X3D Sensor-based Thermal Maps for Residential and Commercial Buildings

Felix G. Hamza-Lup[1]
Armstrong State University
Savannah GA, USA

Paul Borza[2]
Transilvania University
Brasov, Romania

Dorin Dragut[3]
Transilvania University
Brasov, Romania

Marcel Maghiar [4]
Georgia Southern Univ.
Statesboro GA, USA

Abstract

There are many building energy simulation systems on the market today; however, most of them rely on theoretical thermal models to make decisions on the building structural design and modifications. Sustainable methods of construction have made tremendous progress in the recent decades. The example of the German Energy-Plus-House technology uses a combination of (almost) zero-carbon passive heating technologies. A web-enabled X3D simulation system coupled with a cost-effective set of temperature/humidity sensors can provide valuable insights into building design, materials and construction that can lead to significant energy savings, an improved thermal comfort for residents and improved efficiency. We propose a cost effective hardware-software prototype system that can provide real data driven 3D thermal maps for residential buildings. The system can easily scale to provide 3D thermal maps for large commercial buildings.

CR Categories: H.5.2 User Interfaces: GUI; H.5.3 Group and Organization Interfaces: Web-based interaction; I.3.7 Three-Dimensional Graphics and Realism: Virtual Reality; I.3.8 Applications; I.6.8 Types of Simulation: Visual;

Keywords: Thermal Comfort, Thermal Maps, X3D, Building Envelope, Relative Humidity Simulation, Distributed Sensors.

1 Introduction

Sustainable methods of construction have made tremendous progress in the recent decades. For example, the German Energy-Plus-House technology [Voss and Musall 2012] uses a combination of (almost) zero-carbon passive heating technologies and easily adaptable renewable energy technologies in order to build homes which have a positive energy balance enabling the home-owners to sell surplus energy to the national electricity grids and earning additional income.

Thermally deficient western methods of construction hardly tap into the huge potential of applying energy-efficiency technology. Moreover, the economically fastest growing regions in the world are now to be found in the countries of the global south located mainly in tropical and sub-tropical climate zones which have entirely different requirements when it comes to designing energy-efficient and low-carbon houses. With the fast (and often unregulated) economic growth, energy consumption in those parts of the world rises exponentially. The construction sector in those countries adapted fast to the western methods of construction and are now faced with major hurdles in assessing thermal efficiency, especially for large commercial buildings.

The researchers proposed herein a simple and effective, web-enabled thermal simulation system coupled with a cost-effective set of sensors (e.g. temperature, relative-humidity) that can provide valuable insights into building design, materials and construction that can lead to significant energy savings and an improved thermal comfort. The paper is structured as follows: in Section 2 the authors present existing models for thermal energy/comfort simulation and they introduce some basic terminology; Section 3 describes the wireless sensor system that the authors developed for sensor data collection and processing; Section 4 provides details of the data acquisition process and data representation in the X3D simulation for two building categories: residential and commercial; Section 5 proposes a preliminary validation method for thermal models and concludes in Section 6 with a detailed discussion on future expansions of this work.

2 Related Work

Conventional models of thermal representations are in use by construction professionals and HVAC (Heating, Ventilation and Air Conditioning) engineers for many years and they rely on using proprietary thermal analysis software products like: SolidWorks Simulation, Ansys Advantage, Ansys CFX and many others that support CAD-based models integration. However, the intent of this research is to create modeling representation independent of proprietary software packages and their integration solutions.

International standards for thermal comfort for indoor air temperature and humidity as incorporated in the Nicol et al. [1995] lacks representation and measurement methods and interpretation. They deal mainly with thermal comfort and the perceived values of temperatures from the building occupants. In the US alone, National Institute of Building Sciences (NIBS) are proposing (through High Performance Building Council) baseline standards [NIBS 2015] for thermal performance of building enclosures, ASHRAE 90.1-2010, with certain levels of high performances, measurement and verification for design and construction of enclosure assemblies. Peeters et al. [2009] presented a set of values and scales for thermal comfort evaluation in residential buildings. The rooms in each residence are categorized in three groups: bedroom, bathroom and other.

---

[1] email: Felix.Hamza-Lup@armstrong.edu
[2] email: Borzapn@unitbv.ro
[3] email: Dorin.Dragut@student.unitbv.ro
[4] email: MMaghiar@georgiasouthern.edu

Web3D '15, June 18 - 21, 2015, HERAKLION, Greece

ISBN 978-1-4503-3647-5/15/06…$15.00
DOI: http://dx.doi.org/10.1145/2775292.2775300

Many factors (including thermal adaptation) are considered when deciding on the thermal comfort scales. Zhai et al [2006], presents a review on the complex computational fluid dynamics (CFD) simulations used for the past 20 years to model the flow of air in buildings. However, in authors' view, all simulation systems presented are proprietary and too complex to be applied in conjunction with real-time data.

Ham et al. [2014] presents a thermography-based method to visualize the actual thermal resistance and condensation problems in buildings in 3D while taking static occlusions into account. Their experimental results show the promise of supporting retrofit decision-making for as-is building conditions; however, the method is dealing only with converting surface temperature data obtained from an IR camera into 3D visualization of energy performance metrics and possible condensation problems and is not addressing further thermal comfort considerations for as-built buildings. From a visual representation point of view, Wong and Fan [2013] research concurs that the lack of interoperability could be a factor limiting the application of BIM (Building Information Modeling) in building design and needs to be considered earlier in the planning stage for design processes. Through this paper, researchers make an attempt to address the shortage from a thermal comfort simulation perspective and to create an independent visual platform available through a simple web browser.

Moreover, as California lays the groundwork for adoption of a Zero Net Energy (ZNE)-ready code by 2020, it has recently restored its Advanced Homes Program to help meet this goal. This is an interesting attempt to promote innovation and, in this sense, one essential change has been to uncouple the program's targets from code level (i.e., incentives tied to percent better than code) and concentrate on tools and methods to better tie program outcomes to actual home energy performance. This way, the program experience is demonstrating that support on percent "better-than-code" metrics, code-compliance modeling and related tools, may hinder adoption of more advanced technologies and practices, obstruct innovation, and lead to misleading incentives aligned to code rather than to actual home energy performance [Christie et al. 2014].

Rijal et al. [2014] have conducted a thermal comfort and occupant behavior survey in thirty living rooms during the hot and humid season in the Kanto region of Japan. His results showed that the residents adapt to the hot and humid environments by increasing the air movement using behavioral adaptation such as window opening and fan use. The study lacks simulation of thermal transfer of any kind and relies heavily on the statistical analysis performed on respondents based on the perceptive skin moisture sensation. Another study performed by Pitts [2013] deals with transition spaces like entrance foyers, circulation zones, lift lobbies, stairways and atria, and thermal comfort experiences. It both reviews existing reported research into comfort in such spaces, and introduces new information from a range of studies completed in recent years. The outcome of this work suggested only opportunities to reduce environmental conditioning and therefore energy use in such spaces. Lee [2008] developed a novel sensor network powered by the artificial light in order to achieve wireless power transfer and wireless data communications for thermal comfort measurements to implement a comfort-optimal control strategy for an air conditioning system. The focus of this study is the X3D representation of the thermal maps with actual data acquired from the sensor networks. The sensors can be connected to the HVAC equipment actuators, energy-consumption control being realized through the feedback of the thermal map information in the referred space.

From another point of view, in a different study done by Lee et al. [2014], the impact of three newly developed dynamic clothing insulation models on the building simulation is quantitatively assessed using the detailed whole-building energy simulation program, EnergyPlus, version 6.0. The limitations on this particular study were that the new clothing insulation models on energy and comfort was performed only for one particular climate (Chicago, IL, USA) and one particular system type (conventional forced air system equipped with variable speed central AHU and VAV box with reheat coil in each zone). The authors will prove through this research that the sensor system and the X3D thermal representation developed based on the information collected from sensors is independent of these factors (including software-based post-processing of data), and may provide valuable insights into building design, materials and construction, potentially leading to significant energy savings and an improved thermal comfort.

3 Humidity and Temperature Monitoring

The thermal map of a building is dynamic and depends on various factors including the building envelope heat transfer, cooling/heating sources, as well as humidifier/dehumidifier systems. The first means of heat transfer between indoor and outdoor climates occurs through the building envelope via conduction, convection and radiation. The second important means for heat transfer occurs through air exchange (infiltration/exfiltration).

To capture the heat transfer and relative humidity, the main component of the thermal comfort monitoring and simulation system is the data acquisition module. This module is implemented using embedded/smart wireless sensors integrated into a local wireless network. The data acquisition module has several features:

- Sensor dimensions and energy consumption is minimized;
- The hardware components are cost-effective;
- High accuracy for temperature .01°C, relative humidity ±2%
- High reliability (99.9%) of the network;
- Simple command and control communication protocol tunneled through Bluetooth wireless.

The solution for system includes a Bluetooth transceiver and an embedded control system, Arduino Uno [Arduino 2015] based on ATmega328 microcontroller as illustrated in Figure 1.

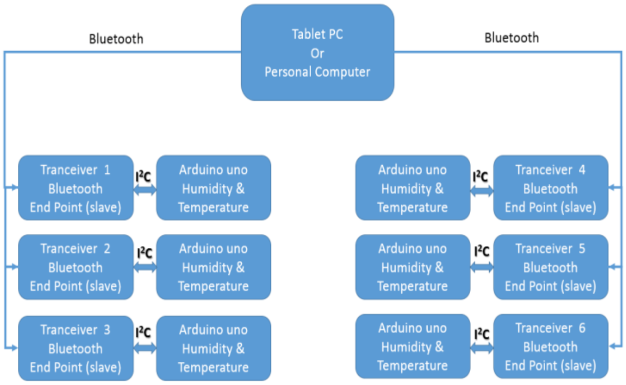

Figure 1: *Block diagram of end-point Bluetooth sensors*

The system concept is based on the idea of shared memory through a shared file. The file is written by several sensors and read by a master (e.g. laptop, tablet or smart phone) once per second. Each line in the file contains the sensor ID, the temperature value (signed integer) and the relative humidity value (unsigned integer). Data is used in the color-coding scheme of the X3D temperature map. On a single Bluetooth node, the system can connect up to 7 smart sensor terminals, however the smart sensors network can be scaled on multiple levels and can include dozens of sensors based on an ID system and in accordance with the network topology. The data communication bandwidth can reach 1Mbps hence real-time data collection and processing is possible.

A cost effective (5$/unit) set of temperature/humidity sensors SHT21 [Sensirion 2015] (illustrated in Figure 2) with potential for mobility are deployed in the corners of each room. We choose to monitor the corners of each room, however other configurations may be chosen based on the architecture or other requirements (e.g. monitoring the HVAC vents).

The sensors are light, accurate and have a short time constant. The power supply is a flat battery that can power the system for several months. The sensor system can be easily scaled to hundreds of sensors and deployed in each room of a building. An 8 to 14 sensor-configuration per room can be chosen depending on the accuracy of the temperature/humidity requirements.

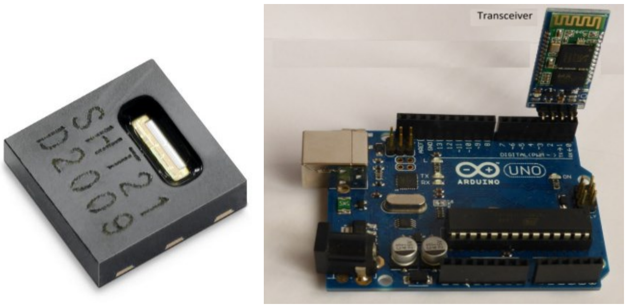

Figure 2: *(Left) Sensirion SHT21 relative humidity sensor; (Right) End-point sensor: SHT21, Arduino, Bluetooth transceiver*

In case of large-scale deployment of a swarm of sensors (e.g. in case of modeling the thermal comfort for a commercial building) the total cost of the sensors system will be reduced by considerations of mass-production.

4 Data Acquisition and Representation

Sensor data acquisition involves a memory buffer located on the end-point that collects temperature and relative humidity samples on the end-point system. The wireless sensors are producing measurement values every second, while the data buffer is consumed by the data acquisition client (DAQ) that plays the role of the master (e.g. a tablet, smartphone or PC), or the data is saved on permanent storage for later use (e.g. playback of sensor data for extended periods of time, weeks or months). Also, the DAQ can be connected on the Internet and thus, the data can be accessed remotely and displayed on other system using a simple browser. The buffer with data samples is circular and the values that are provided to the client for simulation purposes or storage are always the last ones stored into the buffer. Consequently, by design, different sampling rates can be implemented and a real-time X3D thermal map can be obtained.

4.1 X3D Thermal Maps

The building structural design can be easily obtained from various CAD-based modeling tools like SolidWorks [Solid Works 2015] that allows the conversion to VRML format and hence to X3D. The complexity arises when we try to generate a volumetric representation of the temperature and the relative humidity in each room of the building based on the sensor data while allowing easy navigation and enhanced visualization.

Several X3D components have been investigated and their tradeoffs are discussed next. X3D offers a Fog node [X3D Fog 2015] which allows linear or exponential visibility reduction as well as color addition in the environment simulating the humidity vapors in the air as illustrated in Figure 3; however there is no control over the geometry and no possibility of color gradient. X3D geometric primitives (e.g. Box, Sphere) seem to be good candidates for 3D thermal map representation as their R, G, B and α-values (transparency) can provide a 3D temperature map as illustrated in Figure 3- right.

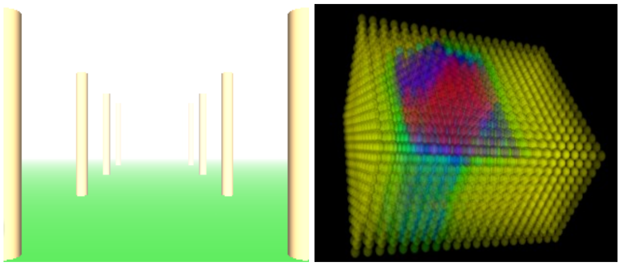

Figure 3: *Possible 3D Representations for temperature: (Left) X3D Fog node, (Right) X3D spheres with modified α-value.*

Since the X3D primitives' position and color/α-values can be controlled in a straight forward manner, the authors choose to model the volume in each room as a set of tangent semi-transparent color spheres. The sphere's color represents the average relative humidity (or temperature) at the respective location (as illustrated in Figure 3 - right). The α-value of the sphere is set in such a way that different levels of transparency can be achieved depending on the view-point distance from the building. Values are interpolated to determine intermediary relative humidity values. Linear interpolation is used currently as illustrated in Figure 4, however, more complex models may accurately and better represent relative humidity/temperature values.

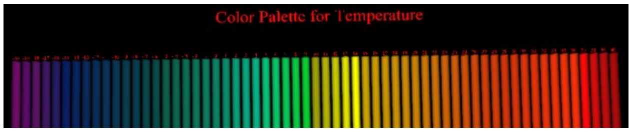

Figure 4: *Bell - shaped gradient colors*

Researchers configured a small house with the set of sensors. They considered each rectangular room as a 3D container of semitransparent, tangent spheres that illustrate the 3D relative humidity map. The sensors have been placed in the corner of each room. The walls are rendered semi-transparent as illustrated in Figure 5 - left and as a wireframe, Figure 5 - right. One can explore different viewpoints and visualize heat distribution in the house volume. As illustrated in this simulation example, the left corner of the building is overheated due to poor attic insulation or due to an insulation defect in the exterior walls.

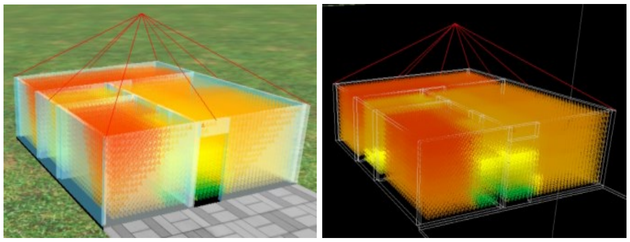

Figure 5: *Web-Browser view of residential building thermal maps: (Left) flat, (Right) wireframe.*

At current rates of 1Hz the sensor generated data can drive a one-frame per second animation of the X3D thermal map using the Bit Management Contact Player plugin [BitManagement 2015] for any Web-browser. Sensor data can also be stored for large periods of time (e.g. months or years) and played-back as a sequence of thermal maps that change color in time, hence thermal map dynamicity can also be illustrated.

4.2 Scaling to Large Commercial Buildings

The X3D semitransparent thermal map is scalable to large commercial buildings, however the difficulty in scaling resides in (1) the sensor placement strategy, and (2) the X3D representation. For sensor placement we consider deploying manually a large set of sensors in each room of the building and keeping one data collector for each level. Data collectors can store large sets of data (e.g. storing one year of sensor data is possible) and can also provide access to the collected sensor data through the existing wired or wireless network implemented in the building. Just as an example, a fourteen sensors per room configuration will place sensors in each corner as well as in the middle of each wall (including ceiling and floor).

In terms of the X3D representation, for large commercial buildings the authors adopted several polygon reduction techniques. First, researchers replaced the spheres due to their relatively high polygonal count, with the Contact Player [BitManagement 2015] tessellation approximately 300 polygons per sphere. Furthermore, researchers investigated the Box primitive (12 polygons), a custom made Tetrahedron (4 polygons) as well as simple Billboards (1-2 polygons). Interactivity rates of 10-15 frames-per-second were obtained with Tetrahedrons as well as with Billboards. Figure 6 illustrates the X3D thermal map for a 6-story commercial building.

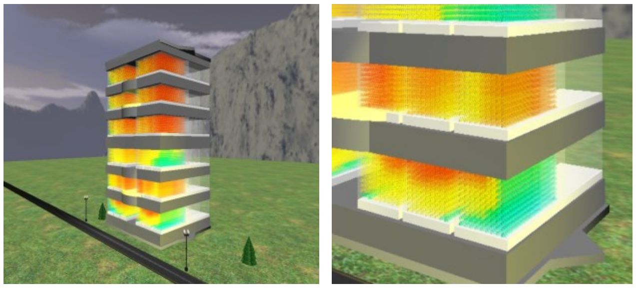

Figure 6: *Web-browser view of commercial building thermal maps: (Left) overall building envelope, (Right) zoom on corner*

The data was artificially generated to replace the sensors data since the authors aimed at proving that the simulation can be easily scaled up to large commercial buildings or even city models.

Scaling the model to various commercial buildings is especially valuable for both researchers and designers of HVAC systems by potential aiding in the pre-construction phase the evaluation of thermal comfort and indoor air quality. It also allows for designers to develop low-energy cooling and heating strategies such as natural ventilation systems and passive heating or cooling systems. This study does not entail a Computational Fluid Dynamics (CFD) part to help with heat transfer in case of non-laminar air flow that may exist in some parts of the designed rooms and that is more computationally intensive. However, as Chung [2015] mentioned, while CFD have been utilized on building components or small-room-size analysis, whole-building energy analysis almost always is a simplified (time-stepped) heat-transfer analysis that does not use CFD. Users can produce results that are representative of the actual interior physics assuming a laminar air-flow, non-turbulent steady-state condition of airflow. Various simulations can be run assuming the locations and placements of the HVAC components throughout the rooms, lobbies and hallways.

The X3D simulator allows building level observations (e.g. roof efficiency, building envelope efficiency) as well as room level observations (efficiency of the HVAC system, cold/hot air drafts, window insulation efficiency, etc.). Moreover, these observations can be made for any time of the day and/or night when large variations of outdoor temperature are possible. Observations can also be made for large periods of time to monitor seasonal (spring, winter, summer) efficiency and thermal/humidity changes. Year-long observations are also possible in order to quantify the building ageing process and estimate energy losses. Many other scenarios can be simulated, for example, the effect of changing internal/external architectural elements on the thermal maps down to simple scenarios like forgetting an outside window or an interior door opened in the building.

5 Simulator Validation Through IR Imaging

The authors have proposed a validation method for the simulation system using infrared (IR) thermography with a thermal imaging camera. The IR images will be taken to expose areas on specific rooms with potential thermal issues that may have been started after construction (for as-built modeling), like poor or inadequate insulation, air leakage, heating and plumbing issues, water damages due to leaks, condensation, mold or identification and location of other potential problems that ultimately will affect thermal comfort.

Building insulation quality becomes a pressing issue nowadays, as heating costs soar and heat leakage and thermal bridges are most common phenomena. Thermal imaging is a powerful tool for determining the energy efficiency of spaces within buildings. Here it will be used for existing construction in case that potential issues are being investigated. The simulation part will confirm the dynamic nature of the issue, while the thermal camera will capture at a certain point in time the overall problem to be addressed. The procedure can save repair time and heating costs due to early issue detection and simulation study performed afterwards. Facility maintenance and facility managers can be involved in this process with the commitment to diagnose and address the issue right after discovery.

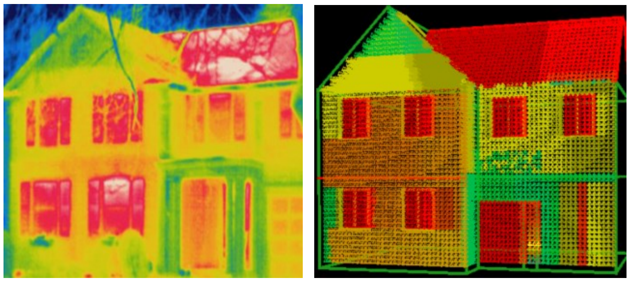

Figure 7: *Validation method through visual comparison of: (Left) IR camera imaging and (Right) X3D thermal map*

The model validation is illustrated through a comparison process as shown schematically in Figure 7. It is assumed that the CAD or BIM models are available at this stage, in order to generate the X3D thermal map of the structure in focus.

6 Conclusions

This research presented a basic and cost effective system for temperature/humidity data acquisition and an X3D module for 3D Thermal Maps representation. The system can be used for assessing the thermal comfort for residential or commercial buildings. The X3D model coupled with the sensor system that we propose can also be employed in the design phase of commercial as well as residential buildings to improve the design of the building envelope and assemblies and generate important energy savings. Another application is in the design and setup the HVAC systems, specifically for commercial buildings where the thermal comfort has to be maintained under various conditions (e.g. large crowds and special relative humidity for storage rooms).

Building energy modeling can be applied early in the design development phase, as a collaborative effort between the energy consultant and the architect. Initial energy modeling scenarios may use forward simulation models such as this X3D computer simulation to predict approximate values for annual energy consumption and energy costs. The study will be expanded for case studies dealing with various human comfort zones during year-round seasons as humidity plays a major role in heat transfer. Many other factors influence human thermal comfort like: metabolic rate, clothing insulation, air temperature, mean radiant temperature and air speed. Psychological parameters such as individual expectations also affect thermal comfort, however this is beyond the scope of this paper.

A direction that the researchers will explore is the data correlation with external temperatures. The detailed analysis of temperature/humidity values recorded by sensors may be correlated with external temperature/humidity data received from weather stations in different locations/regions in US, as they provide relatively accurate readings.

While Building Information Modeling (BIM) is not a new concept for construction industry, the building industry has recently focused more consideration on the practical use of BIM and simulation tools. Even though the intelligence is lost due to transfer of these files (mainly parametric objects) into the X3D environment, the proposed system replaces the virtual model of a building with a three-dimensional virtual prototype containing a swarm of sensors that generates important thermal information ready to be used in design and/or operation of buildings. This allows energy consultants to convey embedded information to the design team to integrate materials and specifications of the building into a database as the building is being designed, and to export input characteristics to other analysis tools, such as CFD or energy simulation for thermal comfort purposes.

One of the most exciting parts of this research is the low-cost of the system to be implemented and the software-free visualization and generation of thermal maps. This process can be useful and can streamline the design and construction phases for HVAC components also. If different stakeholders in the project share a common web-based model that can be used for cost and energy analysis throughout the design and for comfort purposes, ulterior modifications, retrofitting of the HVAC components for comfort of the inhabitants can be eliminated and therefore saving labor and materials during occupancy phase. The model can also be distributed to the contractors and owners in order to improve the communication intent of the design. It is obvious that the system can be used efficiently as a building diagnostic tool for potential issues that may appear after occupancy. These issues may relate to the HVAC or other mechanical/electrical systems within the constructed facility.

On another note, the primary trade-off for the increased accuracy of hourly simulations is the increased time and effort that is required for making larger-scale buildings more interactive in order to illustrate the dynamic changes of the temperature. This simulation should be used during the early planning phase to determine the order of magnitude of impacts related to design alternatives. The type of early design impact analysis allowed by X3D sensor-based thermal comfort simulation may be one of the key aspects of sustainable design, pre-construction, construction and operation phases of the respective residential or commercial building.

References

ARDUINO UNO (2015). “Arduino Uno, technical specifications”. Available online at http://arduino.cc/. Accessed March 3, 2015.

BITManagement (2015). “BS Contact Player” Available online at: http://bitmanagement.com/en/products/interactive-3d-clients/bs-contact. Accessed March 10, 2015.

CHRISTIE, M., ASPER, C., MORTON, J., BERRY, C. and BRAND, D. 2014. “Moving Beyond Better than Code: New Market Transforming Zero Net Energy Aligned Residential New Construction Programs”. Proceedings of the 2014 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: ACEEE.

CHUNG, D. (2015). Historic Building Façades: Simulation, Testing and Verification for Improved Energy Modeling. *Journal of the National Institute of Building Sciences*, Feb., (3), No. 1, 16-21.

HAM, Y., and GOLPARVAR-FARD, M. (2014). 3D Visualization of thermal resistance and condensation problems using infrared thermography for building energy diagnostics. *Visualization in Engineering*, 2(1), 1-15.

LEE, D. (2008). Development of Light Powered Sensor Networks for Thermal Comfort Measurement. *Sensors*. (8), 6417-6432.

LEE, K.H., and SCHIAVON, S. (2014). Influence of Three Dynamic Predictive Clothing Insulation Models on Building Energy Use, HVAC Sizing and Thermal Comfort. *Energies*. (7), 1917-1934.

NIBS (2015). *National Performance Based Design Guide*. Building Enclosures section. Available online at: http://npbdg.wbdg.org/enclosure.html. Retrieved Mar.5, 2015.

NICOL, F., HUMPHREYS, M., SYKES, O., and ROAF, S. (1995). *Standards for thermal comfort*. TJ Press Ltd., UK

PEETERS, L.F.R., DEAR, R. de, HENSEN, J.L.M. and D'HAESELEER, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, 86(5), 772-780.

PITTS, A. (2013) Thermal Comfort in Transition Spaces. *Buildings*. (3), 122-142.

RIJAL, H. B. (2014). Investigation of Comfort Temperature and Occupant Behavior in Japanese Houses during the Hot and Humid Season. *Buildings*. (4), no. 3: 437-452.

SENSIRION (2015) “Sensirion Relative-Humidity Sensor”. Specifications online at: http://www.sensirion.com/. Accessed March 10, 2015.

SOLID Works (2015). Online at http://www.solidworks.com. Accessed February 10, 2015

VOSS, K. and MUSALL, E. (2012). “Net zero energy buildings - International projects of carbon neutrality in buildings 2nd edition, November 2012, Institut für internationale Architektur-Dokumentation GmbH & Co. KG, München, ISBN 978-3-920034-80-5.

WONG, K. D., and FAN, Q. (2013). Building information modeling (BIM) for sustainable building design. *Facilities*, 31(3/4), 138-157.

X3D FOG. The X3D Fog node. (2015) Available online at: http://doc.x3dom.org/developer/x3dom/nodeTypes/X3DFogNode.html. Accessed February 15, 2015.

ZHAI, Z. (2006). Application of Computational Fluid Dynamics in Building Design: Aspects and Trends, *Indoor and Built Environment*, Aug. 2006, vol. 15, no. 4, 305-313.