloud data, building information model data, and spatially resolved infrared thermography data. The visual pattern recognition methods are methods for detecting visual patterns relevant to safety and health hazards. The training of these visual pattern recognition methods relied on validation measures provided by the IAQ and interview data.

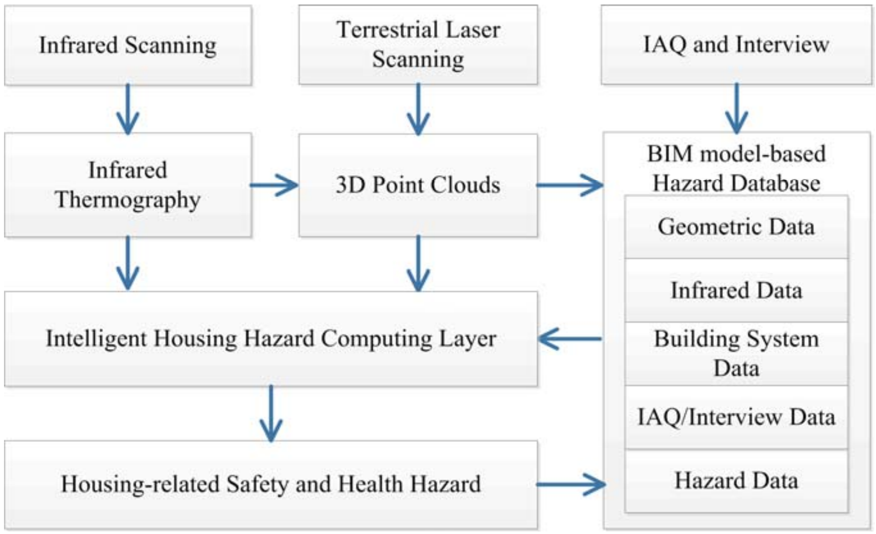


Figure 1. An Integrated Approach for Housing-related Hazard Detection and Management.

Infrared thermography, laser scanning, and sensor data fusion

To understand how infrared thermography and its integration with laser scanning can be used for detecting building hazards, in particular, those impacting occupants' health, it is imperative to draw connections between what can be measured from infrared thermography and what are considered as hazards to healthy homes. As a century-old concept, "Healthy Homes," promotes a safe, decent, and sanitary housing for preventing disease and injury that has received increasing attention nationally. HUD's Healthy Home Rating System (HHRS) was developed based upon the successful Housing Health and Safety Rating System (HHSRS). It can address key issues affecting health and safety due to conditions in the home, provides analysis of how hazardous a dwelling is and provides evidence and statistical information to assist assessors in making judgments. The HHRS provides a method for grading the severity of threats to health and safety in any dwelling, from house, self-contained flat/apartment, non-self-contained flat/apartment, a room rented in a dwelling or house, to a room in a university hall or similar residential building and the means of access and shared or common rooms and facilities. There are 29 summarized hazards listed in the HHRS Hazards Summary Chart across four categories including Physiological, Psychological, Infection, and Safety (Table 1) (HUD 2012).

Table 1. Healthy Home Rating System (HHRS) - Categorization of 29 Hazards.

Physiological	Psychological	Infection	Safety
1. Dampness & Mold 2. Excess Cold 3. Excess Heat 4. Asbestos and manmade fibers 5. Biocides 6. Carbon Monoxide 7. Lead-based paint 8. Radiation 9. Un-combusted fuel 10. Volatile organic compounds	11. Crowding and Space 12. Entry by Intruders 13. Lighting 14. Noise	15. Domestic Hygiene, Pests, and Refuse 16. Food Safety 17. Personal Hygiene 18. Water Supply	19. Falls in bath etc. 20. Falls on the level 21. Falls on stairs etc. 22. Falls from windows etc. 23. Electrical hazards 24. Fire hazards 25. Hot surfaces etc. 26. Collision/Entrapment 27. Ergonomics 28. Explosions 29. Structural collapse

A close examination of the above table and the capabilities of infrared thermography as reviewed in the Relevant Work section suggests several connections. These connections are summarized in Table 2. These detectable defects are quantified using metrics proposed by previous studies and building rating standards. In summary, a list of data that could be collected or computed is provided in Table 3. We assume that the units of analysis in this research are apartments in multi-story buildings.

Table 2. Connections between defects in building envelopes and home hazards.

Detectable Building Defects	Connection to Home Hazards
Moisture Issue	HHRS – Physiological: Dampness & Mold; HHRS – Infection: Domestic Hygiene, Pests, and Refuse
Thermal Insulation Problem	HHRS – Physiological: Excess Cold; Excess Heat
Air Infiltration	HHRS – Physiological: Excess Cold; Excess Heat; Carbon Monoxide; Volatile organic compounds
Thermal Bridge	HHRS – Physiological: Excess Cold; Excess Heat
R-value or U-value	HHRS – Physiological: Excess Cold; Excess Heat

Table 3. Data attribute list.

Attribute Type	Variables	Description	Value/ Unit
Apartment Location Information	Floor	The floor number of the apartment unit and the total floor number	(Number 1)/(Number 2) Number 1: apartment floor number Number 2: total floor number
	Corner	Describe the location of the apartment unit	1: in the corner 0: other
	Inner Garden	Describe the location of the apartment unit	1: face the inner garden

			0: other
Thermal Comfort	Real-time indoor air temperature	Describe the average indoor air temperature taken from moisture meter during data collection	Unit: °F
	Real-time indoor air relative humidity	Describe the average indoor air relative humidity taken from moisture meter during data collection	Unit: %
	Real-time thermal comfort level	Real-time thermal comfort level calculated from ASHRAE Comfort Zone	1: for in the cold area of comfort zone (Left side of the Comfort Zone) 2: for in the comfort zone (Inside of the Comfort Zone) 3: for in the hot area of comfort zone (Right side of the comfort Zone)
	Dew Point	Dew point temperature estimated from real-time average temperature and relative humidity	Unit: °F
Thermal Infrared and Scan Data	Temperature Factor - Thermal Bridge	The temperature factor of the thermal bridge area.	Unit: NA Higher value stands for better condition
	Temperature Factor- Air Leakage	The temperature factor of air leakage area	Unit: NA Higher value stands for better condition
	Missing or poor insulation area	Describe the area missing or poor insulation in square feet	Unit: Square Feet
	Missing or poor insulation percentage	Describe the percentage of the area missing or poor insulation out of the whole exterior wall of the apartment.	Unit: %
	Insulation Grading	The insulation grading calculated based on the Insulation Grading Standard designed by RESNET.	Insulation Grading Standards designed by RESNET Grade I: not infrared detectable anomalies; Grade II: insulation installed with anomalies found to be between 0.5 % and 2% for all inspected walls Grade III: An insulation installation having between 2% to 5% anomalies found for all inspected walls Worse than Grade III: The condition that

			insulation installation having more than 5% of the anomalies found for all the inspected walls
	Insulation Level	Describe the insulation level of the apartment unit when the temperature differences do not meet the requirement for RESNET Standard.	1: good condition 2: fair condition 3: poor condition
	Average R-value	The minimum R-value of the exterior wall area in one room in the apartment unit	Unit: $\mathrm{W/m^2K}$
	Hot Water Riser poor insulated	Whether or not the apartment has hot water riser poor insulated in the apartment	1: Yes 0: No

In Table 3, the temperature factor $f_{R_{si}}$ at the internal surface shows the relationship of the total thermal resistance of the building envelope (R_T, $(\mathrm{m^2 \cdot K})/\mathrm{W}$) to the thermal resistance of the building envelope without the internal surface resistance (R_{si}, $(\mathrm{m^2 \cdot K})/\mathrm{W}$) and can be calculated with measured internal surface temperature ($T_{s,in}$, °C), indoor temperature (T_{in}, °C) and outdoor temperature (T_{out}, °C) according to following Equation 8 (Hens 2008, Kalamees, Korpi et al. 2008)

$$\frac{R_T - R_{si}}{R_T} = f_{R_{si}} = \frac{T_{s,in} - T_{out}}{T_{in} - T_{out}} \quad (1)$$

For the temperature factor, several limit values or guidelines have been set. The following Table 4 lists the guidelines for temperature factor for the thermal bridge on wall base on the Finnish instructions regarding housing health (Kalamees, Korpi et al. 2008).

Table 4. Guidelines for the temperature factor for the thermal bridge on the wall.

Temperature Factor Range	Description
$f_{R_{si}}$<0.61	Includes healthy risks or hazards and should be repaired
$f_{R_{si}}$ 0.61 ~ 0.64	Possibility for health hazards or structure risks, the details/structure must be checked and repairing necessity should be classified
$f_{R_{si}}$ 0.65 ~0.69	Includes obvious hydrothermal defects or faults but fulfills the requirements of the housing health
$f_{R_{si}}$ 0.70 ~0.74	Fulfills of the requirements of the good level, no risks in dwellings with low occupancy
$f_{R_{si}}$ 0.75 ~0.80	Includes some risk in dwellings with high occupancy and low occupancy
$f_{R_{si}}$ over 0.81	Tolerable level

The R-value in Table 4 is estimated using Eq. (2). Its principle is that the overall heat transfer (Q) in the building environment can be described as the combination of thermal convection and radiation.

$$R = \frac{|T_{air,in} - T_{air,out}|}{\alpha_{convective} \times |T_{air,in} - T_{wall,in}| + \varepsilon \times \sigma \times |T_{wall,in}{}^4 - T_{reflect,in}{}^4|} \quad (2)$$

where ε is the surface integral emissivity, σ is the Stefan-Boltzmann constant # ($5.67 \times 10^{-8}\ W/m^2K^4$), $T_{wall,in}$ is the surface temperature of inside surface of the exterior wall and $T_{reflect,in}$ is the reflected temperature.

In this study, we have advanced the capability of infrared thermography in detecting and quantifying defects related to building hazards on two fronts: (1) developing a sensor fusion method to transform traditional infrared thermography into spatially resolved infrared thermography; and (2) developing an intelligent building hazard detection method based on spatially resolved infrared thermography. The detailed methodology to accomplish these objectives is shown in Figure 2. In the following, we provide a detailed description of each step.

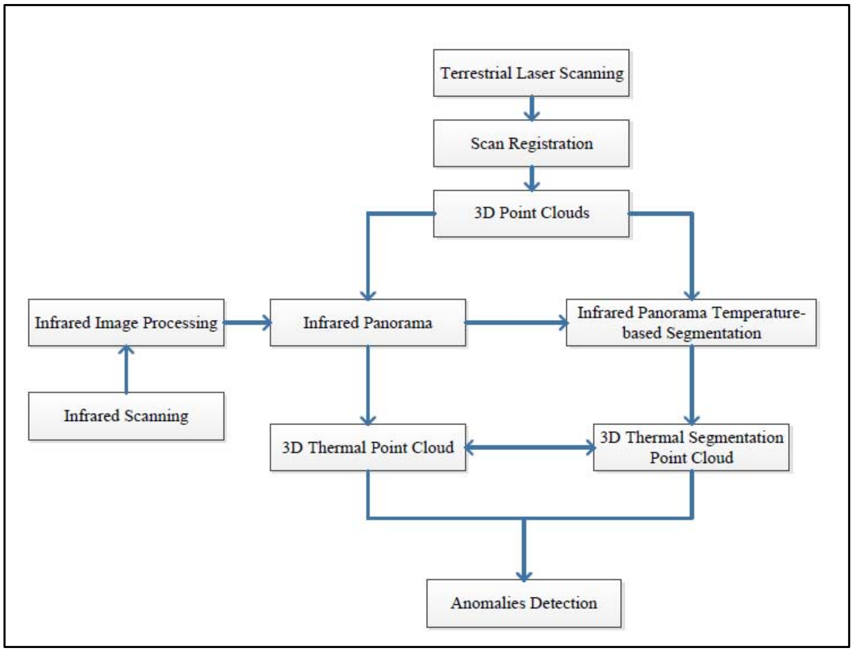


Figure 2. Generation of Spatially Resolved Infrared Thermography and Building Hazard Detection.

Infrared Scanning: Infrared thermography cameras are used to collect infrared images and co-registered RGB photos.

Terrestrial Laser Scanning: Terrestrial laser scanners are used to collect point cloud data of building structures. To provide sufficient 3d information of the building, one or more scans were collected per room (Figure 3).

Figure 3. 3D view of scanned living room and bathroom

Infrared Image Processing: This step involves converting infrared image data into a data matrix that preserves temperature information (Figure 4).

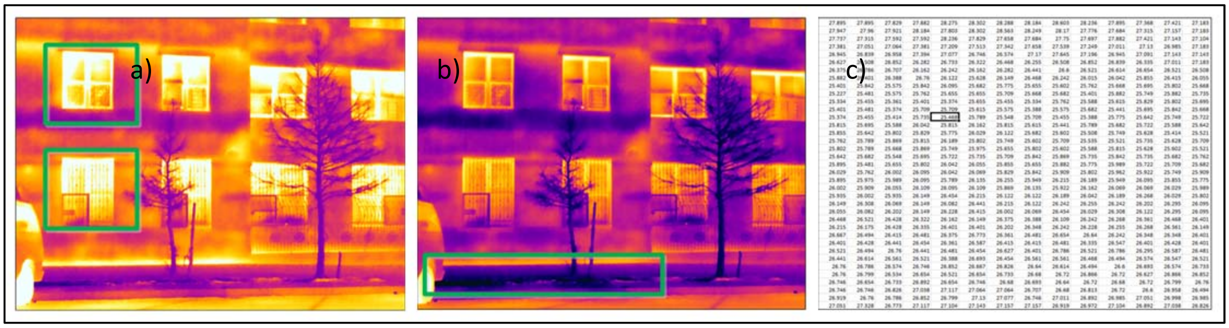


Figure 4. Same infrared image with different temperature scale and its temperature in the matrix (a: 23.2°F ~ 40.4°F; b: 31.8°F ~ 40.87°F).

Terrestrial Laser Scan Registration and output 3D point clouds: Scan data are processed into project point cloud data and registered into a common coordinate system.

Infrared Image Stitching (Panorama): This step involves stitching infrared images into a panoramic image that can later be used to project onto point cloud data. The steps for RGB image stitching include (1) Feature Detection: identify image features (2) Feature Description: extract feature descriptor for each feature (3) Feature Matching: find candidate matches between features (4) Feature Correspondence: find a consistent set of (inlier) correspondences between features. RGB image stitching usually has a problem with color correction and matching infrared images does not have this problem because the temperature of the same location usually stays constant during the inspection. Infrared images of the same location usually can be easily adjusted to the same color and can have a good match with each other even without color correction and matching. However, as shown in the infrared image processing step, infrared images may lose texture and pattern information with different temperature scales and temperature palettes. This could lead to difficulty in detecting image features useful for image stitching (Figure 5).

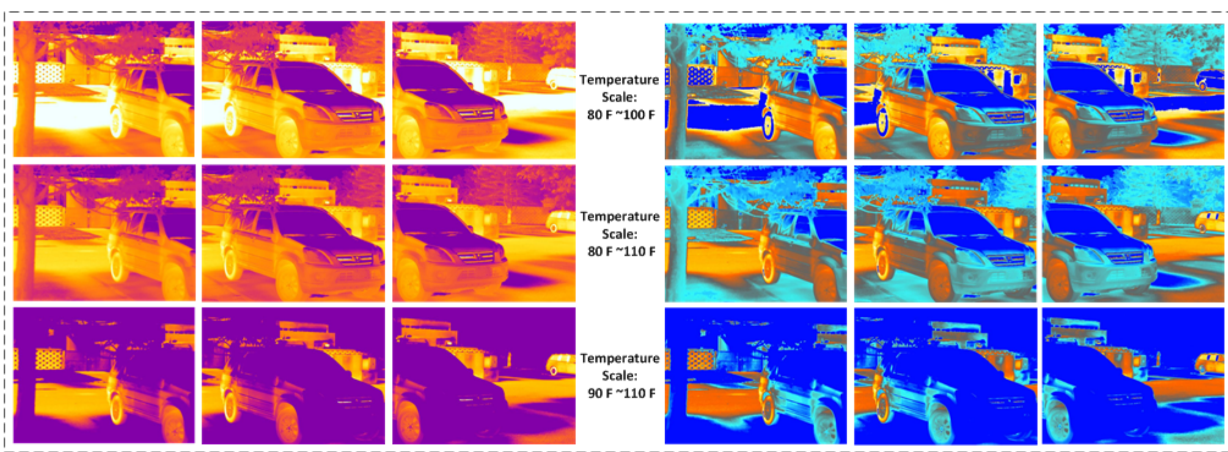


Figure 5. The effect of temperature scale and color palette on infrared images.

Figure 6. Feature points detected in three infrared images.

To address this issue, our approach tries different temperature scales and finds the best result in terms of a number of feature points, matched points, and inliers. Once the transformation between images with highest inliers was calculated, these images can be combined to form a panoramic image that can be transferred to any color scale and color palette with a fixed transformation (Figures 6 and 7).

Figure 7. Matched SURF points, including outliers.

The same approach can also be applied to indoor infrared images although interior infrared images usually have fewer feature points and inlier points. Figure 8 shows an example of combining several interior infrared images.

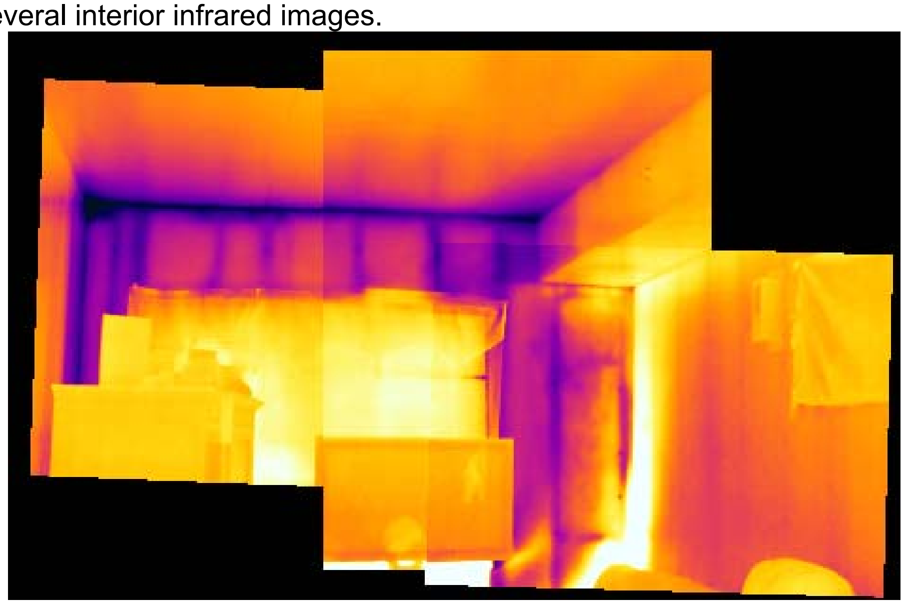


Figure 8. Automatic indoor infrared image stitching result.

Infrared Temperature-based Segmentation: In this step, panoramic infrared thermography data are segmented to isolate areas with homogeneous temperature distribution (Figures 9 and 10). We apply temperature based segmentation methods in contrast to threshold based methods ((Vidas, Moghadam et al. 2013), (Ham and Golparvar-Fard 2014)). Temperature based segmentation can isolate the areas with different temperature and lead to a better result. In this research, we applied the temperature based segmentation to both single infrared image and panoramic images. The results are shown in Figure 11.

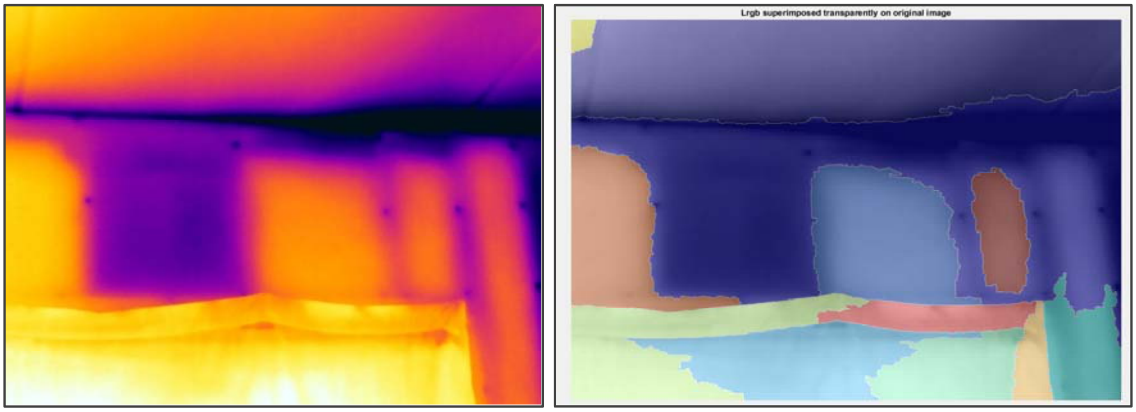


Figure 9. Infrared image and segmentation result.

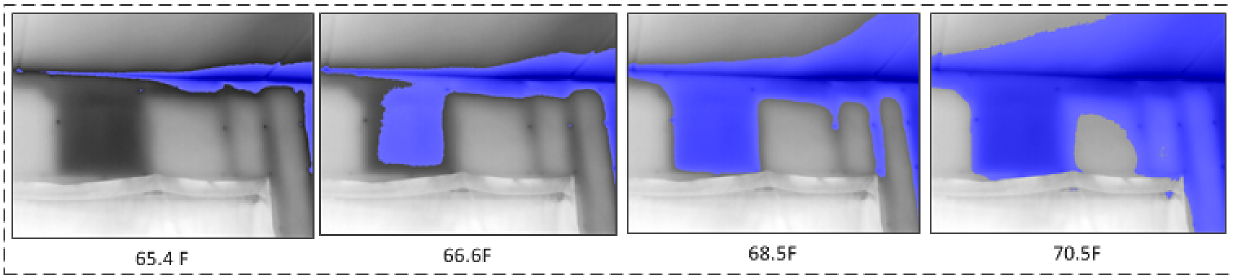


Figure 10. Infrared images with cold alarm (blue area means temperature lower than the threshold value).

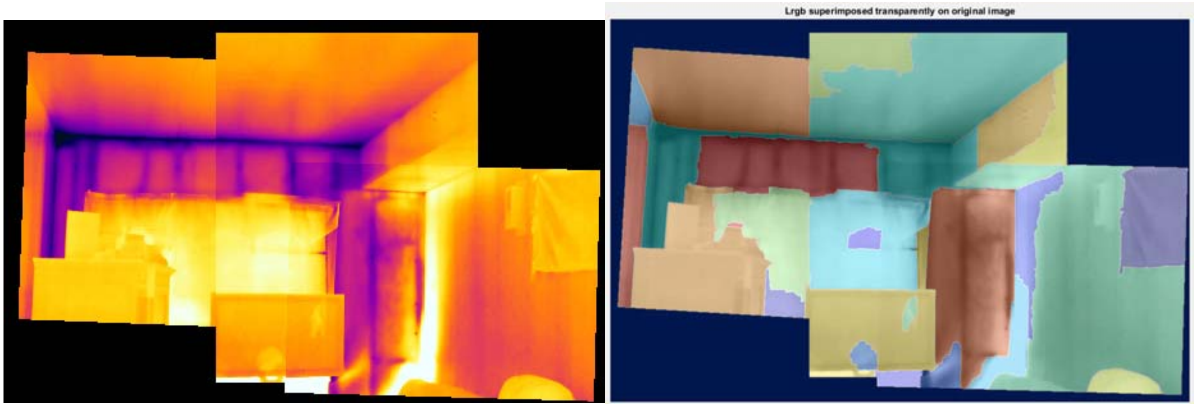


Figure 11. Indoor infrared image stitching and segmentation results.

Infrared and Infrared Segmentation Project to 3D Point Cloud: In this step, segmented infrared images are projected onto the 3D point cloud. The principle behind the projection is to identify common points in both infrared images and point cloud data and compute the transformation between infrared images and point cloud data. Figures 12 and 13 show 3D thermal models of one building and an apartment as the result of data projection. Since the infrared images are already segmented, this projection will lead to quick quantification of the size of different temperature areas (Figure 14).

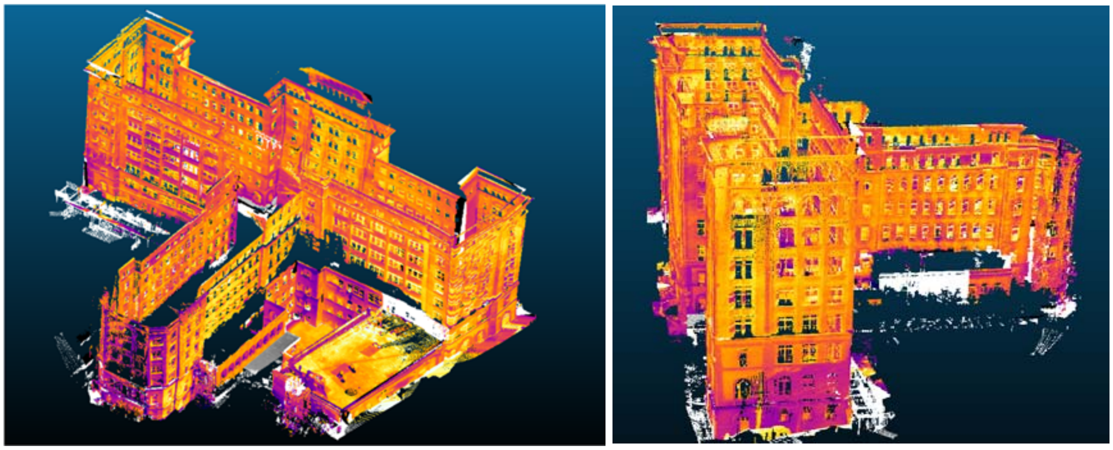


Figure 12. 3D thermal model of building exterior area.

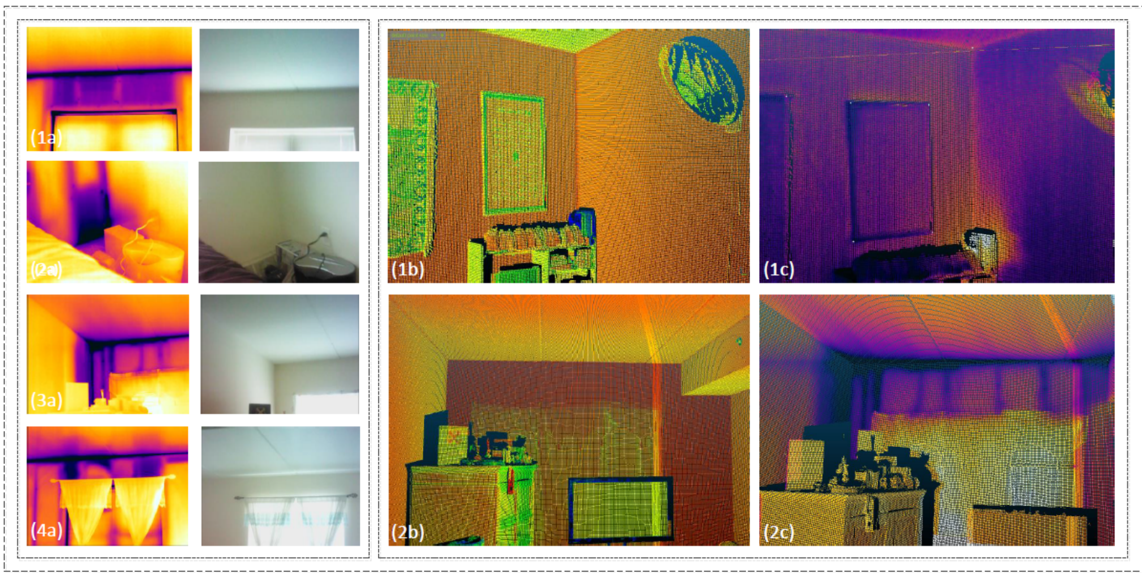


Figure 13. Raw data and 3D thermal point cloud. (a) Infrared thermography and digital images, (b) LiDAR point cloud, (c) 3D thermal point cloud.

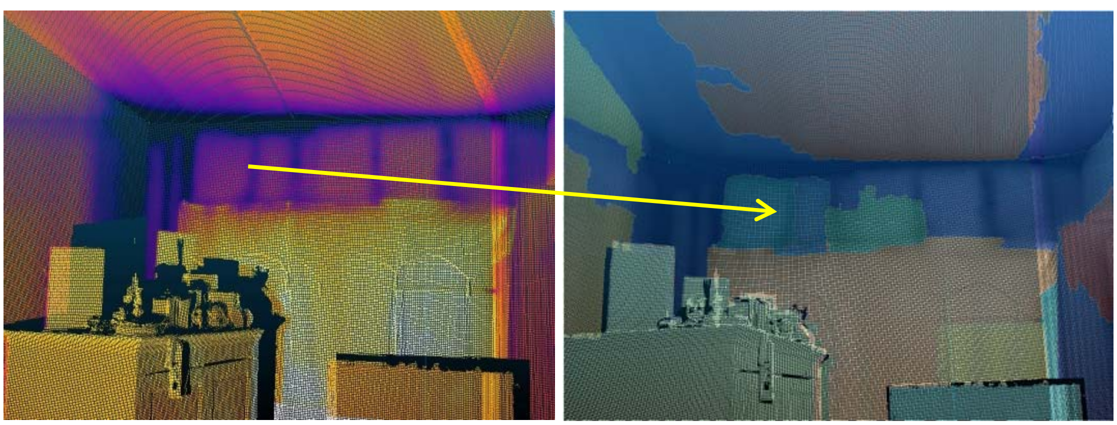


Figure 14. 3D thermal model and their paired 3D temperature-segmentation model.

Point Cloud Segmentation: The 3D thermography data analysis process can be further facilitated by conducting segmentation of indoor scan data. The purpose is to divide scan data into subsets corresponding to different structural elements. One segmentation method that can be utilized is the RANSAC-based segmentation method. Figure 15 shows the segmentation results for one sample living room. It can be seen that all the structure elements and furniture are clearly segmented and marked out with a different color. Based on the segmented 3D thermal model, all the attributes that are relevant to building performances can be calculated and estimated (Figure 16). These estimates become the basis for understanding the performance of buildings and the indication of indoor air quality problems.

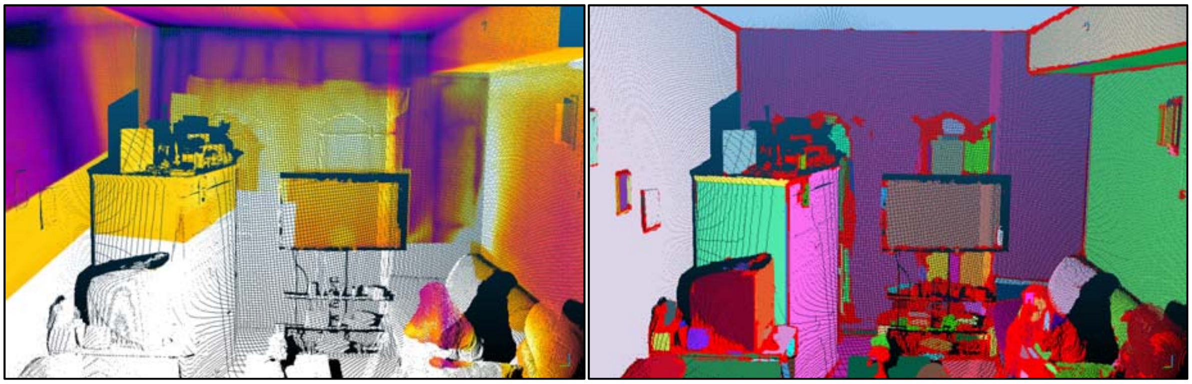


Figure 15. 3D thermal model and segmented 3D point cloud.

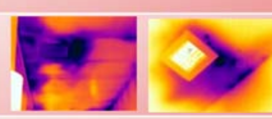
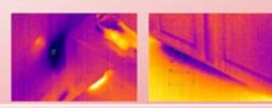
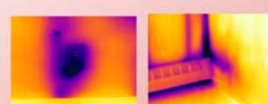
Defect Types	Description	Infrared Image	Quantification
Poor/ missing insulation	Missing or poor insulation areas appear as light/dark colored patches with distinct edges outlining the problematic areas.		1. Poor or missing insulation area (sf) 2. Percentage of missing insulation (%)
Wet insulation	Wet insulation is often temporary and usually appears as areas without distinct edges.		1. Wet insulation area (sf) 2. Percentage of wet insulation area (%)
Moisture	Moisture areas usually appear as dark/cool areas without distinct edges.		1. Moisture issue area (sf)
Air leakage / Air infiltration	Air leakage usually appears as light/dark areas in building corners or near structural joints.		1. Temperature factor (f_{Rsi})
Thermal bridge	Thermal bridges usually appear as light/dark areas with linear features as they are often related to structural components that penetrate the insulation layers.		1. Temperature factor (f_{Rsi})
Hot water Riser	Components of HVAC systems are not well insulated, causing elevated temperature in part of wall surfaces.		1. Hot water riser surface area (sf) 2. Hot water riser surface temperature (°F)

Figure 16. Extracted building hazard related defects.

Indoor Air Quality (IAQ) measurements

The measurements were performed in 31 participating households (15 from Building 1, 16 from Building 2). For all days when indoor measurements were performed, equivalent samples were taken outdoors. Temperature, relative humidity, carbon monoxide and carbon dioxide were measured and data logged using an IAQ-Calc Indoor Air Quality Meter 7525 (TSI Inc., Shoreview, MN), a direct reading instrument. This instrument has been specifically designed for indoor air studies. The concentration of airborne particulate matter was measured and data-logged using Dustrak DRX Aerosol monitor (TSI, Inc., Shoreview, MN). This instrument provided real-time measurements of airborne particle concentrations corresponding to PM1, PM2.5, PM10, Respirable (PM4) and Total PM size fractions. Airborne particle size distribution was measured using AeroTrak Handheld Particle Counter 9306 (TSI, Inc.), which measures particles in six size channels ranging from 0.3 to 10 μm. Total particle number concentration was measured using a P-Trak condensation particle counter (TSI Inc., Shoreview, MN), which counts all particles larger than 20nm in size. These direct reading instruments were operated for 45-60 min, and average values, as well as another statistic (min and max values, 5th-95th percentile range), were recorded.

Twenty-four-hr PM2.5 concentration was measured using an SKC Inc. (Eighty Four, PA) Personal Modular Impactor with 2.5 μm cut size and 2 μm pore size 37 mm PTFE filter (SKC Inc.). The required flow rate was provided by a small pump XR5000 (SKC Inc.) calibrated for the impactor's operating flow rate of 3 L/min. To collect a 24 hr sample, the impactor was mounted on a tripod, connected to a pump and left in each sampling location for 24 hrs. The collected particle mass and the corresponding mass concentration was determined by weighing each filter before and after sampling. Prior to weighing, the filters were equilibrated in a weighing room at a steady temperature (20-22 C) and relative humidity (40%) for at least 72 hours.

The concentrations of culturable bacteria and fungi in the air were determined by taking air samples with a portable SAS Super 180 air sampler (Bioscience International, Rockville MD). The sampler features a collection flow rate of 180 L/min and has been used in our previous studies (Yao and Mainelis 2007). The trypticase soy agar (TSA) and malt extract agar (MEA) were used as sampling media for bacteria and fungi, respectively. Antibiotics were added to MEA plates to prevent the growth of bacteria and fungicide was added to TSA plates to prevent the growth of fungi. After sampling, the agar plates were incubated at room temperature and after a given growth time (24-48 hours for bacteria and 48-72 hours for fungi) the resulting microbial colonies were counted, and the concentration of airborne culturable microorganisms was determined. Given the sampler's high collection flow rate and the risk that the collected organisms could desiccate (Mainelis and Tabayoyong 2010), sampling time was limited to 5 min for each sample. During each measurement, three consecutive samples for bacteria and fungi were taken.

The concentration of total fungi (includes culturable and non-culturable) were determined by taking air samples with an Air-O-Cell (Zefon International, Inc., Ocala, FL) spore trap operated at 15 L/min. Samples of 5 and 15 minutes were taken at each location. After sampling, the spore traps were sent to EMSL Inc. (Westmont, NJ), a certified laboratory, for speciation and quantification of the collected fungal spores. The measurement of total fungal concentration in addition to culturable is important because non-viable microbial particles are also known to cause negative health effects (Robbins 2000).

Interviews
We conducted individual interviews of building residents and of building owners/operators from June 2014 through March 2016 in accordance with IRB-approved questionnaires and human subject protocols. Individual resident participants from 31 households (15 from Building 1, 16 from Building 2) were asked about their perception of building quality, air quality in the building, comfort, concerns related to living conditions, household activities that could impact indoor air quality, and health problems such as asthma events and other illnesses. Questions about asthma included inquiries about asthma events in the household in the past 12 months and at any point (categorized as asthma – ever). The structured building resident interview guide appears in Appendix C.

Conventional Facility Condition Assessment. A final information source was a pair of reports commissioned as part of this project from a commercial provider of facility condition assessments. This consultant sent an expert assessment team to each building for one day and summarized their observations and recommendations in an independent 3rd party report.

Advisor Focus Groups. Additionally, at key points during the research, we convened and consulted a Professional Advisory Group. The advisors, drawn from the ranks of well-respected housing development and services firms, building science/energy/contractor firms and firms specializing in industrial hygiene allowed us to compare our work to best industry practices and to test the usability and acceptability of our methods and findings on industry practitioners and potential adopters. Over the course of the research, we worked predominantly with 3 advisors.

Data and Findings

In this project, three sources of data, including spatially resolved infrared thermography of building exteriors and interiors, indoor air quality data collected in building interiors and outdoors, and interview data of building residents, were collected and integrated to explore new ways of detecting building hazards (Figure 17). One important focus of this project was on testing whether the spatially resolved infrared thermography, a non-destructive and non-invasive building inspection method, can be indicative of indoor air quality issues discovered by indoor air quality sampling and resident interviews.

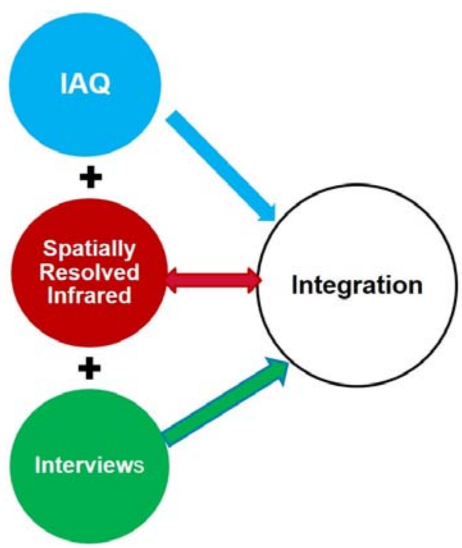


Figure 17. Data Collection and Analysis Framework.

The proposed data collection and integration framework were validated with two multi-family apartment buildings in Northeastern US (Figures 18 and 19). Building 1 was a historic building that was transformed from an abandoned hospital built in 1926. Today includes:

- 132 energy-efficient apartments, 39 of which are set aside for families coming out of New York City's homeless shelter system
- The Early Childhood Discovery Center, a Head Start program
- The Home-based Childcare Training Institute
- Family support services that link Bronx Residents to critical resources
- A commercial kitchen that incubates small food businesses
- The Urban Horizons Family Health Center, a healthcare center operated by the Institute for Family Health

Building 2 is one of the largest multi-family Energy Star certified buildings in the U.S. It includes:

- 128 affordable apartments, 39 of which are set aside for families coming out of New York City's homeless shelter system
- 85% efficient boilers and hot water heaters, low-flow faucets and showerheads, green roof, including a roof garden, Energy Star appliances/fixtures, and energy-efficient windows
- Nontoxic building materials and finishes
- Half an acre of green space, including over 40 new landscaped street trees and a rooftop farm.
- Art installations that promote environmental conservation
- Active Design elements that encourage residents to take the stairs, e.g., signs such as "Burn calories, not electricity."

Figure 18. The site of Building 1.

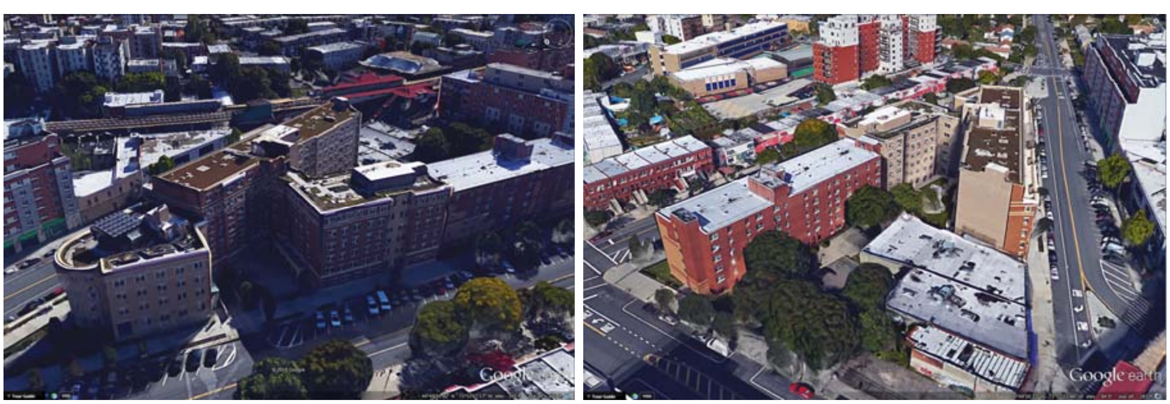


Figure 19. The site of Building 2.

Spatially Resolved Infrared Thermography Data

In this research, one FLIR T650sc infrared camera (FLIR Systems, Inc., Boston, MA) and one Faro terrestrial scanner (FARO, Inc., Lake Mary, Florida) were used for collecting infrared thermography and laser scan data. During post-processing, all the data are grouped into three categories: (1) Exterior Area; (2) Common Area; and (3) Apartments. The exterior area typically includes the exterior parts of the building such as exterior walls and roofs. The common area includes basement, corridor, electrical room, fire pump room, gas meter room, head start room, commercial kitchen, laundry room, and stairs and telephone equipment room in Building 2 and boiler room, corridor, electrical room, cellar garage, janitors' closet, laundry, mechanical room, recycle room, and stairs and telephone communication room in Building 2. In addition, 31 apartment units were selected for detail analysis in Building 1 and Building 2. Apartment types included studio, one bedroom, two-bedroom, and three-bedroom apartments.

A total of 1609 infrared images were captured for 31 apartments in two buildings after field data collection. These infrared images are integrated with lidar data to generate 3D thermography data. The integrated data are used to identify defects and locate these defects in the 3D thermal model. The major types of defects detected from this process are described in the following. As discussed previously, there are many different types of defects that can be identified and located through thermal imaging. These defects include poor or missing insulation, moisture issue, air leakage or air infiltration, thermal bridge, and poorly insulated hot water riser.

Poor or missing insulation: Poor or missing insulation can impair the thermal performance of building components significantly. Through infrared cameras, improperly installed or damaged insulation will appear as a patch with well-defined edges that outline the problematic areas (Balaras and Argiriou 2002) (Figure 20). In this case study, almost one-half of 31 apartments had this type of issue (Figure 20). In order to obtain sufficient information on poor insulation, a minimum temperature difference is required during the inspection. According to the RESNET Interim Guidelines for thermographic inspections of building and FLIR thermal imaging guidebook, the minimum inside and outside temperature difference of the wall surface is 10°C/18°F for a period of 4 hours is recommended. After all the missing and poor insulation areas had been detected and located, a 3D thermal point cloud was used to calculate the areas (ft^2) of anomalies. Based on the calculated data, the RESNET Insulation Grading Standards (Residential Energy Services Network (RESNET) 2013) were used to grade the insulation condition of each apartment. The RESNET Insulation Grading for Thermographic Inspections of Building classifies insulation condition into three categories:

- Grade I: no anomalies found through infrared camera
- Grade II: 0.5% to 2% for all inspected walls
- Grade III: 2 % to 5% for all inspected walls

In this study, the conditions of some apartments were far worse than Grade III. We added Grade IV to describe the situation when more than 5% of anomalies were found with an infrared camera. According to the RESNET Standard, at least a 10°F temperature difference between indoor and outdoor environments is required for applying the standard. However, most of the data collected for Building 1 during summer did not meet this requirement. Hence, a winter visit to Building 1 s also was made to collect data to meet this requirement.

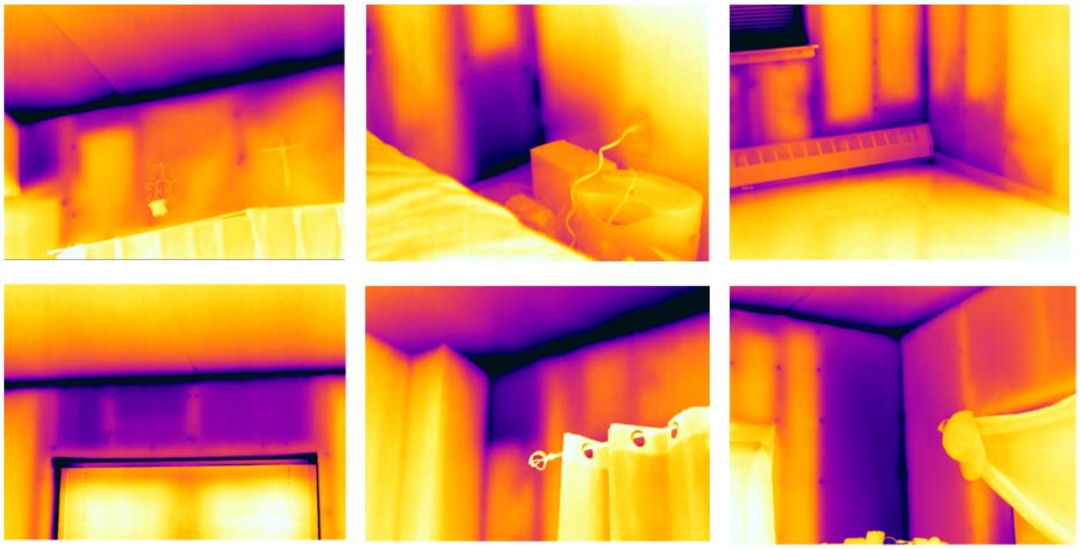


Figure 20. Example Missing Insulation (Sections with missing or poor insulation are indicated by the cooler colors).

Moisture issue: Moisture is the most common form of deterioration detected in a building. Locating moisture through infrared thermography is relatively straightforward since water has high thermal conductivity and heat capacity. Moisture in building envelope systems could be the result of air infiltration. This is because air infiltration allows warm moisture to go through wall assembly systems and condense and accumulate at cold spots. These condensations can lead to reduced insulation value, mold growth, and structure element deterioration. The following shows examples of moisture issues detected in the studied buildings (Figure 21).

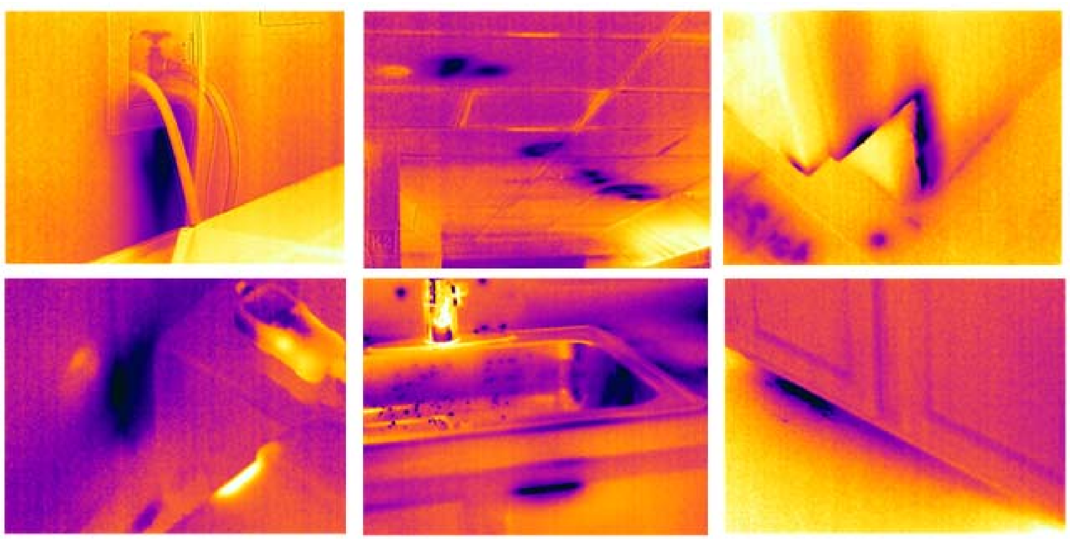


Figure 21. Examples of moisture issues.

Air infiltration: Air infiltration can lead to high energy consumption and condensation in building envelope systems. Although adequate air exchange is essential for occupants' health, many buildings have a far greater rate of air exchange than what is necessary. Air infiltration is usually caused by poor design and/or construction which allows air to move across thermal perimeters. It is recommended that air infiltration inspection works better when indoor air flow is controlled. This can be achieved using a blow door device or controlling air flow settings in HVAC systems.

In the context of this project, both are not feasible. In this study, air leakage issues are detected mostly in wall assembly systems (Figure 22). In Building 2, some of the power outlets on the exterior wall became a point of cold-air entry in apartments. In the worst case, it was observed that an outlet had a temperature of 55°F while the indoor and outdoor temperatures were 75°F and 40.5°F, respectively (Figure 23).

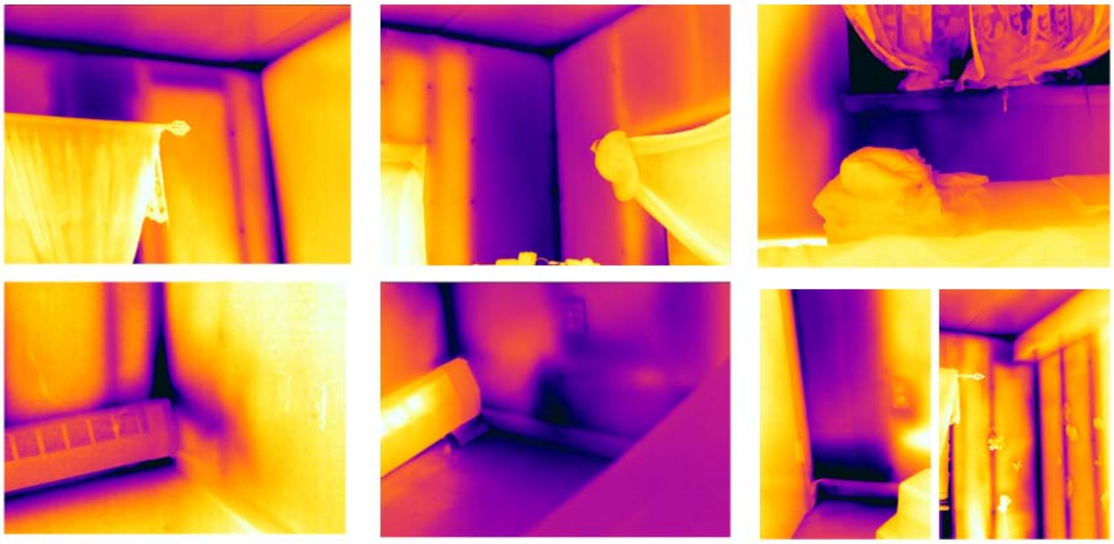


Figure 22. Examples of air infiltration.

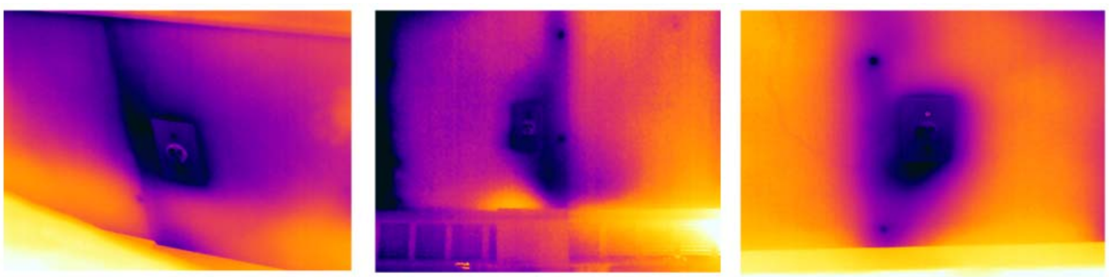


Figure 23. Cold Air Infiltration through Wall Sockets.

Thermal bridge: Thermal bridges are the elements or areas that are characterized by high thermal conductance with respect to the homogeneous multilayer envelope structure. Thermal bridges can lead to an increase of energy requirement for heating up to 30% of the extra thermal losses through building envelope during the winter season (Theodosiou and Papadopoulos 2008)). In our investigation, numerous examples of the thermal bridge were detected and evaluated (Figure 24).

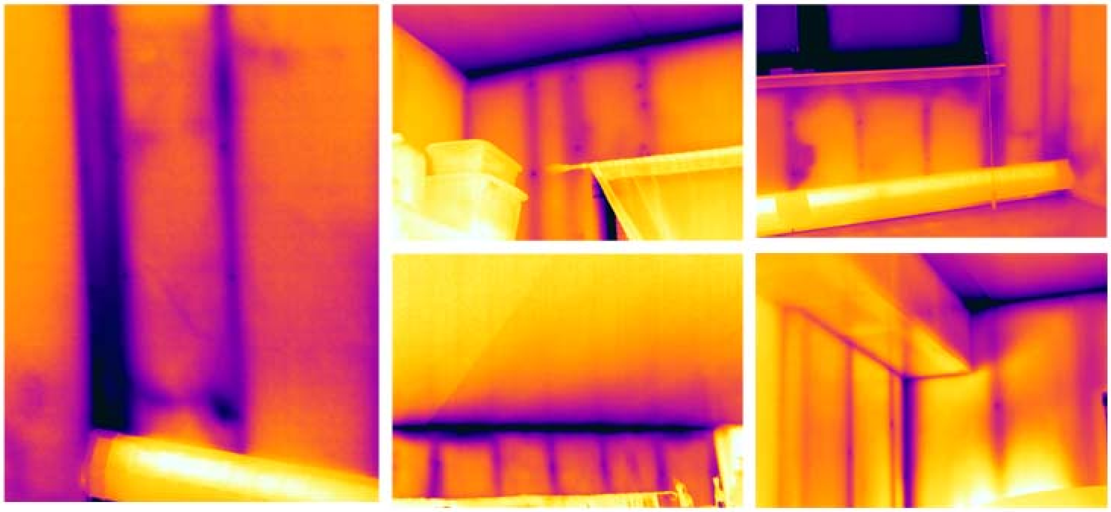


Figure 24 Examples of thermal bridge issues.

Poorly insulated hot water riser: During field data collection for Building 2, we noticed that some of the hot water riser pipes were not well insulated (Figure 25). The highest temperature difference between the wall cover of the riser and surrounding wall in the same room can reach up to 13.2 °F. In this particular building, three out of fifteen apartments had a temperature difference of 10°F, seven of fifteen apartments had the temperature difference higher than 5°F, and 66% of apartments had the temperature difference higher than 4°F. Insulating the pipes that carry hot water can help reduce the convective heat loss from pipes and increase the delivered water temperature for end use apartments. On the other hand, if the heat gain from poorly insulated hot water pipes cannot be controlled, it may lead to an overheating issue in the room.

Figure 25. Poorly Insulated Hot Water Risers.

One important numeric attribute that was also calculated based on infrared thermography is R-value, which measures the thermal resistance of a given wall assembly system. The R values were calculated for all the apartments we have inspected during the winter season as a large indoor, and outdoor temperature difference is often a prerequisite to achieving accurate R-value calculation.

Table 5 and Table 6 list the defects detected in both buildings. For detailed information regarding the attributes listed in both tables, please refer to Appendix E. It is important to note that the tables list only the results from data collected during the winter season. Building 1 had also been inspected during the summer season. However, the manifestation of building defects during the summer was not nearly as clear as during the winter. This is likely due to lack of sufficient temperature difference between indoor and outdoor environment during the summer.

The extracted building condition data show that there are large variations in apartment conditions (Figures 26-28). Some apartments had a significant deficiency in building insulation, which could impact occupants' thermal comfort and lead to other building hazards such as indoor quality issues. To summarize the conditions of insulation in the inspected apartments in Building 1 and 2, we categorized the buildings into three categories including good insulation, fair insulation, and poor insulation. The distribution of the studied apartments across these categories is shown in Figure 29. Overall, the data analysis shows varied conditions in these apartments, some of them having alarming concerns on thermal performance and hazardous conditions. The field study shows that the employed spatially resolved infrared thermography method is able to generate systematic measures that can be used to gauge the performance of the apartments. These quantified building performance attributes form the basis to correlate with other data streams to gain a better understanding how these factors correlate with each other. Statistical analyses were applied to these data streams to understand their correlations, and they are described below.

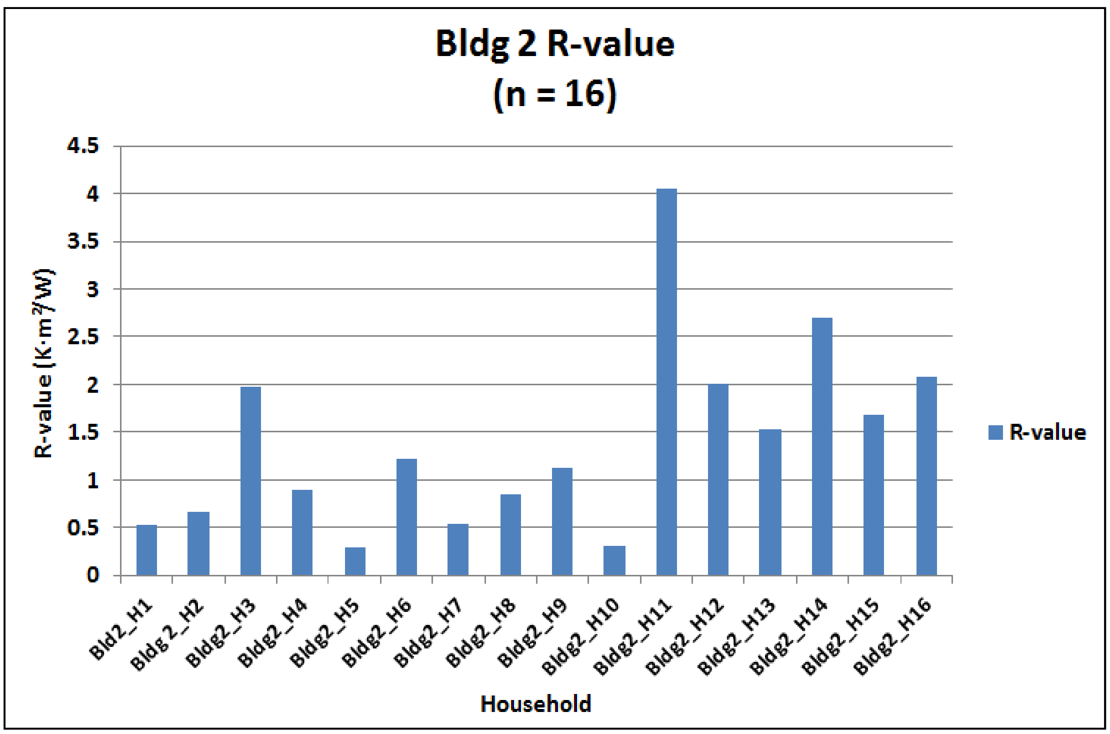


Figure 26. R-Values for Apartments in Building 2.

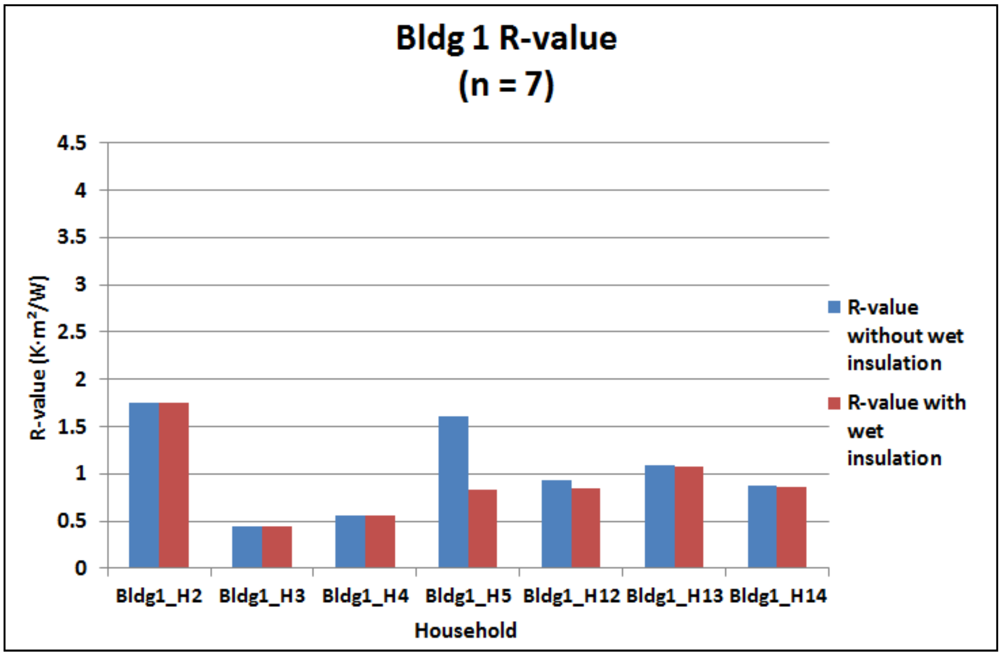


Figure 27. R-Values for Apartments in Building 1.

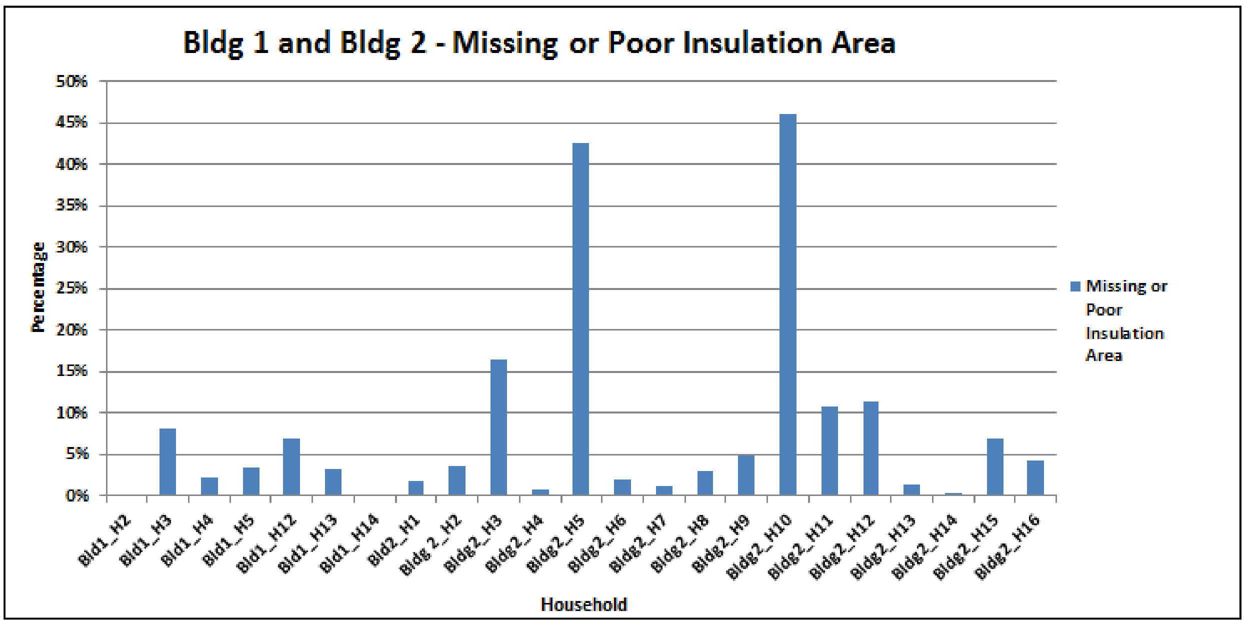


Figure 28. Percent of Poorly Insulated Areas in Apartments in Building 1 and 2.

Attribute (Median value)	Good Insulation (n = 4)	Fair Insulation (n = 10)	Poor Insulation (n = 6)
Thermal Bridge Temperature	70.55	71.15	65.75
Thermal Bridge Temperature Factor	0.78	0.87	0.63
Air Leakage Temperature	65.85	65.15	58.70
Air Leakage Temperature Factor	0.69	0.74	0.55
Missing Insulation Area (sf)	0.68	3.91	24.82
Missing Insulation Area (%)	0.22%	1.53%	10.59%
R-value	0.89	1.37	0.63

Apartment with Good Insulation Condition (Missing Insulation Area < 0.5%)
Apartment with Fair Insulation Condition (Missing Insulation Area < 5%)
Apartment with Poor Insulation Condition (Missing Insulation Area > 5%)

Figure 29. The Insulation Conditions of Studied Apartments in Buildings 1 and 2.

Table 5. Defect Detection Results for Building 1 during the Winter Season.

Code	Indoor and Outdoor Temp Difference	Thermal Bridge Temp.	Temp. Factor-Thermal Bridge	Air Leakage Temp.	Temp. Factor-Air Leakage	Missing Insulation (ft^2)	Missing Insulation (%)	Insulation Grading	Wet Insulation (ft^2)	Wet Insulation (%)	Moisture Level	R-value
H2	29	70	0.80	68	0.73	0.00	0.00%	1	0.67	0.15%	3	1.76
H3	27	73	0.97	65.2	0.68	38.69	16.34%	4	0.00	0.00%	3	0.44
H4	22	67.1	0.91	66	0.87	8.24	2.29%	3	0.11	0.03%	3	0.56
H5	42	69	0.93	68.4	0.91	29.70	7.12%	3	0.11	0.03%	3	0.83
H12	43	59.5	0.63	59.3	0.63	13.33	6.88%	3	12.10	6.24%	3	0.85
H13	33	64.1	0.81	62.8	0.77	50.39	9.21%	3	0.34	0.06%	1	1.08
H14	38	63.2	0.78	59.7	0.68	0.70	0.13%	1	12.57	2.34%	3	0.86

Table 6. Defect Detection Results for Building 2 during the Winter Season.

Code	Ind/out Temp Difference	Thermal Bridge Temp.	Temp. Factor-Thermal Bridge	Air Leakage Temp.	Temp. Factor-Air Leakage	Missing Insulation (ft^2)	Missing Insulation (%)	Insulation Grading	Wet Insulation (ft^2)	Wet Insulation (%)	Moisture Level	R-value
H1	30	64.5	0.62	61.5	0.52	1.40	0.55%	2	3	0.53	5.2	1
H2	31	68.3	0.73	67	0.68	3.60	1.41%	2	3	0.67	4.1	0
H3	32	67.2	0.64	66.7	0.62	13.00	5.25%	4	3	1.97	0	0
H4	39	74.3	0.91	67.2	0.73	0.65	0.26%	1	3	0.90	13.2	1
H5	35	64.3	0.68	55.1	0.42	36.50	14.30%	4	3	0.30	5.9	1
H6	38	75.2	0.82	64.3	0.54	1.79	0.70%	2	3	1.21	1.2	0
H7	30	66.8	0.71	64.5	0.63	0.99	0.39%	1	3	0.54	0	0
H8	32	66.9	0.62	58.4	0.35	2.63	0.83%	2	3	0.85	12.6	1
H9	36	73.4	0.95	63.7	0.68	4.21	1.65%	2	3	1.13	0	0
H10	37	67.7	0.75	58.1	0.49	36.30	19.62%	4	3	0.31	0	0
H11	31	73.4	1.06	73.3	1.05	9.32	3.65%	3	3	4.06	10.2	1
H12	31	74	0.94	70.9	0.84	9.02	3.58%	3	3	2.01	6.2	1
H13	33	74.5	0.88	72.6	0.83	1.13	0.61%	2	3	1.52	0	0
H14	52	79.7	0.90	68.5	0.68	0.45	0.18%	1	3	2.70	7.2	1
H15	43	71.2	0.87	64.3	0.71	5.89	2.31%	3	3	1.68	4.3	0
H16	44	71.1	0.89	66	0.77	3.30	1.29%	2	3	2.09	3.9	0

Household Demographics based on Interview Data

From the participating 31 apartments, there was a predominance of female-headed households (84%). In Building 1, the median age of the enrolled subjects was 58, while for Building 2 the median age was 42.5. In Building 1, 53% of household members represented in the sample included residents 20 years or younger. In Building 2, 42% of household members represented in the sample included residents 20 years or younger. Approximately 20% of the combined sample are Spanish speaking; 20 reside in a 2-bedroom apartment, and the rest in 1 or 3 bedrooms (6 respondents in a 1 bedroom, and 5 respondents in 3 bedrooms). Additional data on the building subjects as recorded in the interviews is integrated into the 3-stream findings (IAQ, scans, and interview data).

Professional Advisory Group Data

Overall, the members of this group responded very positively to our methods for cost-effective detection of housing health and safety defects, as shared in formal in-person and webinar-based presentations and also in written form.

"I think overall the process outcome is very useful to me, as an owner and technical member of my real estate development team."

"The findings do align with building professional practices; detection of defects which leads to repairs. Less weight is generally given to "human behavior and perception" and in many cases less is done with "IAQ" testing, before engaging in proper remediation of building defects."

However, they also shared some reservations about the broad adoption of these methods feeling that, as currently developed, they rely too heavily on professional-grade instruments and analyses.

"The instruments and sampling/analysis used in the project are more advanced and more expensive and require more training than is typically available when affordable housing investigations are conducted. "

The Advisors offered sage input into any future commercialization endeavors including an imperative to target the system to different users.

"… as an owner operator, if you are "selling" this approach to me, I would like to hear more about how it will help my bottom line, and help my tenants feel more comfortable, reduce my work orders and how much the additional testing will cost, and will there be a return on investment? If I am wearing my technical building auditor hat, I would be interested in "how do I perform this similar testing" "

"Focus on use of infrared cameras as an add-on to current practice."

"Looking to work with groups like SWA, AEA, and Bright Power may be another route."

Findings from the Conventional Building Condition Assessments

From these assessments, we learned that:

- Building 1 appears to have minor outdoor air infiltration issues and inadequate kitchen ventilation.
- Building 2 appears to have significant water infiltration issues, especially around windows and on upper floors. There appears to be missing insulation above many windows. The building appears to be somewhat under-ventilated.

Integrative Findings: IAQ measurements, questionnaire data, and infrared scans

The findings from the integration of IAQ measurements, questionnaire data, and infrared scans are provided in Appendix D. These findings and their description are divided into two parts. Part A relates the measurements of particulate matter parameters and the residents' responses to questions pertinent to indoor air quality and health, especially when it comes to the prevalence of asthma in the investigated households. Part B focuses on our integration of IAQ measurements, questionnaire data and infrared scans. The summary presented below highlights the main findings from the two parts.

Statistical analysis

Since the data were non-normally distributed, non-parametric tests were performed for the analysis. The associations between independent linear variables were obtained through Spearman correlation, r_s. Independent ordinal variables were associated with gamma correlation, G and odds ratio, OR. When data were stratified into two or three groups, the difference of the mean between the groups was analyzed by Mann-Whitney U test and Kruskal- Wallis H test, respectively. Statistical analysis was performed with IBM SPSS Statistics 23.0, and statistical significance was accepted at p-values <0.05 and borderline significance was accepted at p values <0.10. For many IAQ measurements, ratios of indoor to outdoor data (I/O) were determined. I/O values above 1 suggest prominent indoor sources and values below 1 suggest higher contribution by outdoor sources. The I/O ratio of 1 (and the corresponding line in figures) indicates that the concentration of a pollutant indoors is equal to that outdoors. The symbol "°" in the graphs are the extreme values as determined by the SPSS software with respect to its interquartile range.

Integration of IAQ measurements and questionnaire data

We have observed that the presence of combustion sources in investigated households is a major variable determining the levels of particulate matter (PM). In households where smoking was reported, the average PM2.5 concentration was about 40 μg/m^3, while in the apartments where no smoking was reported the average concentration was about 20 μg/m^3. The difference was statistically significant (p=0.009). When combustion sources indoors such as the burning of candles or incense were included in addition to smoking, the average PM 2.5 concentration was about 60 μg/m^3 , while in the group that had no combustion sources the average concentration remained about 20 μg/m^3 , and the difference was statistically significant (p=0.002). A similar relationship was valid for the PM2.5 indoor/outdoor (I/O) ratio. In the apartments where indoor smoking and burning of candles or incense was reported, the ratio was above two. In the apartments where no indoor combustion sources were reported, the ratio was below one. The difference was statistically significant (p=0.001). In general, the indoor/outdoor ratios higher than 1 indicate the presence of particulate matter sources inside the apartments, whereas the ratios below 1 suggest that the particulate matter is infiltrating indoors from outdoors.

The observations were similar when total particle number concentration and not PM2.5 mass concentration was considered. In the apartments where smoking was reported, the average I/O was close to two, whereas in the apartments where no smoking was reported the indoor/outdoor ratio was about 0.9 (p=0.049). Based on the observations above, smoking contributes to both high particulate matter mass concentration as well as to high particulate matter number concentration.

One of the main reasons why the presence of particles was investigated was to correlate its presence with the residents' reports of prevalence of asthma within investigated the households. The households where cases of asthma within the past 12 months have been reported had higher total particle number concentration by approximately a factor of two compared to the apartments where no asthma events in the past those months have been reported, and this difference was statistically significant (p=0.044). Also, the indoor/outdoor ratio of total particle number concentration was substantially and significantly higher in those households where any household member had a history of asthma (p=0.024). When we considered not the total particle number concentration, but the mass concentration of PM 2.5 particulate matter and its relationship with the reports of asthma, the results were similar. In the households where asthma cases in the past 12 months have been reported, the average PM2.5 concentration was about 40 µg /m^3 whereas in those apartments were no asthma cases in the previous 12 months had been reported the average PM 2.5 concentration was about 15 µg /m^3 (p = 0.01). When we considered the cases where there was a history of asthma ever reported by anyone in participating households, the average indoor/outdoor ratio of PM2.5 in those households was about 1.5, whereas the indoor/outdoor ratio for the households that had never had asthma cases was about 0.9, and the difference was statistically significant (p=0.032). The difference in I/O ratios was also significant (p=0.049) when asthma cases in the last 12 months were considered.

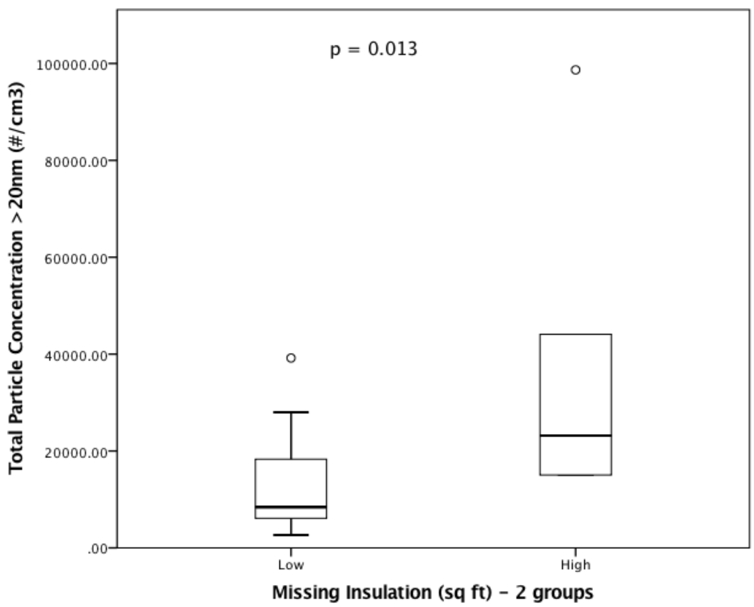
The presence of biological particles also had an effect on residents' response to questions about asthma events. First of all, we observed a clear and positive relationship between indoor temperature and the concentration of culturable mold (p=0.044) and total mold (p=0.009). The measured indoor/outdoor ratio of culturable mold was significantly correlated with the reports of the mold by the residents. The presence of total mold as measured by the investigators was correlated with the reports of moisture indoors by the residents (p =0.029). Data on relative humidity indoors also suggested its role in the presence of culturable mold indoors as well as its indoor/outdoor ratio. In the first case, the relationship was borderline significant with p = 0.066, whereas in the second case p=0.022. Reports of moisture by the residents was also correlated with observed indoor relative humidity with p=0.002. Households with asthma cases reported in the last 12 months had a somewhat higher concentration of culturable mold and somewhat higher indoor/outdoor ratio of culturable mold. In both cases, the difference was borderline significant. When it comes to total mold, the households that had asthma cases in the past 12 months had higher total mold concentration, and the difference from households without asthma was statistically significant with p = 0.019.

Integration of infrared measurements, IAQ measurements, and questionnaire data

The infrared thermography, laser scanning, and sensor data allowed us to determine the number of parameters describing building performance (Figure 16). A preliminary investigation was performed to correlate all of those parameters with IAQ measurement data and questionnaire reports. From all the investigated building performance parameters, the determined amount of poor/missing insulation showed the best correlation with the IAQ measurement data and questionnaire reports. Thus, these associations were investigated in more detail. Missing insulation was determined in both Building 1 and Building 2 for the total sample size of 20 apartments. These 20 apartments are a subset of the 31 apartments for which IAQ measurement sets and questionnaire reports were described earlier. The questionnaire data were compared for both samples sizes n= 31 and n = 20, and no significant difference was found (p>0.05; See Appendix D for details). This suggested that the subset where infrared scans were performed (n=20) is a representative sample of the 31 apartments.

Percentage of missing insulation (expressed as % of the area relative to the wall area) in each apartment correlated well with missing insulation values expressed in square feet (ft^2), r_s= 0.992, p <0.001. Thus, the apartments were stratified into categories with low, medium and high levels of missing insulation based on the % of missing insulation in each apartment: missing less than 0.5%, between 0.5 and 5 % and above 5%, respectively, according to the RESNET standard. The missing insulation values (expressed as ft^2) between the "low", "medium" and "high" groups were statistically significantly different according to Kruskal-Wallis H – test [χ^2 (2)=16, p <0.001], with mean rank of 2.5 for "low", 9.5 for "medium" and 17.5 for "high" level groups. This strong correlation allowed us to choose missing insulation (ft^2) as a dependent variable for further analyses.

The comparison of total particle number concentration in the three apartment groups according to the missing insulation amount ("low", "medium" and "high" groups) was statistically significant, χ^2 (2) = 6.33, p = 0.042 with a mean rank total of particle concentrations of 11.5 for "low", 7.4 for "medium" and 15 for "high". The particle concentrations in groups "low" and "medium" were not significantly different from each other (U =11.0, p = 0.103). The "high" group had greater particle number concentration compared to the "medium" group (U =8.0, p = 0.008) with a mean rank of 6.3 for "medium" group and 12.17 for "high" group. Thus, the data from "low" and "medium" groups were pooled together into a new "Low" group (N=14). The "high" group had a significantly higher particle number concentration than the "Low" group (U = 15, p = 0.013) (Figure 30a) with a mean rank of 8.57 for "Low" level and 15.0 for "high" group. In the subsequent text, when the comparison is made between only two groups, the "Low" group has N=14 and encompasses "low" and "medium."



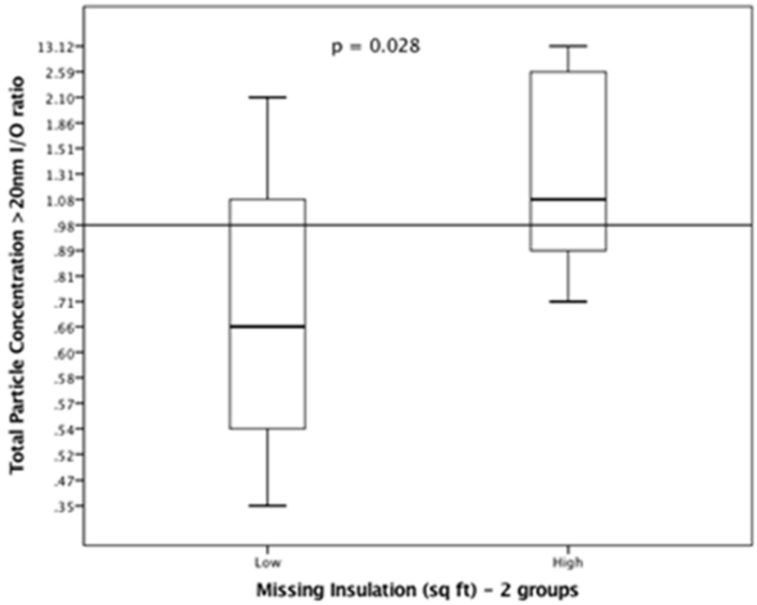


Figure 30. a. Indoor particle number concentration stratified by missing insulation levels (ft^2). b. I/O particle number concentration ratio stratified by missing insulation levels (ft^2).

Further investigation into the presence of total particles was done by comparing the I/O ratios of total particle number concentration for apartments with different levels of missing insulation. The groups “low” and “medium” were not significantly different from each other (U =18.0, p = 0.389). The “high” group had a greater number of particles compared to the “medium” group (U =11.0, p = 0.020) with the mean rank of 6.6 for “medium” group and 11.67 for “high” group. Similarly, as above, the “low” and “medium” groups were pooled together into a new “Low” group (N =14). Here, the indoor/outdoor ratio of total particle number concentrations in the “high” group was significantly greater than in the “Low” group (U = 19, p = 0.029) (Figure 14b) with mean rank of 8.86 for the “Low” group and 14.33 for the “high” group.

When the amount of missing insulation was correlated with the mass of PM 2.5 particles, the difference in PM2.5 concentrations was not statistically significant between groups with different missing insulation levels. This suggests that missing insulation was critical for allowing penetration of smaller particles indoors, but it did not have a statistically significant effect on the penetration of larger particles indoors. The reports of mold noticed by the residents were also higher in those groups that had higher amounts of missing insulation. The apartments with the higher levels of missing insulation seemed to be mostly corner apartments, and the difference between corner and non-corner apartments was statistically significant with p= 0.025. It should be mentioned that the corner apartments also had a substantially and significantly higher total particle number concentration with p =0.012. The amount of missing insulation was also higher in apartments located on Floors 6 and above and the difference was significant from apartments located between floors 1 and 5 with p =0.029. The observed amount of missing insulation also seems to have a correlation with the participants’ health. In the household group that had a high amount of missing insulation out of 16 participants, 12 had reported a history of asthma at any point in time, whereas in the “Low” group there were 4 households and none of them had a history of asthma. The difference between the two groups, i.e., apartments with “Low” and “high” amounts of missing insulation, was statistically significant with p=0.006. We calculated the odds ratio of 4.0 that apartments having elevated levels of missing insulation would have a history of asthma. However, there was no difference in the amount of missing insulation observed and the presence of asthma in participating households in the past 12 months.

These data allow us to infer that thermographic scans are capable of rapidly determining missing insulation and that the amounts of missing insulation are correlated with the presence of total airborne particles indoors as well as their indoor/outdoor ratio. The presence of particles, in turn, may bear relation to residents' health, especially to the asthma history of any member in the participating households. Because the sample size is limited, these data and findings should be verified by a future study employing a larger sample size.

Overall, in our data analysis, we looked at the relationship between the missing insulation and particle concentration, temperature and relative humidity, bioaerosols, and apartment location. Some relationships between these data sets were statistically significant, while others were borderline significant and provided a direction of the relationship between different data streams. Figures 31-34 show relationships between the various data streams.

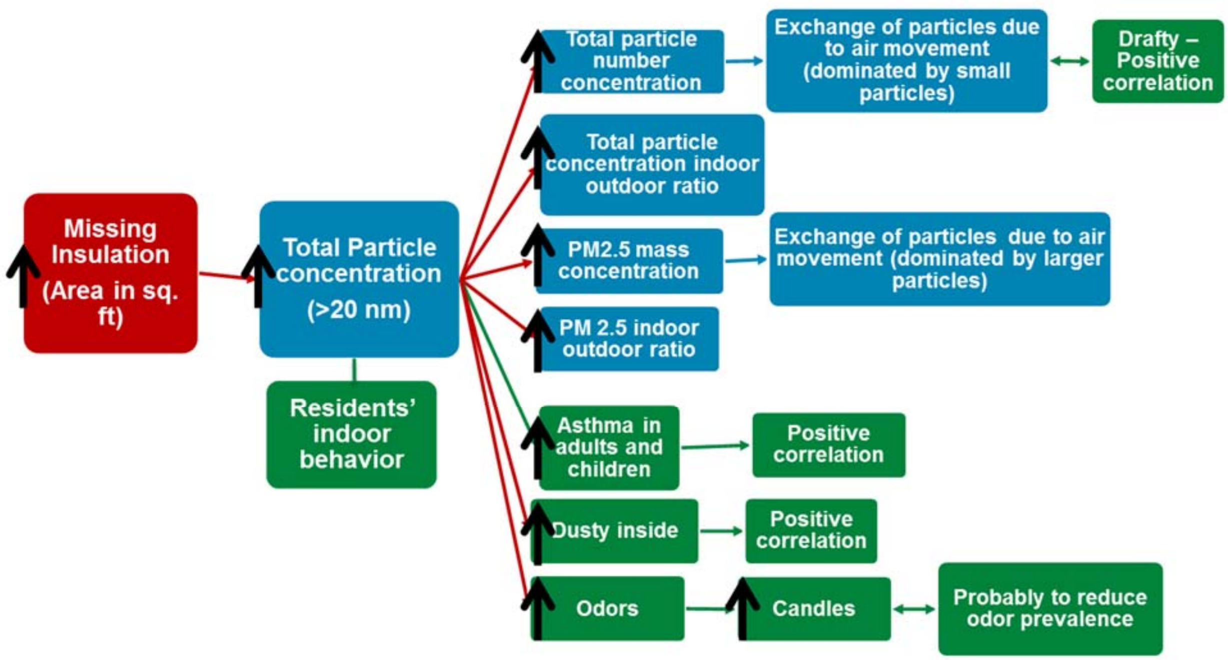


Figure 31. Association between missing insulation, particulate matter measurement data, and relevant questionnaire data.

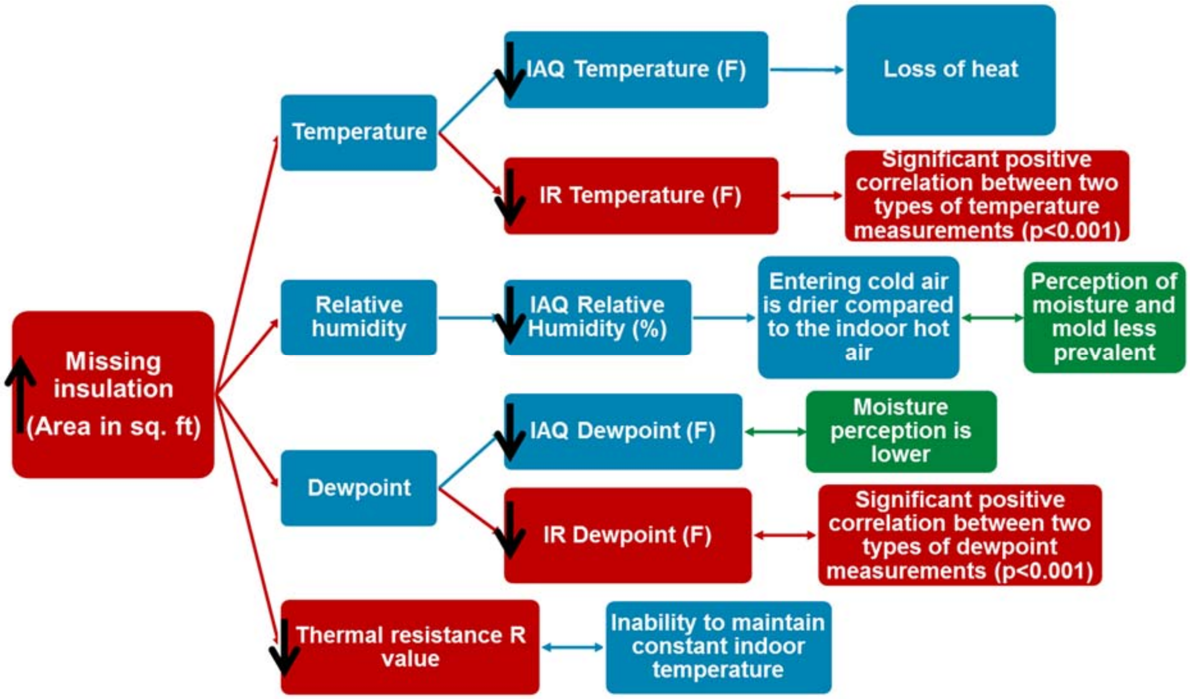


Figure 32. Association between missing insulation, indoor comfort parameters, and relevant questionnaire data.

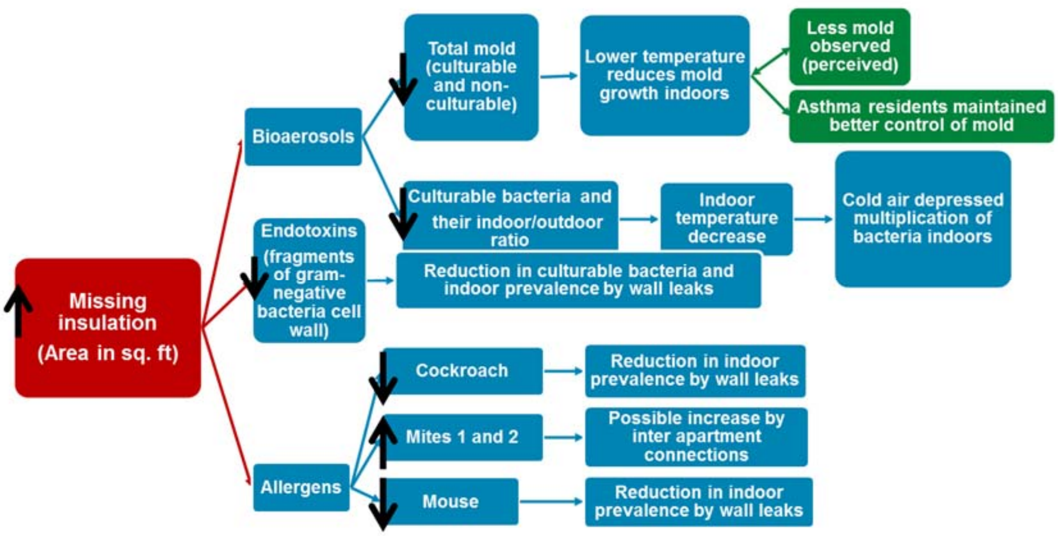


Figure 33. Association between missing insulation, bioaerosols, allergens and endotoxins.

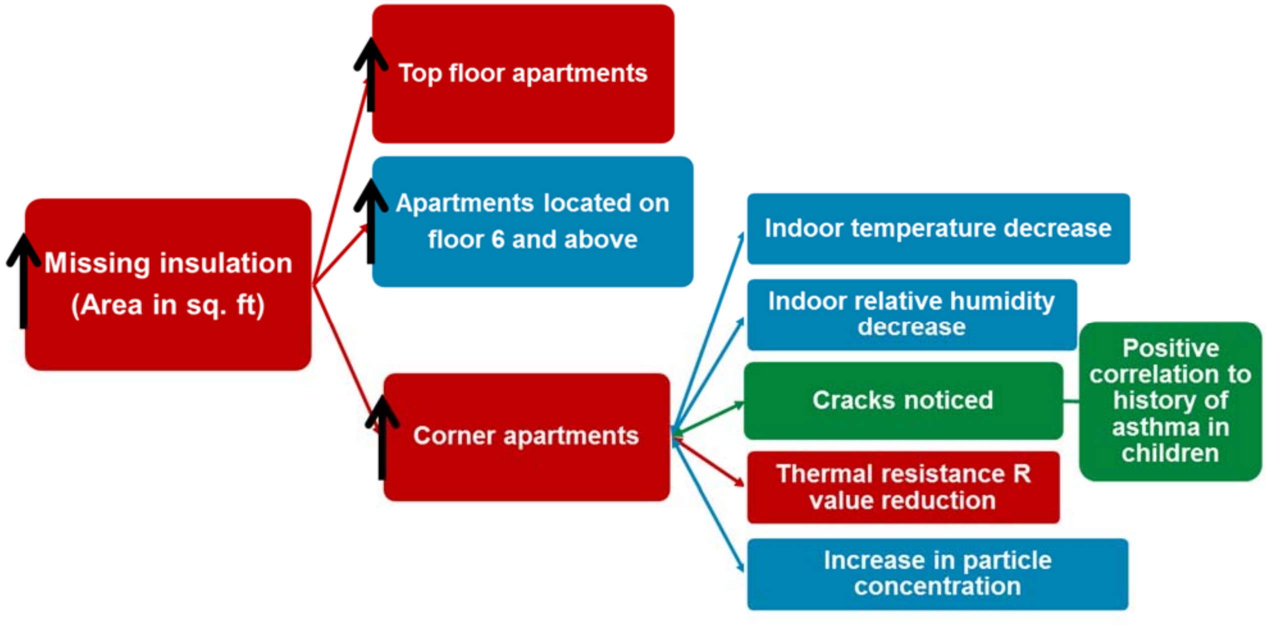


Figure 34. Association between missing insulation and apartment locations.

Conclusions and Recommendations

This study in part explored the integration of infrared thermography and laser scanning for building hazard detection. The integration allows quick and objective measurement of common building defects that are found in homes. A systematic method that consists of infrared and laser scan data collection, data fusion from different data streams, and data analysis was developed. The proposed approach was validated on two large multi-family multi-story buildings. A total of 31 apartments were surveyed and analyzed according to several quantitative metrics including moisture issue, thermal bridge, air infiltration, and missing insulation. The evaluation shows varied conditions in these apartments, some of them having alarming concerns on thermal performance and hazardous conditions.

A subset of 20 apartments was selected for more detailed analysis and integration of infrared thermography and laser scanning, indoor air quality measurements and questionnaire data. Among the investigated building defect parameters, missing insulation showed a clear and significant correlation with the concentration airborne particles as well as the indoor/outdoor ratio of those particles, i.e., higher (I/O) ratios in apartments with a higher percentage of missing insulation. These findings suggest that missing insulation is conducive for particle penetration from outdoors to indoors. The reports of mold noticed by the residents were also higher in those groups that had higher amounts of missing insulation. This again suggests that missing insulation is conducive for mold penetration. Since mold is a known allergen, its presence indoors constitutes a potential health hazard. The apartments with the higher levels of missing insulation seemed to be mostly corner apartments; concurrently, the corner apartments also had a substantially and significantly higher total particle number concentration. Since the observed concentrations of airborne particles had a significant correlation with the residents' reports of asthma cases, one can conclude that building defects such as missing insulation have a direct effect on the residents' well-being.

The field study shows that the proposed method can generate systematic measures to gauge the performance of the building and individual apartments and that the rapid scanning of building performance via infrared thermography and laser scans correlate with other data streams such as indoor air quality data and questionnaires. The integration of the different data streams helps to develop a more complete picture of building performance and residents' health.

We recommend that HUD support: (1) future research on analytics similar to what was developed here; and, (2) creation of a data repository of annotated thermal images for training these algorithms. Additionally, we recommend that a start-up company be formed to commercialize our approaches as discussed below.

Next Steps: Future Development of Cost-Effective Methods for Health and Safety Hazards Detection

In the HUD-funded project, we developed a set of innovative pre-commercial techniques for collecting and interpreting spatially resolved infrared thermographic data. In subsequent on-going research, we are marrying that professional-grade technology to an emerging set of consumer-grade infrared thermography, indoor air quality measurement technologies, and an end-user dashboard display system to create a market-ready building performance evaluation tool. This system, which we have named SPIRIT (Spatially Resolved Infrared Thermography system) will be capable of delivering extremely low-cost evaluations of health and safety hazards in residential and other buildings. The research has already filed a notice of invention with Rutgers Office of Research Commercialization (ORC). Preparations to file a patent application are ongoing.

For multifamily building applications, we further envision that BIM models will be used as central data repositories for storing and managing discovered hazard data. Today, facility managers use BIM models extensively, often as the cornerstone of a Building Management System (BMS). For the two buildings evaluated under our HUD-funded work, we have incorporated safety and health hazard data into BIM models that we created. BIM supported hazard data recording and analysis should prove useful in understanding and documenting how housing-related hazards evolve spatially and temporally.

Product Development Plans

We envision four future products each belonging to our Spatially Resolved Infrared Thermography system (SPIRIT). These are depicted in Table 7.

Table 7. SPIRIT: Components for Future Development

Product	Description	Type of Products	License
SPIRIT Sensor Pack	A mobile spatially resolved infrared thermography system consisting of hardware and post-processing software packages.	Hardware and Software	Proprietary
SPIRIT Analytics	The software package includes analytics tools for intelligent interpretation of spatially resolved infrared thermography data.	Software	Open Source
SPIRIT Portal	A cloud-based tool for multi-scale visualization and exploration of multi-sourced home data (e.g. densely annotated spatially resolved infrared thermography, indoor air quality data, and lidar data)	Software	Open Source
SPIRIT Data Universe	A database of multi-temporal spatially resolved infrared thermography data, indoor air quality data, infrared data from consumer grade thermal devices, and weatherization data (All of which with rich descriptions or densely annotated ground truth defect information)	Data Products	Secured Access

Dependent on available funding, our next steps are 1) collect more data in scaled up pilots to: train our software algorithms to detect key patterns with increasing speed and accuracy; 2) develop and test a user-friendly tutorial and visualization template for various user groups (Figures 35 and 36); and, 3) develop the legal and transaction bases to introduce SPIRIT to market.

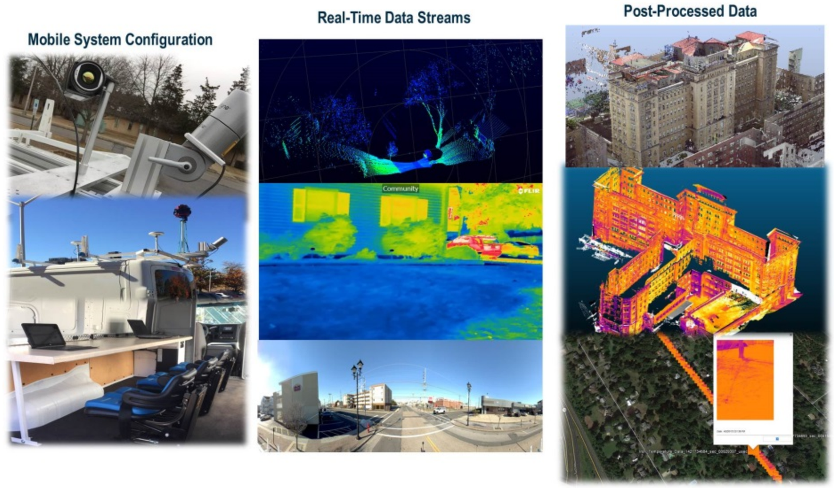


Figure 35. A mobile spatially resolved infrared thermography system.

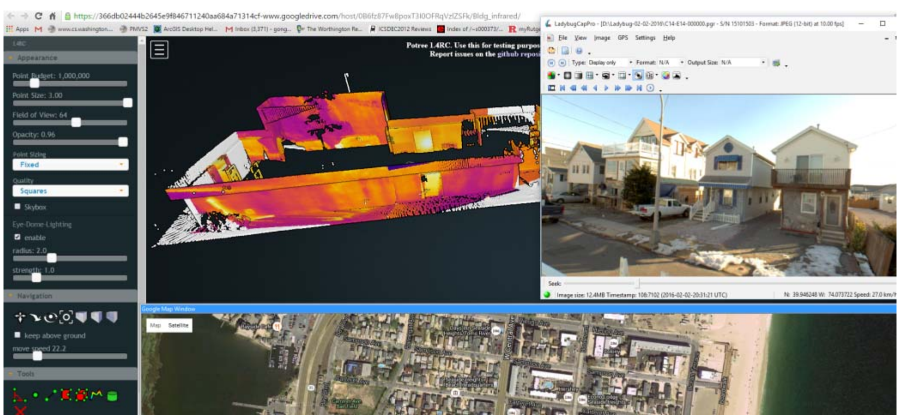


Figure 36 .Web-based visualization of spatially resolved infrared thermography

Target market(s)

We have identified energy auditing, energy efficiency retrofit, and weatherization providers, healthy homes providers, property management companies and building codes officials as target markets. In targeting the energy efficiency market, we expect that many resulting improvements will also benefit health. As demonstrated above, leaky buildings not only denigrate energy efficiency, they further expose occupants to harmful particulates and moisture, which may result in mold. A key part of this HUD-funded research has been to test how well our methods predict comfort- and health-related benefits.

In the U.S., and globally, investment in building energy efficiency is increasing at a greater pace than overall building construction. Currently, in the U.S., investment in energy efficiency accounts for approximately 2.4% of construction investment, an increase from 2009 (International Energy Agency 2015). This growth is driven by government investment (at various levels), based on energy, environmental and economic regulatory and voluntary policies, and corresponding investment by industry and consumers.

Figure 37 illustrates the typical energy efficiency retrofit business process. We believe that our technology can contribute value at several points in that process.

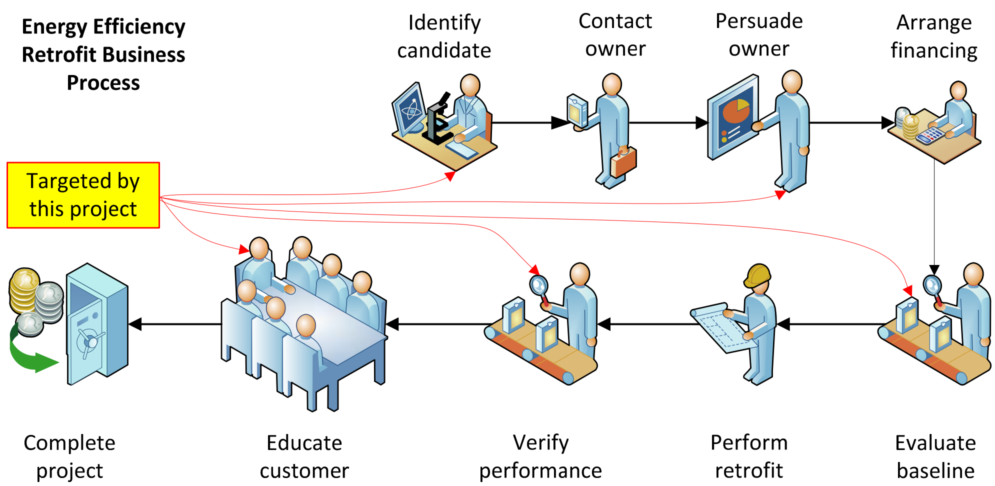


Figure 37. Energy Efficiency Retrofit Business Process

Market Barriers

Barriers to additional development of our cost-effective detection methods include a lack of pre-commercialization and commercialization funding, the need to provide perhaps extensive training inputs for targeted market segments, emerging protocols for data standardization, privacy concerns, and an uncertain regulatory regime regarding energy, environment, and health. Key learnings from the Professional Advisory Group during the HUD project proved helpful both in characterizing market barriers and in discussing possible strategies to overcome them.

Very recent advances in the integration and miniaturization of laser scanning and infrared thermography (FLIR 2017) support that the greatest opportunity for commercializing the SIPIRT approach lies in the analytical portion of our work. It is exciting to see the elements needed to promote wider adoption of our approach are falling into place.

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