DESIGNING FOR THE HUMAN FACTOR: ECONOMIZER EFFICACY AND THE CONSIDERATION OF THE USER

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ABSTRACT

Modern buildings must anticipate high levels of sustainable building performance, involving knowledgeable occupants, renewable systems, and climate-specific strategies. In swing season-dominated climates, passive environmental controls should be thoroughly considered. One strategy is the air-side economizer which uses diurnal temperature swings to provide cooling. A thermostat is set, and when the outdoor temperature dips below that point the economizer draws cool air from outside, flushing the warm interior air. This system can be simulated with reasonable accuracy; however, because it can be affected by the user, any unpredictable behavior can reduce simulation accuracy. This study investigated to what extent human behavior influenced the performance of economizer-based HVAC systems, based on physical observations, environmental data collections, and energy simulations of a residential building in Los Angeles, California. This study revealed that tangible measures for alleviating problems, such as user-friendly interface design and the incorporation of human behavior into energy models could enhance their predictive capacity.

1 INTRODUCTION

There is tremendous potential to save energy by using economizers (essentially whole house fans connected to a smart thermostat) in residential construction in California climate zone (CZ) 8, yet they rarely appear at the residential scale. Economizers can be used in any dry climate where the diurnal temperature swing is significant enough to take advantage of the difference in interior and exterior temperatures. Because economizers do not remove humidity, arid to semi-arid climates provide ideal conditions; even during the warmest months the evening temperatures regularly fall to within or below the thermal comfort zone, as defined by ASHRAE 55, yet humidity remains low throughout the majority of the year (1).

To use an economizer, the occupant sets a thermostat, and when the outside air temperature is below the temperature set point, the economizer is triggered; it pulls air in from outside and flushes out the warm interior air with cooler exterior air, usually during the night. If there is sufficient mass and insulation in the residence, it will cool down and remain sufficiently cool during the following day. Combined with daytime closing of blinds and the use of overhead ceiling fans to reduce the effective temperature, thermal comfort can often be obtained without the use of air conditioning. In previous studies, it was shown that it is possible in half of California's sixteen climate zones to design homes that can be comfortable without the need for air conditioners (2) (3). Typical heating and cooling set points for these climate zones are 70 F (heating) and 80 F (cooling). The economizer typically only provides cooling in California, and this study is only concerned with the cooling set point (80 F). This means that anytime it is below 80 F outside the economizer will turn on and bring in fresh outside air. California climate zone 8 has sufficient hours below ASHRAE's thermal comfort zone throughout the year to merit the usage of an economizer.

Economizers require a degree of foresight to use effectively. On a typical summer day the user must turn the economizer on before going to bed so that it runs all night. It must then be turned off once outdoor temperature rises above the comfort low, to prevent warm air from being introduced. Because this system relies heavily upon the user to operate, the indoor thermal comfort is subject to any interference that might affect the user – if the economizer is not turned on the night before there will be reduced thermal comfort the following day. In theory, this concern can be alleviated by pairing the economizer to a thermostat that uses the occupant's comfort high and low set points to determine the economizer's operating schedule. However, the introduction of a thermostat can add a degree of complexity that can interrupt the operation and performance of the economizer. This study investigates the degree to which the user affects an economizer's performance and the resulting thermal comfort.

1.1 Residential Case Study

During the early architectural design phase of a 70-unit, energy efficient, low-income housing project in southern California's CZ-8, a careful analysis was made of indoor air temperature predictions. Using the software program HEED (Home Energy Efficient Design), results showed that the indoor temperature would always fall within the comfort range defined by ASHRAE Standard 55 (1). Critical to achieving comfort levels was the economizer's ability to provide up to twenty air changes per hour during the evenings, when outdoor temperatures were below the comfort range. The case study building, completed in 2010, incorporates some passive strategies to compensate for not having air conditioning. The units were designed with high mass first floors, blown-in insulation, stack ventilation up the stairwell, and the upper floors have a second layer of drywall, to increase the decrement factor. Blinds were provided at all windows, and overhead ceiling fans were installed throughout each unit. The thermal comfort operating procedure for the units involves setting the heating and cooling set points into the thermostat, keeping the windows partially open throughout the night (to exhaust the warmed interior air), using blinds during the daytime to reflect incoming radiation, and using overhead ceiling fans to reduce the apparent temperature. Unlike a commercial application, where an economizer (and knowledgeable technician) might be responsible for this operation, this project uses individual economizers in each dwelling unit. All the occupants are therefore responsible for their own thermal comfort. If the occupants do not follow the proper procedure, the indoor environment can be negatively impacted. If the system is to be operated by *any* occupant then, it must be understandable by all occupants, not only the most interested and knowledgeable (4).

New computer simulations were run, and data have been gathered from several individual units. Initially, an argument was made that reducing electricity use justified the use of economizers. Although minimizing the building's energy consumption was important, the comfort of the occupants was the primary concern. The defining issues were the comfort of the residents during the hottest days of the year, and the annual energy consumption of the dwelling; the metric chosen for thermal comfort was indoor air temperature in Fahrenheit, and energy use intensity (EUI) in kBTU/ft^2/year for energy consumption.

The most significant impact on the indoor air temperature is the exterior air temperature. CZ-8 has desert-like conditions, with summer temperatures regularly exceeding 80 F during the daytime. Over the course of the testing period (June – September), the local temperature was equal to, or above 65 F for 74.3% of the time, and under 65 F for 25.7% of the time. The highest recorded temperature during this period was 94.9 F, and the lowest was 58.0 F. In a given day the temperature could be expected to fluctuate by over 20 F during the testing period. Even during the warmest periods, there were no days where the temperature did not drop below 80 F at some point. The daily lows typically fluctuated between 60 F and 70 F consistently, and only rose above 70 F during a brief heat wave in August (Fig. 1).

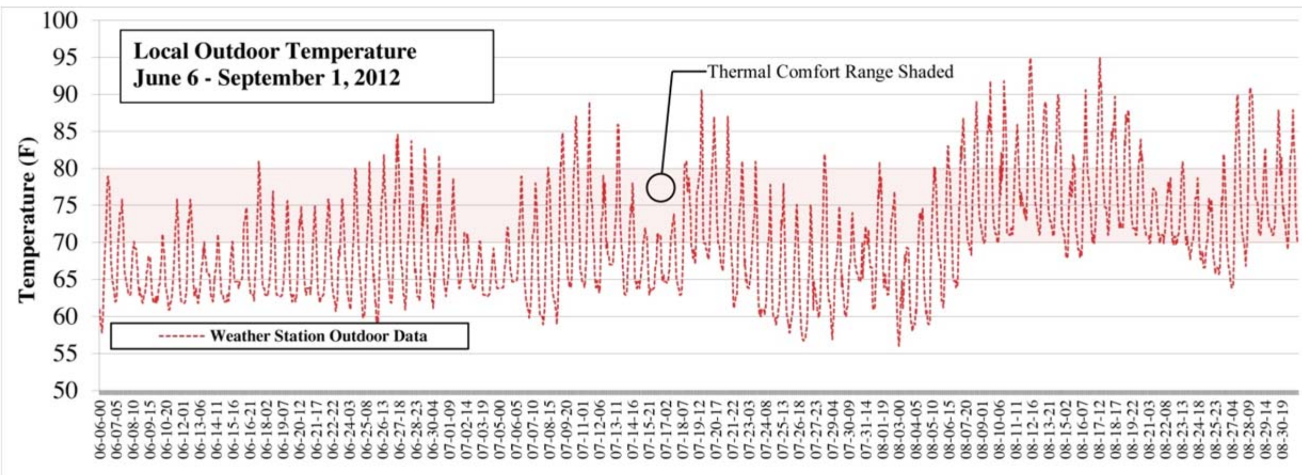

Fig 1: Local Outdoor Temperature

With a cooling set point at 70 F, the economizer could be expected to provide cool air almost every day throughout the summer months, except during the August heat wave.

1.2 Software Results

HEED was used to predict the indoor temperatures of the observed units throughout the testing period to confirm the suitability of using an economizer. The model was run using a thermal comfort zone between 75 F and 80 F to confirm the ability of the economizer to provide cooling for the unit. The sharp drop at the end of June is when the default furnace turned off for the season. Until that point the economizer did not need to provide much cooling because the outdoor temperature was not high enough to warrant its use. In mid-July, when the outdoor temperature began to increase, the indoor temperature can be seen following along, but rarely does it exceed 80 F. It is not until the August heat wave that predicted indoor temperatures regularly exceed 80 F. However, the ceiling fans would bring the effective temperature down by up to 4 F, helping to keep the indoor temperature within the comfort range. The model forecasted that the majority of hours would fall within the thermal comfort zone throughout the entire summer (Fig. 2). There was a significant discrepancy between the predicted indoor temperatures and the measured indoor temperature. The recorded indoor temperature in all the units tested was consistently higher than HEED's predictions (Fig. 3). The recorded temperature averaged almost 4.5 F warmer than the predicted temperature, and sometimes was considerably more. There were also several instances in July and August when the recorded temperature was over 15 F above the predicted temperature (Fig. 4).

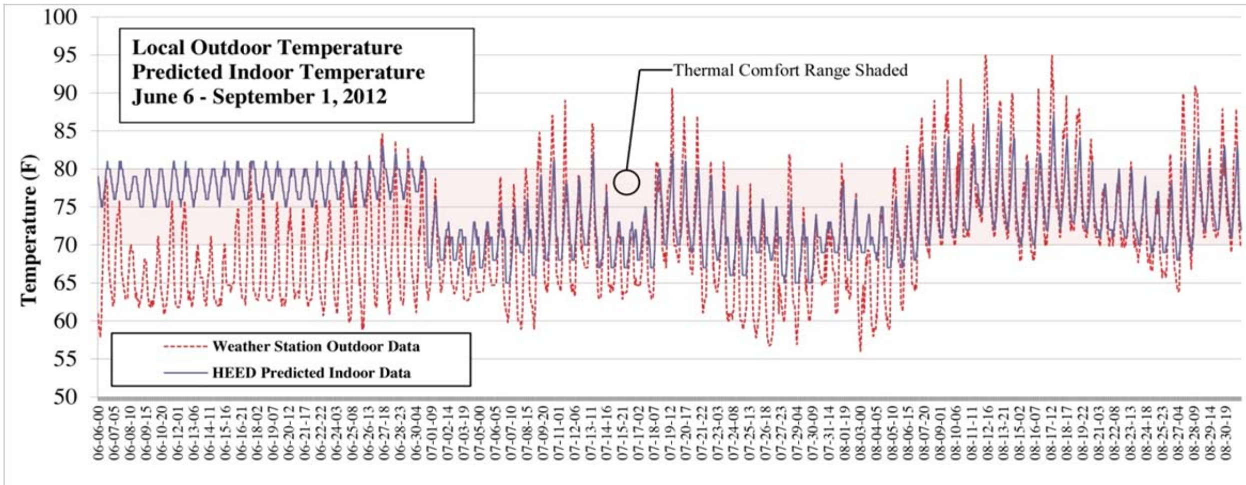

Fig 2: Local Outdoor Temperature, HEED Predicted Indoor Temperature

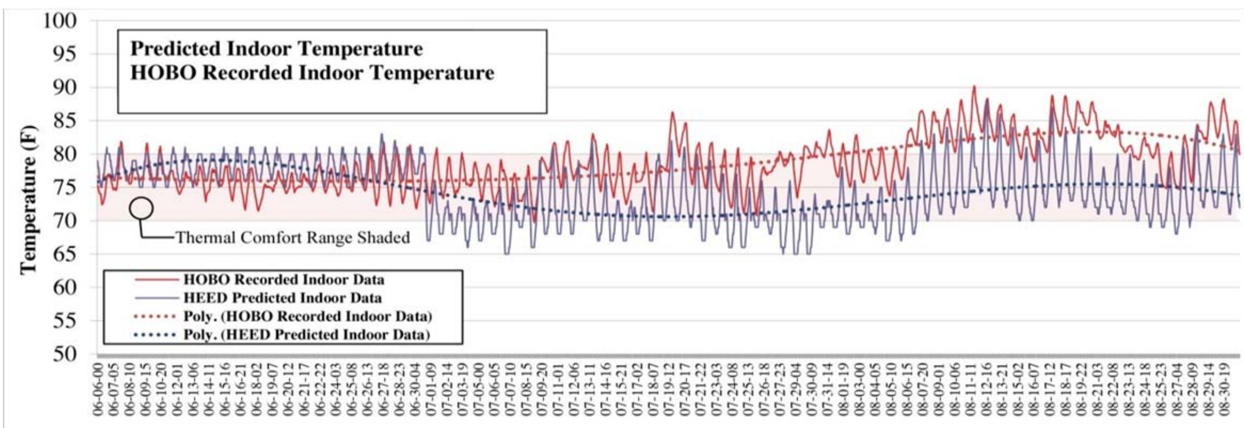

Fig. 3: HEED Predicted Indoor Temperature, HOBO Recorded Indoor Temperature

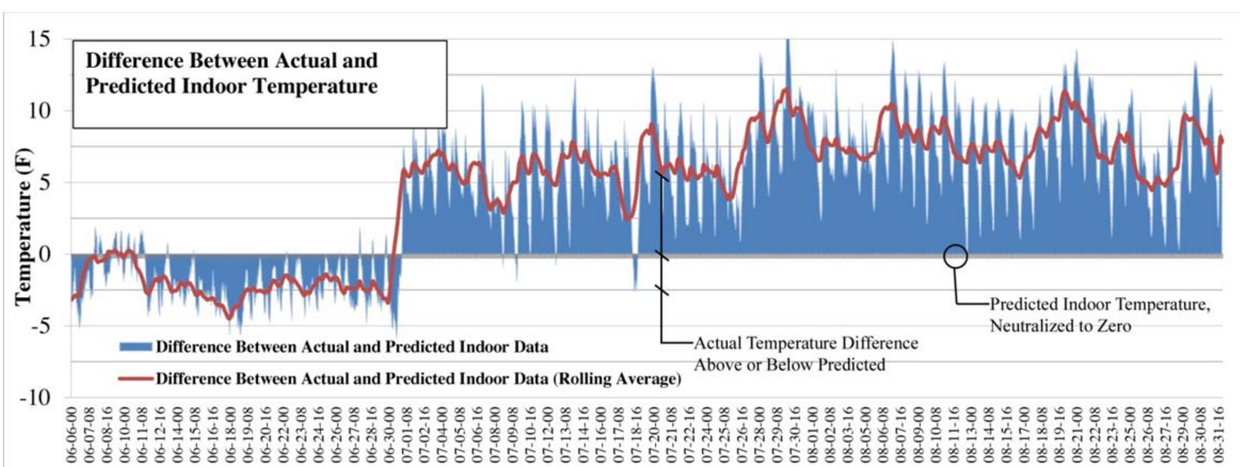

Fig. 4: Difference Between Actual and Predicted Indoor Temperature

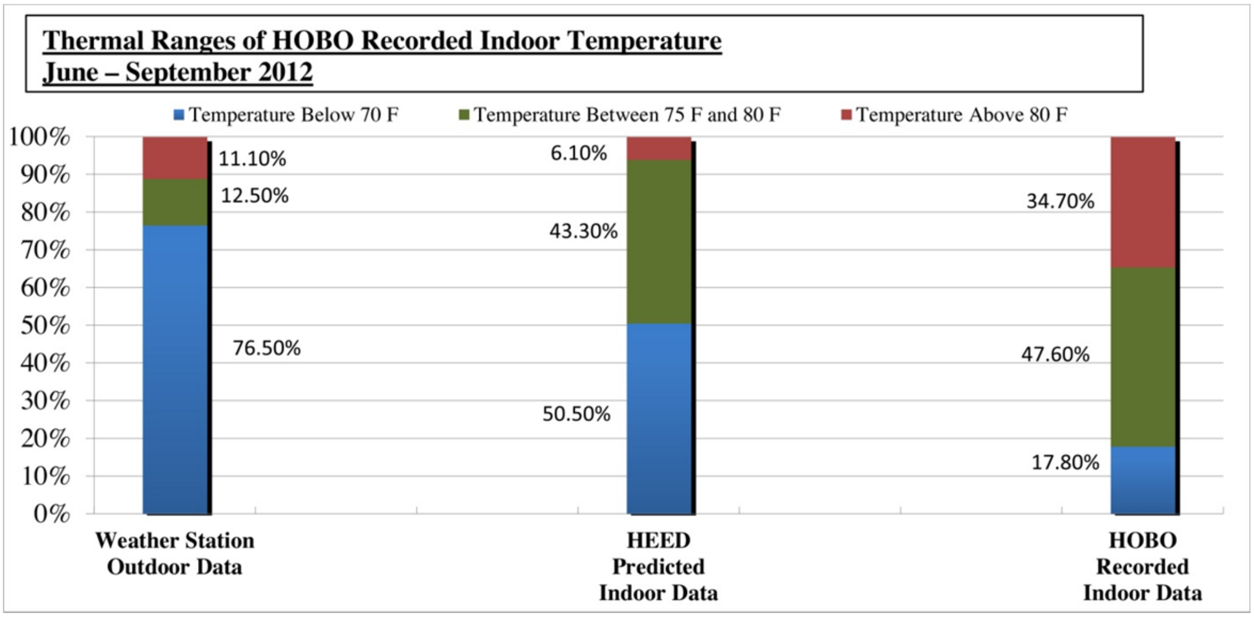

Fig. 5: Thermal Ranges of HOBO Recorded Indoor Temperature

Across the testing period the recorded indoor temperature exceeded 80 F for 34.7% of the time, significantly higher than the 6.1% predicted by HEED (Fig. 4, Fig. 5). Additionally, indoor temperatures dipped below 70 F only 17.8% of the time, despite outdoor temperatures dropping below 70 F for 76.5% of the testing period. The highest recorded indoor temperature during this period was 90.2 F, and the lowest was 69.7 F. 47.6% of summer months experienced thermally comfortable temperatures within the unit- comparable to HEED's prediction of 43.3%. The discrepancy is with the percentage of hours that fall outside of the comfort range. HEED predicted 50.5% of all interior hours would actually fall below the comfort range, while in reality it was only 17.8%. HEED predicted 6.1% of hours to be above the thermal comfort threshold but in reality 34.7% of hours exceeded this threshold.
From these measurements it's apparent that the building is prone to overheating if left untreated. Speculation over the root of the issue included mechanical error, user error, and digital modeling error.

Mechanical error was considered as a potential source of the high indoor temperatures. To test that the system was installed correctly and in working condition, the author and the building's superintendent individually tested each economizer in this study. Testing consisted of lowering the cooling set point to below the outdoor temperature, with the thermostat in "cooling" mode. By observing the interior and exterior dampers opening and closing based on the set points, it was possible to confirm that the economizers were working properly. All of the economizers were determined to be working correctly.

Based on repeated interviews and discussions with the tenants, user error was suspected as a cause of indoor temperatures because most of the tenants interviewed were not familiar with how to operate their economizers and appeared to be operating them incorrectly. Additional examination of this possibility led to the conclusion that despite their best intentions, the tenants were "short-circuiting" their economizers. This possibility is expanded later.

The HEED model was checked for accuracy and against the constructed building to confirm the details of the model matched those of the building. HEED was considered appropriate software based on previous studies (5). The number of air changes per hour achieved by the actual economizer was also measured and incorporated into the model. Additionally, actual weather data from a weather station located near the site was used to ensure the model was being tested under conditions that paralleled the case study building. In particular, dry bulb temperature, relative humidity, direct radiation, and diffuse radiation as measured by the weather station were incorporated into the weather data file used in the model. The result of this vetting process was predicted temperatures that were parallel to, but lower than observed temperatures. The polynomial lines in figure 3 run parallel to each other after the furnace turns off at the end of June. In reality, there was no furnace operating in the building in June, hence the discrepancy. The fact that these lines are parallel indicates that the model is accurately predicting the fluctuation in temperatures but not the base temperature. On average the predicted temperatures remained within the comfort zone for the majority of the time (78%), confirming the appropriateness of the choice to use an economizer. Incidentally, the majority of the remaining time was predicted to be below the comfort zone, not above it.

An analysis of this discrepancy led to closer examination of the model's assumption about the occupant. HEED assumes the occupant correctly adjusts the windows, blinds, fans and thermostat every day, and this operation schedule cannot be changed in the software program. By comparison, the occupants in this case study behaved erratically and very differently from HEED's assumptions, which may account for the temperature discrepancies in figures 3 and 4.

2 METHODS AND APPROACH

Data loggers from Onset Computer Corporation were placed inside five dwelling units to record dry bulb temperature, relative humidity, and in some cases amperage at the economizer. By measuring the economizer's amperage it was possible to determine their operating schedule. When compared against the indoor and outdoor temperature data, the amperage data helped determine if the economizer was operating at the correct time of day. From this data, combined with information from tenant interviews, it became apparent that the economizers were not being used correctly; they were generally operating during midday when outside temperatures were warmest, and the thermostat set points were regularly observed to be outside appropriate operating temperatures.

2.1 Economizer Usage Data Pre-Intervention

Figure 6 shows economizer usage during a week in June, when there was sufficiently cool outdoor air to operate the economizer during evening hours, yet amperage data indicates that it is being used in the afternoon.

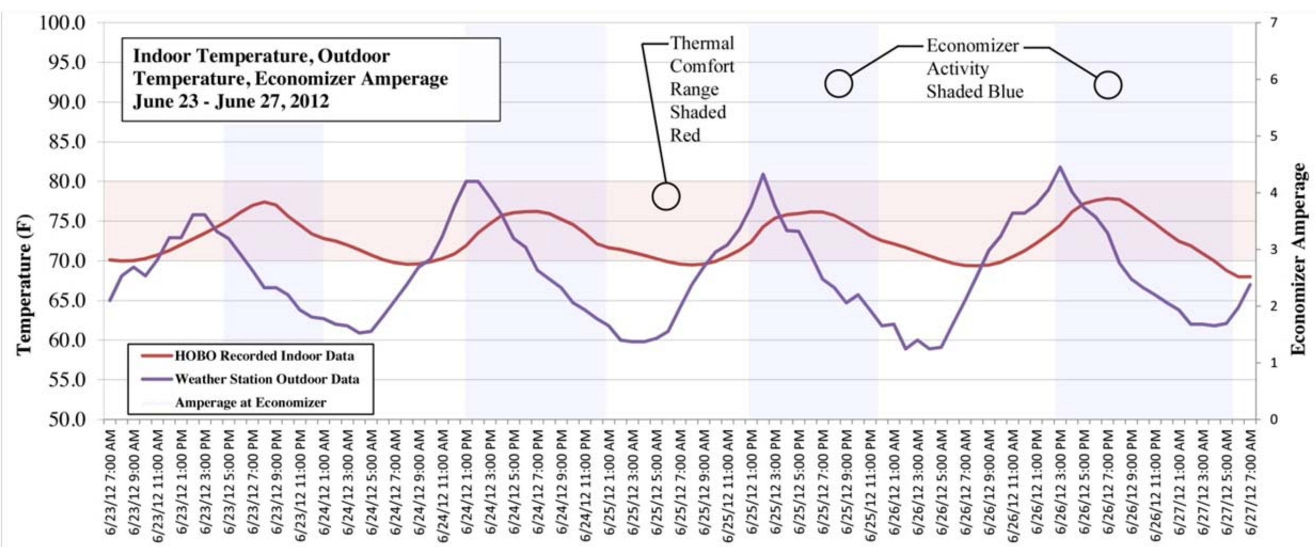

Fig. 6: Indoor Temperature, Outdoor Temperature, Economizer Amperage

The economizer was on between 1:00 PM and 5:00 PM on each of the days it operated (Fig. 6). This timing follows the warmest part of the day, shown by the economizer (shaded pink) consistently turning on at the peak of each day's outdoor high (purple line). The indoor temperature (red line) predictably rises, despite the intention of the economizer to be a source of cooling.

This instance is typical of the various dwelling units observed in the study and is likely due to the occupant's misperception of the economizer for an air conditioner, as indicated by the incorrect thermostat settings (Fig. 7). The thermostats were regularly observed with very low set points, which prevented the exterior dampers from opening and allowing night flushing to ever occur. The words HEAT and COOL appear on the thermostat, and while selecting HEAT provides heated air, selecting COOL does not provide chilled air. The COOL setting is actually the trigger for the economizer, which provides fresh or re-circulated, but not "cool" air. It is evident from the 82 F indoor temperature and the selection of FAN ON mode that the occupant was trying to force cold air from their HVAC system (Fig. 7). This is very detrimental to the thermal comfort, because a 35 F COOL setting would prevent the economizer from bringing in exterior air during any of the months tested, when it's needed the most. Despite repeated conversations with the tenants to explain the correct settings, each site visit yielded unrealistic settings. These variables, including misleading labels, different fan modes, and the override switch on the economizer create a complex scenario that demands a user educated in HVAC systems, beyond what can be reasonably expected in a multi-family residential project. As economizer-based HVAC systems are not commonplace, occupants cannot be expected to possess familiarity with their operation.

Fig. 7: Thermostat set to FAN ON mode, cooling temperature set point set to 35 F

2.2 Economizer Usage Data Post-Intervention

To confirm the suspicion that user error was the primary source of warm interior temperatures, several thermostats were locked in the "AUTO" position, removing the occupant's ability to adjust its settings. These tests were to confirm the economizer could function in a predictable manner, and only lasted several days due to the removal of the tenant's control. All of the tenants were willing to participate, and there were some successes in operating schedules with reduced indoor temperatures. The economizer's turned on at more appropriate times during the day and provided the nighttime cooling as designed to do (Fig. 8).

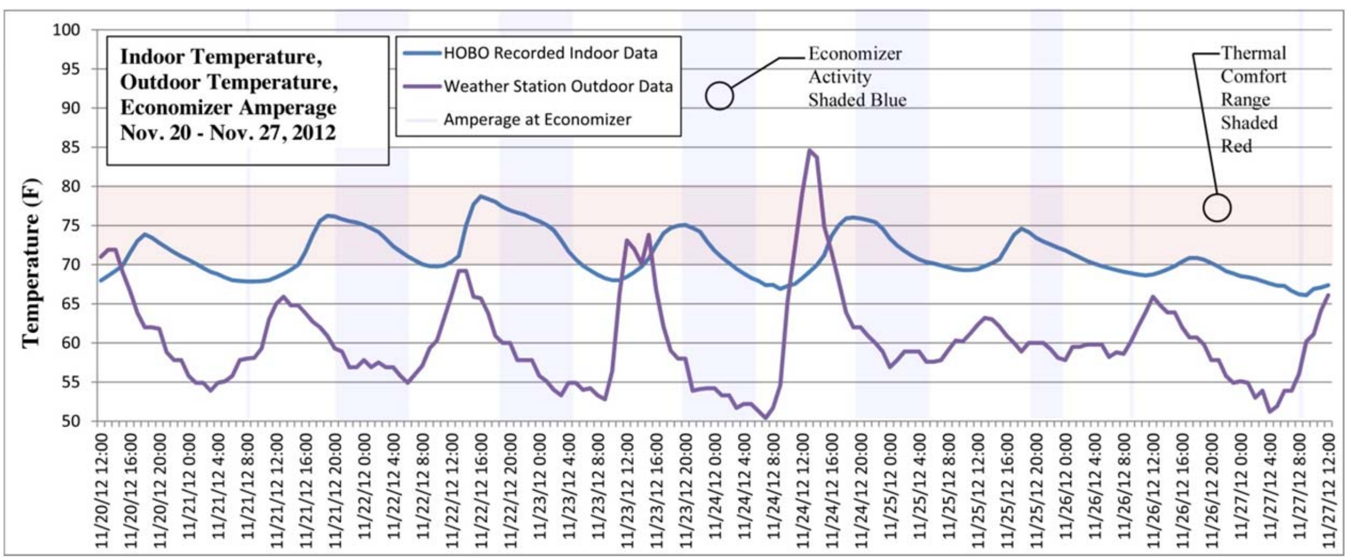

Fig. 8: Indoor Temperature, Outdoor Temperature, Economizer Amperage

3 RESULTS

3.1 Perception of Economizer and Thermostat to Users

The occupants in this study were repeatedly observed interacting with the economizer as though it was an air conditioner, and despite explanations about proper set points and when to use the economizer, the data overwhelmingly displays this error in perception. Because the thermostat appears to provide cooling, the occupants expect it to do so. The data suggests that the economizer was turned on when the occupant wanted instant cooling, unaware that this system, as a thermally delayed system is required to begin operating long before the effect is to be noticed. Although it provides up to 19 air changes per hour, the cool air needs time to chill the building materials within the unit to provide the maximum effect. To achieve cooling on a warm summer day, the economizer needs to have been operating through the preceding evening, and the occupant needs to then insulate their apartment from the warming exterior. Throughout the study it was difficult to successfully convey the idea that the economizer is used to provide *tomorrow's* cooling, not *today's*. The complexity of the user interface was concluded to be a hindrance to its operation because it allowed the user to believe they were setting it correctly when in fact they were "short circuiting" its correct operation.

By forcing the air handler to stay on (FAN ON mode), and setting the cooling set point as low as possible, the user could hear and feel air moving through the ducts and their apartment (Fig. 7). Furthermore, because it is not easily determined whether the economizer is operating with outside or re-circulating indoor air, the fan could potentially remain on indefinitely, indicating to the user that there is a problem with the system's ability to cool the air and not a problem with the settings. This process led the tenants to believe that they were doing everything in their power to provide cooling and to assume the system was broken. Interviews with them lead to the conclusion that it was at this point that they generally gave up trying to "fix" it, and because the air coming he ducts was as warm as or warmer than the indoor air, they generally turned the unit off and relied on the effective cooling provided by the overhead fans.

Whereas air conditioners are generally clear in what they are providing (immediate cool air), the combination of an economizer attached to a traditional thermostat leaves room for miscomprehensions and confusion of what the individual settings do. This discrepancy, combined with the engrained notion of instant HVAC results, is thought to be the root cause of the observed indoor temperatures.

3.2 Problems with Using the Economizer

- Users were generally unfamiliar with the definitions of heating and cooling set points. If these set points are reversed or set incorrectly the thermal comfort will be negatively affected. Unlike a high-efficiency air conditioner, energy reductions in economizer-based HVAC systems require correct settings.
- The thermostat does not display outdoor temperature data so the occupant cannot be sure whether the economizer, if operated at that precise moment, will provide cooling.
- Tenants must be aware that if it is hot inside, and it is hot outside, it is too late to use the economizer for comfort at that moment. To successfully operate an economizer, the user must be educated on its operation, and understand the lag time in its use (6) (7).
- If the user is uninterested in, or unwilling to learn about its operation, the resulting energy wasted by a constantly re-circulating air handler could outweigh the potential benefits provided by the economizer.
- Narrowing the thermal comfort zone reduces the number of hours the economizer will operate, because it will only operate when the outside temperature is within the specified range. This is the opposite of an air conditioner, where narrowing the thermal comfort zone will cause it to turn on more frequently. Once again, educating the user is important.

3.3 Preliminary Recommendations

3.3.1 Design Recommendations

Perhaps the best method of reducing energy consumption is to create an HVAC system that can perfectly predict the user's desires, automatically adjust to fluctuating exterior conditions, and accommodate multiple thermal comfort ranges simultaneously. In theory, if the user is able to input detailed personal thermal preference data into the HVAC system, the HVAC system should then be able to choose most efficiently how it will provide conditioning. To that effect, the more user types a given system must accommodate (in this case there was a minimum of 70 different users, though probably closer to double that) the more automated it should be (8). While that was the original intention of connecting the economizer to the smart thermostat, the details of the pairing resulted in increased complexity that thwarted correct operation.

Short of having a fully automated system, there should be clear signals indicating when a setting needs to be changed to maintain or achieve thermal comfort. If the economizer is being used only during the day, and never at night, there should be some indication to the user that it is not being used as designed. For these residential units, it would have been helpful to have a readout of the outdoor temperature, so the indoor temperature could be compared against it, and the user could determine when to run the economizer (8). Additionally, there should be some indication to the user when the system is using fresh air or re-circulated air, so that they may decide to change their set point accordingly.

Another method is to use a timer to trigger the economizer instead of a thermometer/enthalpy sensor. While this would likely result in occasional anomalies, on the whole it would be much simpler to use, especially if the fresh/re-circulated air feature were removed. In this case study, the indoor air temperature might have stayed in the comfort zone more often if the economizer had a simple on-and-off switch.

3.3.2 Software Recommendations

Human behavior should be factored into energy simulation software programs. The individuality of human behavior, both amongst different users and by the same user over a period of time, can be approximated with algorithms designed to replicate "agent" behavior. A sensitivity analysis of energy savings or comfort modeling could be done on occupants' behavior.

3.3.3 Management Recommendations

One idea to ensure thermal comfort while still achieving energy savings is to combine the economizer with an air conditioner. With revisions to the interface, a combined package like this could serve to provide comfort during climatic anomalies while still operating with some of the efficiencies offered by the economizer. Precautions would need to be designed in however to prevent overreliance on the air conditioning side of the unit, and user error as observed in the case study.

In large-scale residential projects, where many different users will all be operating HVAC systems of the same design, the system should be tested to confirm usability, and thus the system's viability. This could be in the form of an online simulation or a physical mockup. While this may be difficult to justify at the time, it can be thought of a preventative measure and could also incorporate training. The downside risk of not doing this is to have to completely retrofit the building. Currently, in this residential complex, the building management is taking bids on installing individual central air conditioners in each of the apartment units.

All multi-family buildings, not only high-rises, should be required to undergo some degree of commissioning once occupied. This would have prevented the overheating of this building from the beginning, avoiding the many man hours devoted to solving the problem, and now the huge expense of removing the economizers and installing air conditioners.

4 <u>CONCLUSIONS</u>

This specific building was chosen for several reasons:

- It is a LEED Platinum building, the first such multifamily project in Los Angeles County.
- It was designed to reduce energy consumption by including an extensive solar panel array, a ground source heat pump, Energy Star® appliances and lighting, and blown-in insulation, and high efficiency low-e windows
- It has an economizer-based HVAC system that was designed to be operated by the tenants.
- It is located in California CZ-8, a climate zone shown by computer simulation, to have characteristics appropriate for the use of economizers to maintain occupant comfort most of the year. This specific building performed well in simulations.

Economizers in this climate zone should save energy compared to an air conditioner and be able to provide thermal comfort during most of the summertime. Anecdotes by occupants and measured values showed that the temperatures were not in the comfort zone. Indoor and outdoor temperatures were recorded and compared against amperage at the economizers to better understand how the occupants of the building were operating their economizers and how their performance might be improved. It was deduced that the occupants were not correctly operating their economizers. User interface problems and a misperception that the economizer is an air-conditioner were two of the largest problems. It is apparent that at least in this case, the computer simulations were overly optimistic. Human behavior needs to be accounted for to make accurate energy and thermal comfort predictions.

5 <u>REFERENCES</u>

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