Towards Occupancy-Driven Heating and Cooling

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Editors' notes:
HVAC systems are eventually needed to maintain comfort for occupants, and as a result sensing and leveraging user context information is critical for the energy-efficient operation of buildings. This article describes an occupancy-driven HVAC control framework for more effective heating and cooling management.

—Yuvraj Agarwal, University of California, and Anand Raghunathan, Purdue University

Heating, ventilation, and cooling (HVAC) accounts for 38% of building energy usage, and over 15% of all U.S. energy usage, making it one of the nation's largest energy consumers. Programmable thermostats have long been thought to reduce the energy required for heating, ventilation, and cooling (HVAC) by 20%–30% by tailoring the conditioning of buildings to the daily activity patterns of their occupants [5]. These expected savings, however, have not come to fruition. In fact, recent studies have found that households with programmable thermostats actually have higher energy consumptions on average than those with manual thermostats [9]. As a result, the EPA recently suspended the Energy Star certification program for all programmable thermostats, effective December 31, 2009.

Advanced sensing technologies and advanced building operation techniques can be used to reclaim the energy savings that were expected from—but not realized by—programmable thermostats. This energy savings is a *low hanging fruit*: a large amount of energy can be saved at a very low cost. To achieve this goal, we are producing *occupancy-driven heating and cooling* technology, in which novel sensing systems extract information about the occupants to more strategically and effectively deliver comfort based on occupants' needs.

The impact of many otherwise effective energy saving technologies is limited by high initial cost, because they can take years or even decades to produce a positive return on investment. The American Recovery and Reinvestment Act of 2009 allocated $5 billion toward helping low-income families improve the weatherization of their home. However, this money is only expected to achieve a small percentage of the national target for energy reduction, and achieving the actual target will require many billions more. In preliminary work described in Section II, we deployed sensors in 8 homes and demonstrated a 28% reduction per household in the energy required for heating and cooling, at the cost of only $25 in additional sensors [7]. The final sensing solutions produced by this research is expected to cost less than $100–$200 per home in hardware, and less than $0.10 per square foot in office buildings. It will also be easy to retrofit existing homes and buildings. This cost profile will give more *bang for the buck* to federal stimulus money: we expect a cost of less than $10 billion in

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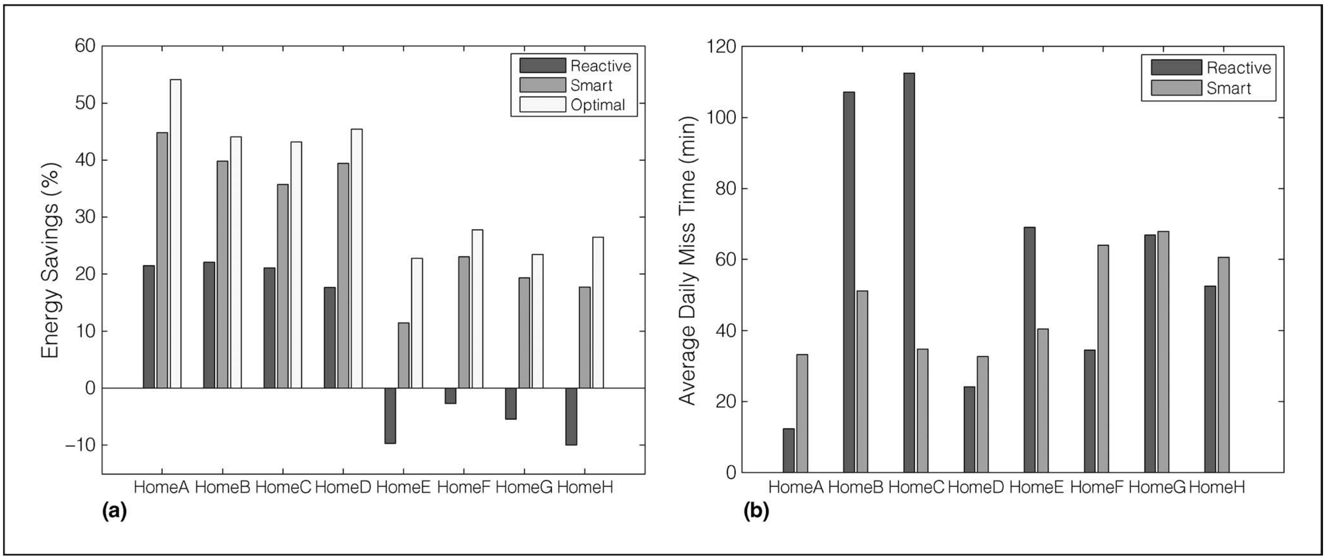

Figure 1. Based on data collected in eight homes, the smart thermostat saves more energy than reactive systems and sacrifices less comfort. (a) Expected energy savings for eight households; (b) home miss time benchmark.

hardware to equip all 130 million homes in the United States with our system, saving an estimated 113.7 billion kWh nationwide per year.

However, we have found that achieving the full potential of occupancy-driven heating and cooling requires more than simply connecting a thermostat to motion sensors; it requires a fundamental shift in the design goals of buildings and equipment. Buildings have dynamic occupancy and operations; as such, typical HVAC and building equipment—built for steady state operation, cannot provide the speed and efficiency required to adapt to the building occupancy dynamics. We need new types of heating and cooling equipment and new designs for building envelopes that cater to dynamic building operation. Strategic delivery of comfort to occupants would also need coordination between the building equipment and the building envelope.

Preliminary Results: The Smart Thermostat

Programmed thermostatic control operates on a predefined *setback schedule*: the house or office building is conditioned to a *setpoint* temperature when the occupants are typically active, and floats to a more energy efficient *setback* temperature when the occupants are typically away or asleep. This approach wastes energy in several ways. First, the occupants may leave home earlier than the schedule they programmed the thermostat with; the system wastes energy because it continues to heat the home until the scheduled time of departure. Second, the setback temperature is well above the safety limit for the house, causing energy consumption even while the house is vacant. This type of *shallow setback* is typically used as a safety precaution, in case the building actually is occupied at that time. Third, the occupants become uncomfortable if they return earlier than expected because the system is not scheduled to heat the house until much later. This causes people to reduce their use of setback schedules, or stop using them altogether. Over 50% of households that have programmable thermostats are reported to not use setback periods at night or during the day [3]. We designed and evaluated the *self-programming thermostat* that automatically chooses the optimal setback schedule based on historical occupancy data [6].

An alternative to the programmable thermostat is the *reactive thermostat*, which uses motion sensors, door sensors, or card key access systems to turn the HVAC equipment on and off based on occupancy [8]. However, our preliminary studies found that reactive thermostats save less energy than programmable thermostats in residential buildings and in four out of eight households actually increased energy usage by up to 10% [6], as shown in Figure 1a. This same phenomenon has been observed in previous studies of programmable thermostats [4]. In summary, the energy saving potential of reactive thermostats is limited by their inability to respond quickly to building occupants.

In preliminary work, we created new thermostat designs that control heating and cooling based on occupancy. The first system, called the self-programming thermostat, learns an optimal schedule for a household based on historical occupancy patterns, and is most suitable for homes with consistent schedules. The second system, called the *smart thermostat*, also leverages historical patterns but also tries to respond in real-time to changes in occupancy. This approach is more suitable for homes with highly variable and unpredictable occupancy We trained a hidden Markov model (HMM) to use the time of day and features of the sensor data to detect building vacancy to within about 5 minutes of when occupants actually left, without falsely detecting building vacancy when residents were simply sitting still in the house. We also used historical trends to predict the time that residents would return to the house to preheat the home immediately before they return. We used preheating which improves occupant comfort and also saves energy by allowing the most efficient heating stage to be used, instead of the heating stage with the fastest response time. We evaluated this system using empirical sensor data traces from eight homes and survey studies of 36 people that were performed using personal interviews on a daily basis for four weeks [7]. This algorithm achieved 28% energy savings on average, using the Energy Plus simulator and our model of a residential building, and operated correctly using as few as 3–5 motion sensors per home, for a total cost of about $25 in additional hardware per home. In contrast, the Bay Web reactive thermostat saved less energy, and even increased energy usage in four of the homes.

The key challenge of this research is *thermal lag*: people can change location very quickly, but a building can take more than an hour to change 5°–6°. Thus, even in the absence of sensing errors, it is not possible to achieve idealized operation that heats and cools exactly when and where the building is occupied, with perfect human comfort and no energy waste. High thermal lag entails that the system must heat and cool *in anticipation* of future occupancy. Being too aggressive about energy savings, however, will sacrifice human comfort, shorten the lifetime of the equipment, and even cause more energy waste because of rapid equipment cycling. On the other hand, being too conservative will waste energy by conditioning unoccupied spaces. Our research attempts to address the question: *How should decisions about equipment operation be made, given the uncertainty of future building occupancy?*

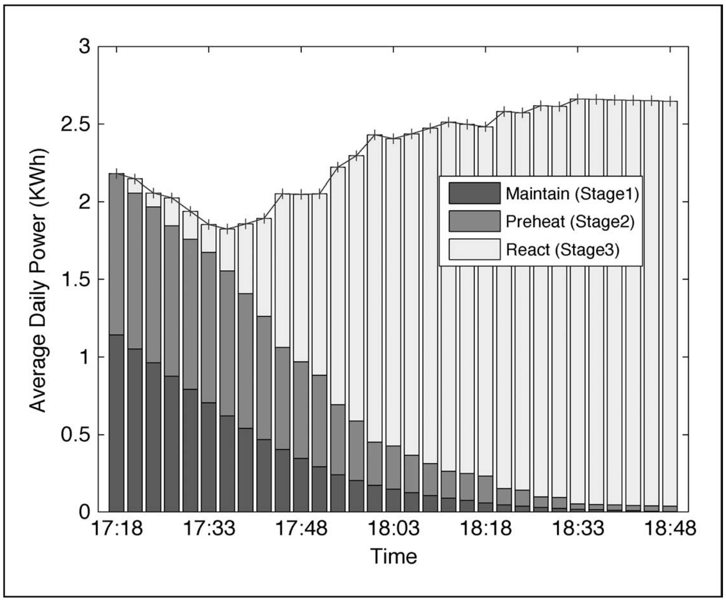

Figure 2. Expected energy to preheat for each target time.

The biggest challenge of the smart thermostat is deciding when to preheat the home, given uncertainty about when occupants will return. Figure 2 shows the expected energy required to preheat an average residential building at every time from 5 pm to 7 pm, assuming the occupants will arrive at 6 pm with a 20-minute standard deviation. If the system preheats much earlier than the occupants usually arrive, it wastes energy due to maintaining a high set point temperature for an unoccupied building. If the system preheats much later than the occupants usually arrive, it wastes energy because it must react quickly with the inefficient but fast-reacting Stage 3 electric heating system. The optimal preheat time changes based on the house response, the equipment efficiency, the weather, and many other unpredictable factors.

Dynamic building controls

Using building occupancy to control heating and cooling requires more than simply connecting a thermostat to motion sensors; it requires a fundamental shift in the design goals of buildings and equipment. For example, conventional buildings and HVAC equipment are typically designed for efficient steady-state operation. However, our preliminary work and analysis indicates that the limiting factor on energy savings will be the speed and efficiency with which a building can *dynamically respond* to building occupants. Newer types of heating and cooling equipment and new designs for the building envelope are needed that improve the efficiency of dynamic building operation. There is also need for control algorithms to electronically coordinate the equipment and building envelope to more strategically deliver comfort to occupants. These techniques will be integrated into a comprehensive solution for *occupancy-driven heating and cooling*, which encompasses all relevant components including sensing, control, equipment, building design, and user interfaces.

Smart zoning

We are working on new techniques to coordinate multiple independent heating and cooling elements within the same thermal zone, i.e., within the same building in locations that are not thermally insulated from each other. Conventional thermostatic control assumes a single piece of equipment that uniformly conditions an entire zone, and if multiple thermostats coexist in one zone they are known to "fight" with each other. Our occupancy-driven approach, however, implies that truly efficient operation requires the coordination of multiple building components, including active building envelope components and possibly multiple different types of equipment in the same zone. Each heating and cooling component will have a different cost profile and will affect some parts of a zone more than others. Our work attempts to address the following question: *How can multiple heating and cooling components in the same zone be coordinated to maximize comfort delivery and minimize energy?*

We are leveraging existing sensing and modeling infrastructure to coordinate multiple components using model-based predictive control. This approach enables more fine-grained control than statically zoned systems, allowing for further optimization based on occupant location. The sensing system uses a dense deployment of temperature and humidity sensors, to learn an empirical model of thermal response in each part of a residential building under study, given the outdoor weather, indoor conditions, state of the windows and doors, and the operating parameters of each component. It also generates a model of the rooms, building layout, sensor locations and types, and the locations and activities of occupants. These learned models will enable the system to compose multiple components to strategically target locations where comfort is needed most.

This system is currently under development for a model residential building. Previous work done on zoned HVAC systems in commercial buildings have used magnetic reed sendors on doors along with motion sensors to determine room occupancy [2]. Although this technique is quite accurate in commercial buildings, where doors are opened when entering and exiting a room, it might not work as well in residences, where doors are kept open most of the time. In preliminary work, we designed and built active registers that can be wirelessly activated to open or close on an individual basis to control air flow. Closing the registers for unoccupied rooms can help heat or cool the occupied rooms much faster. Directing more air flow into occupied rooms can prevent wastage of energy which would have been spent in conditioning unoccupied rooms as well as maintain occupant comfort. This would involve determining real time room occupancy status in the home. Based on the occupancy changes, the registers of the vacated rooms would be closed, and the registers of the newly occupied rooms would be opened. However there are challenges to this approach, as rooms within homes are not thermally insulated from each other. Also, closing the registers for unoccupied rooms may lead to unwanted changes to the temperature of occupied rooms having open registers sharing the same duct way. These challenges require determining the effect of open or closed registers on the temperature in other rooms. Building on results from previous studies [11], [12], we used the experimental bench-top testing framework shown in Figure 3c to verify that the closed registers block nearly 100% of air flow. We are performing controlled empirical experiments to measure the temperature response of all combinations of open/closed configurations, and use this as a model to more directly deliver comfort to occupants of the building.

This system improves on similar existing systems [1] because all active registers are controlled

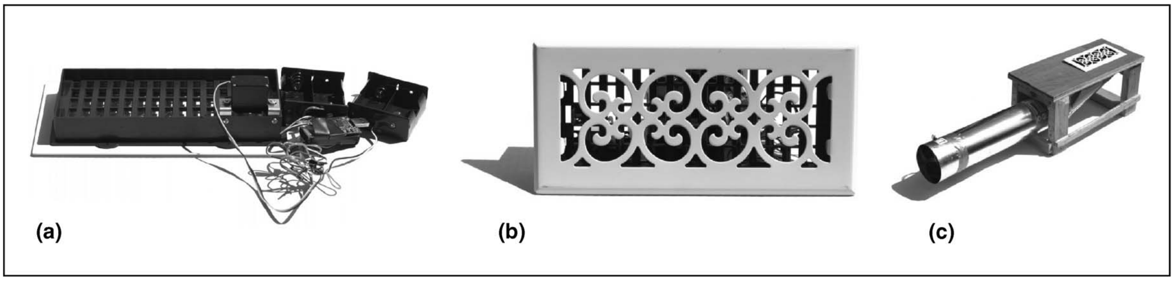

Figure 3. A wirelessly controlled active register (a) was verified to have almost no air leakage in bench-top tests (c). (a) Wireless controller; (b) face plate of active register; (c) bench-top test rig.

independently, even though they are in the same thermal zone. Our preliminary analysis of occupancy in homes shows that, when a home is occupied, the occupants use only a fraction of the house and this fraction can be easily predicted. These results indicate potential for substantially more energy savings than the approach based on complete zone control.

Equipment with efficient dynamic response

Conventional heating and cooling equipment are designed for efficient steady state operation, but are not designed for fast and efficient dynamic response. However, Figure 2 illustrates that the limiting factor of a reactive system is the high energy cost of responding quickly to dynamic building occupancy. In order to fully realize the benefits of occupancy-driven dynamic equipment operation, we are revisiting the fundamental design decisions of conventional equipment to create new designs optimized for dynamic response.

Fast response times are typically associated with low energy efficiency. For example, oversized equipment will heat or cool more quickly, but will be less efficient for steady state operation, and air-based heat pumps are highly efficient but have slow response, while gas or electric heat has a fast response but lower efficiency. Forced air systems can typically provide comfort quickly because the air transfers heat directly to occupants. However, fan energy and resistance in ducts are significant sources of energy loss. On the other hand, studies have shown that the pump energy of hydronic systems is less than the fan energy expended in equivalent forced air system [10], and in-slab hydronic systems are excellent at holding steady-state temperatures. However, they also have slower dynamic response than forced air systems due to high thermal mass. Our work intends to address the question: *How can heating and cooling equipment be designed to simultaneously achieve fast dynamic response and low energy usage?*

We are building and evaluating a new occupancy-driven equipment design that uses hydronic heat transfer to drive convective air flow. This novel, silent, and efficient unit can provide heating, cooling, and humidity control. In heating mode, it operates as a convective radiator. In cooling mode, it operates in a counter-current configuration as air is naturally circulated by thermal convection through the unit, and flows via displacement cooling to cool occupants in the room. This convection-based approach eliminates the high thermal mass typically used in hydronic systems, and combines the speed of air-based delivery systems with the efficiency of hydronic systems. This approach also reduces wasted energy due to thermal conduction to walls by providing comfort directly to the occupants. For example, displacement cooling provides a cool, “pool” of air on the floor. This cool air naturally moves toward heat sources in the space (occupants or heat generating equipment), and flows up the heat source following thermal convection currents. This is in contrast to a typical forced air system, which provide air at high velocity to a space in order to evenly mix all of the air in the room. More energy is required to cool the whole space, instead of the heat sources directly, and also more energy is lost to the outdoors because the walls are in contact with the mixed room air. Another advantage of this design is that zoning of hydronic systems is simple and translates directly into energy savings at the heat source, while zoning of forced air systems produces diminishing returns

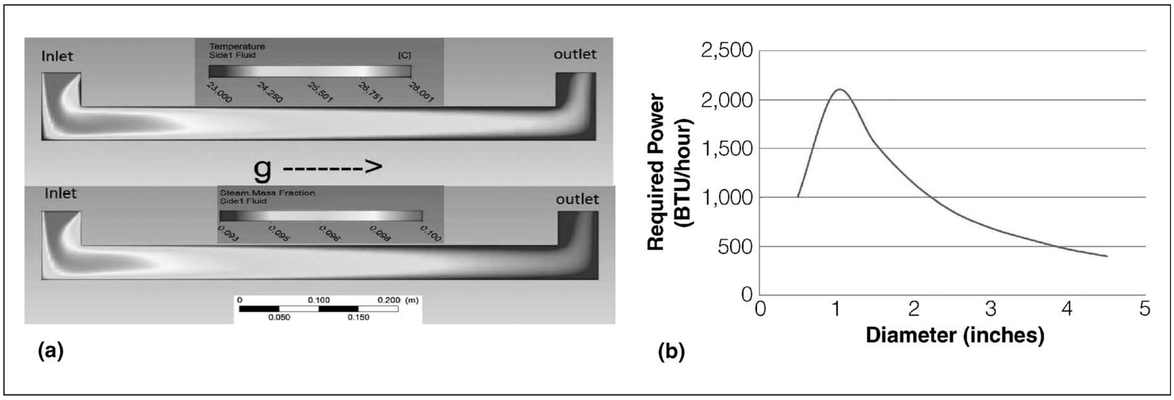

Figure 4. Computational fluid dynamics (CFD) optimization of the diameter of 91-inch long cooling channels. (a) Temperature and steam mass fraction along a 91-inch cooling channel and (b) optimum of the cooling flux as a function of the diameter of the channel.

due to the typical single- or two-stage configuration. This allows simpler and more efficient comfort delivery to individual zones based on occupant location.

In preliminary work, we built and evaluated a prototype of this patent-pending technology using standard hydronic components, and initial test data promise potential for significant efficiency and comfort optimization through further analysis and design. We are planning to optimize the configuration and number of the components within the unit, materials lining the case, pump speed, and water temperature delivery. We are developing analytical tools to generate design data specific to convection, since convective factors differ from the criteria used for designing typical forced air systems. As an example, a computational fluid dynamics (CFD) optimization of the diameter of 91-inch long cooling channels within the notional convective cooling system was conducted. The entering air is cooled and de-humidified by the water-cooled jacket of the passage. For the particular set of parameters considered, the most efficient diameter of the passage which would lead to the highest cooling flux is 1 inch. Figure 4a shows contours of the temperature and steam mass fraction along the channel; and Figure 4b shows the pronounced optimum of the cooling flux as a function of the diameter of the channel. Similar studies, coupled with computer numerically controlled (CNC) fabrication methods will allow for the fabrication of the final prototype units that will be integrated into sensing systems to result in a synergistic system. The product of this research will be a commercializable terminal unit as a *plug and play* component that can be used in lieu of, or in tandem with, conventional systems to improve the overall dynamic response profile.

Dynamic building envelopes

We are creating new architectural approaches to improve the efficiency of dynamic building operation through strategic allocation of thermal mass, in coordination with shading and thermal exchange. Thermal mass in a building typically improves energy efficiency by helping to maintain stable temperatures, reducing the need for heating and cooling at the peak of diurnal temperature swings. For example, buildings in Arizona with high thermal mass are cooler during the day and warmer at night. However, this approach also increases the energy required for dynamic response to occupants. Buildings tend to accumulate heat during the day and therefore require more energy to cool them when occupants return in the evening. The goal of our research is to create a *dynamic building envelope* that relieves this tension by employing thermal mass only when it is advantageous to do so, thereby improving the efficiency of dynamic response without sacrificing the efficiency of steady-state operation.

An important focus of this work is to allow a building to dynamically manage its thermal mass to simultaneously reduce peak loads and provide fast dynamic thermal response, in a cost-effective fashion. We are developing a new architectural approach

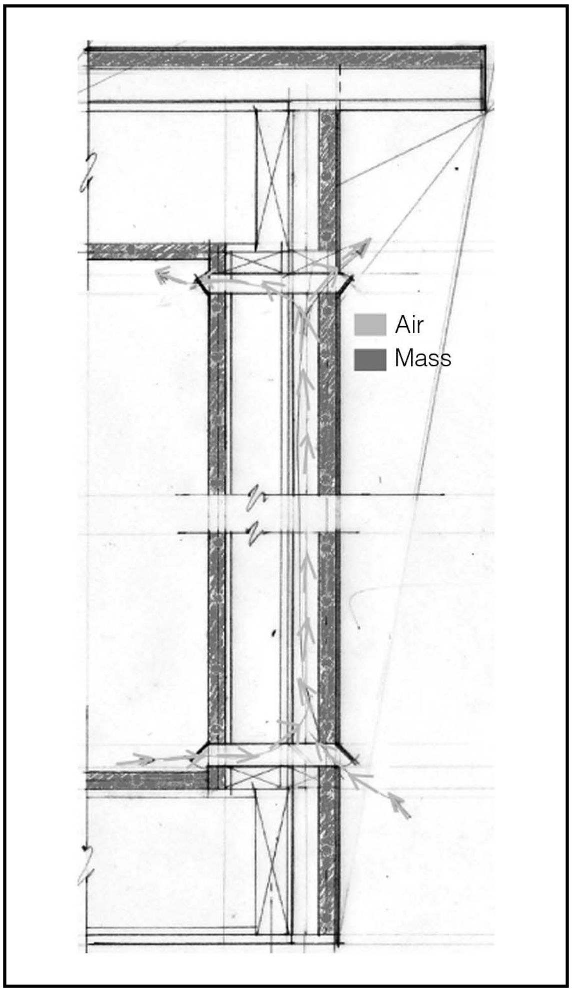

Figure 5. Dynamic building envelope.

for mass allocation in the building envelope that will improve the dynamic response of the building. The basic approach is to allocate more mass on the exterior of the thermal envelope, and to strategically employ it only when needed using a solar wall design. A *solar wall* is an air gap on the exterior of a building that can use solar energy for either heating or cooling. It has both interior and exterior electronically-controlled vents that can be configured as a solar-driven convection heater or to create ventilation in the fashion of a solar chimney, as illustrated in Figure 5. In our research, we explore the effect of allocating a substantial fraction of a building's thermal mass in a solar wall. This configuration can be used to store solar energy much like a battery by closing all vents when the building is unoccupied. When the occupants return, this energy can be quickly released by configuring the vents appropriately for fast and efficient heating or passive convective ventilation. We will combine this approach with an active brise soleil so that the mass can alternatively be used to reduce peak cooling loads, in cases where the building is occupied during the day. The system will also respond to the user opening or closing windows and vents, in order to maximize the effect on ventilation. We will develop two variants of this approach. In the first variant, some of the modularized panels of the test building will have an integrated container that can be filled with dense matter found locally such as sand, to provide high thermal mass while minimizing shipping weight. In the second variant, the wall panels will be augmented to store and release a thermal medium such as water on both the interior and exterior of the thermal envelope, as illustrated in Figure 5, thereby enabling dynamic changes to the mass allocation. Thermal mass can be added to maintain interior temperatures, for example in the morning before the outdoor temperature rises. A thermal medium such as water can be supplied through pumps and/or rainwater collection, and can be transferred between the interior to the exterior as needed. The outcome of our research will be new principles for mass allocation and dynamic building envelope design, along with empirical studies that quantify the cost/benefit trade off of the two system variants.

These new design goals of buildings and equipment lay the foundation for next generation buildings that will autonomously monitor and respond to building occupants, to achieve much greater energy efficiency. We are coming up with new sensing and modeling techniques to estimate both current and future occupancy, and new control algorithms to strategically deliver comfort only as needed. We are also coming up with new technologies to improve the dynamic response of buildings, which will further improve the expected energy savings. This is a fundamental shift from conventional design, which optimizes for steady-state efficiency rather than dynamic response. Our work focuses on practical, low-cost solutions that can be readily translated to market. In preliminary studies, we demonstrated a 28% reduction per household in the energy required for heating and cooling, at the cost of only $25 in additional sensors [7]. Thus, our technology can reclaim the 20%–30% energy savings that was expected from but not realized by programmable thermostats [5]. The ongoing research is expected to increase these gains substantially for existing buildings, which will help propel the nation towards its goal of a 25% improvement in the total energy efficiency of existing buildings across the country by 2030, as defined by the Architecture 2030 Challenge and reiterated by President Obama.

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