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Humans and Nature in the Loop: Integrating occupants & natural conditioning into advanced controls for high performance buildings

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ABSTRACT
Post Occupancy Evaluation plus Measurements (POE+M) has revealed that thermal, visual, acoustic and even air quality standards derived through controlled experimentation alone does not ensure comfort or health in buildings. Introducing human input into environmental standards and into user centric controls is critically needed for a sustainable future. For over a decade, CMU's Center for Building Performance & Diagnostics has been gathering POE+M data from over 1500 workstations around the world and testing the benefits on innovative environmental control systems. The separation of ambient and task conditioning, the provision of task controls, the introduction of occupant voting and bio-signal inputs into ambient and task set-points, offers major gains in comfort, task performance, energy savings, as well as health and wellness.

KEYWORDS
Humans in the Loop, Internet of Things, Task and Ambient Conditioning, Bio-signals, POE

INTRODUCTION

Addressing the seriousness of climate change and resiliency necessitates breaking out of the control impoverished, reflective, sealed commercial buildings of today. These buildings are often driven by first least cost, treat humans as a liability by hiding sensors and controllers, and treat nature as a liability by blocking natural solar heating and sealing out natural ventilation and cooling. These buildings are not intelligent and not resilient. Next generation buildings will embrace the Internet of Things (IoT) to make every point of service – every air diffuser, light fixture, heating or cooling unit, window, shade and plug point - a point of sensing, control and intelligent feedback (figure 1). Sensor and control rich environments will engage humans and nature as assets for ensuring indoor environmental quality, organizational flexibility, individual health and productivity, as well as ecological sustainability.

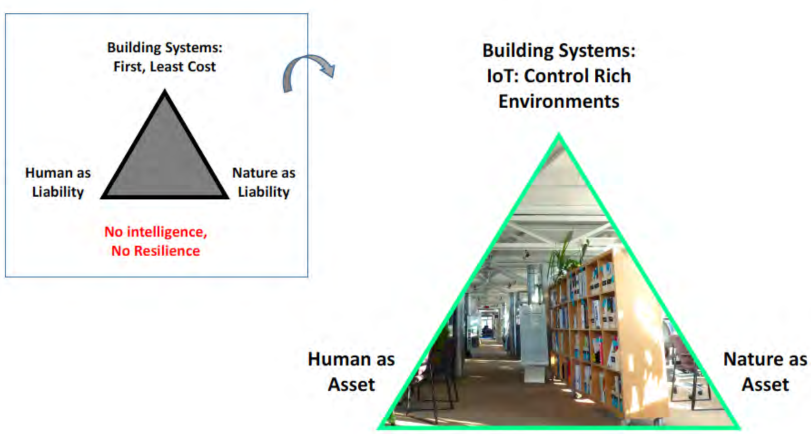

figure 1. Next generation buildings will be IoT control rich, treating humans and nature as assets

Post Occupancy Evaluation plus Measurement (POE+M) in 70 Federal Facilities

Over the past 20 years, The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University and the U.S. General Services Administration (GSA) launched a nation-wide effort to complete post occupancy evaluations in federal facilities before and after the investments to improve the quality of the federal workplace. A National Environmental Assessment Toolkit (NEAT) was developed that critically merged user satisfaction surveys (long term and right now surveys) with physical measurements of environmental conditions and expert walkthroughs and interviews to capture the technical attributes of the building systems that supplied the thermal, air quality, lighting, acoustic and spatial performance (Loftness 2009, Aziz 2012, Choi 2012). Armed with national and international IEQ standards & thresholds, teams of Carnegie Mellon faculty and graduate students surveyed, measured and recorded conditions in over 1600 Workstations in 70 GSA buildings to build the NEAT data base, completing studies with recommendations, and leading to numerous Masters and PhD dissertations. The term POE+M was coined to emphasize the importance of simultaneously recording user satisfaction at given environmental conditions and given physical configurations of the building systems.

CMU POE+M = User Satisfaction (COPE) + Environmental Conditions (NEAT) + Technical Attributes of Building Systems (TABS)

For example, comparing field measured air temperatures with "right now" satisfaction Reveals: that US buildings are unacceptably and unnecessarily cold in summer (figure 2); that highest user satisfaction with air quality is achieved at CO_2 thresholds of 600 ppm ($p<0.05$) not the 1000 ppm presently used; that the highest satisfaction with lighting quality is achieved at less than 250 lux, given the computer intensive tasks in the office today. POE+M data bases offer a wealth of environmental learning and innovation (CBPD 2013), and should be the basis of both educational and professional commitments to field studies.

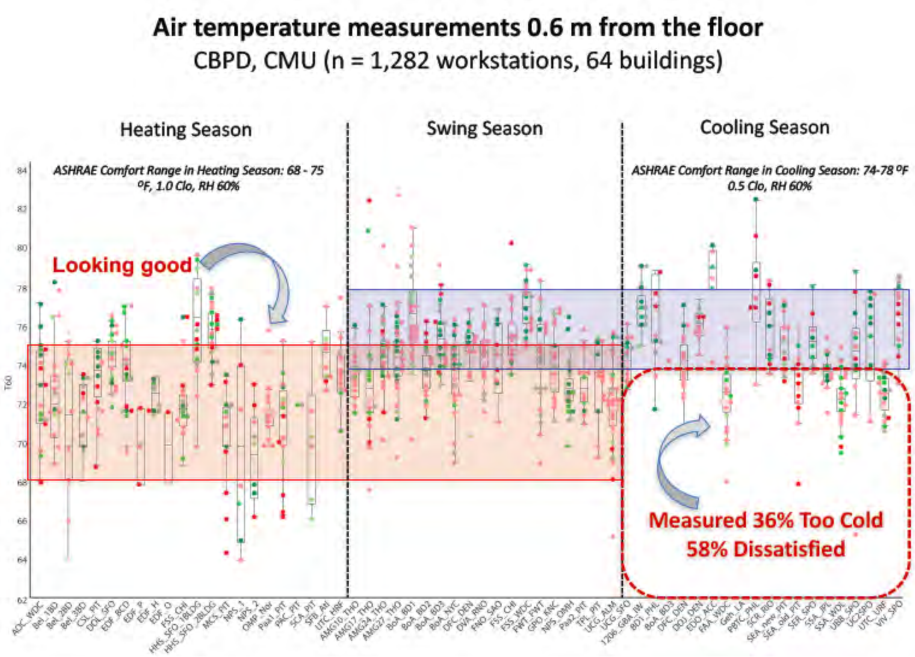

figure 2. Comparing field measured air temperatures with "right now" satisfaction reveals that US buildings are unacceptably and unnecessarily cold in summer.

"Are Humans Good IEQ Sensors? Using occupants as sensors for thresholds that matter."

With measurements in 1600 workstations in 64 buildings in the POE+M database, the 2014 CMU Dissertation of Jihyun Park used a rich array of statistical methods to definitely answer the research question 'Are Humans Good IEQ Sensors". The thermal, air quality, lighting and acoustic findings are both critical to building operation and future design, and statistically significant (Park 2015). The dissertation identified five building environmental conditions (NEAT) or physical conditions (TABS) significantly impacted thermal satisfaction: Air temperature at 0.6 m from the floor; Radiant temperature asymmetry with façade; Size of Zone; Window Quality; and Level of Temperature Control. These findings challenge existing design and engineering practices as well as existing comfort standards. For example, in 391 perimeter workstations, satisfaction with thermal conditions (-1 to +1) cannot be achieved unless horizontal radiant asymmetry is contained below 3.4oF ($p<.001$), not the 18oF presently in the code (see figure 3). The highest user satisfaction with thermal conditions in summer is achieved at 76.5oF ($p<0.05$), not the 72oF so prevalent as a year round set-point in the field, and occupants in spaces with hidden or locked thermostats will be 20-40 % less satisfied with air temperature in their work area ($p<0.01$). Beyond thermal satisfaction, the research continued to identify the building environmental (NEAT) or physical (TABS) conditions that significantly impacted satisfaction with air quality, lighting quality and acoustic quality.

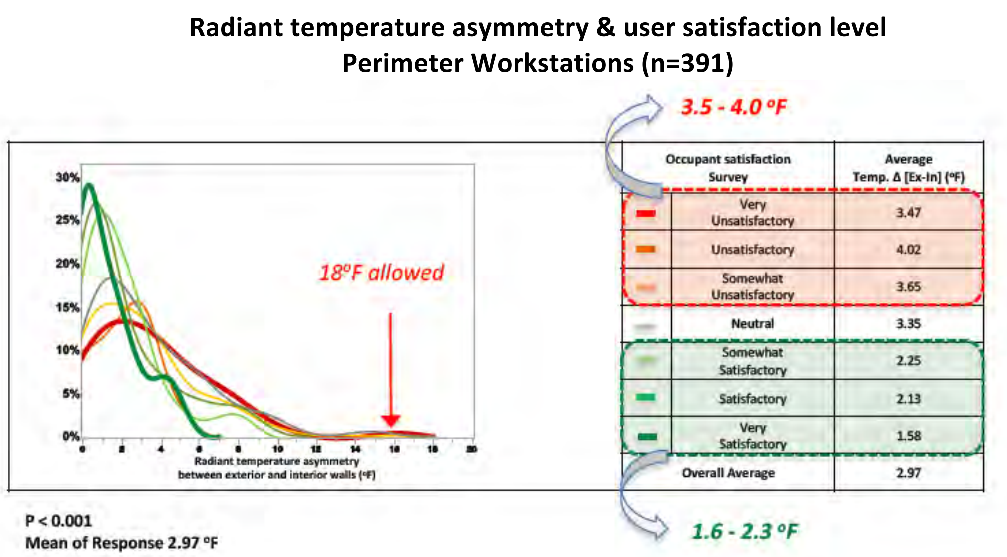

figure 3. Comparing measured horizontal temperature asymmetry with "right now" satisfaction suggest ASHRAE standards need to reduce acceptable delta's from 18F to <5F (Park 2015).

The CMU Intelligent Workplace: A Living Laboratory of Systems Integration for Performance

The Intelligent Workplace is one of the most sensored and controllable workplaces worldwide, shifting from traditional settings with one control for every 20 occupants to 20 controls for every occupant. With the emergence of wireless sensors and controllers and the Internet of Things (IoT), the IW is a testbed for the engagement of occupants as both sensors and controllers for the improvement of environmental quality and energy conservation.

In addition to field POE+M studies, the faculty and graduates in the Center for Building Performance have been testing the performance of innovations in component and integrated systems in the Intelligent Workplace at CMU. In collaboration with Siemens Corporate Research, Siemens Building Technology and the U.S. Department of Energy (DOE), this living and lived in laboratory supported two years of research on "Advanced, Integrated Controls for 40% Energy Savings in Building Operations" (figure 4) (Siemens 2012). A combination of seasonal controlled experimentation and computer simulation revealed that up to 75% of the ventilation energy, 36% of the heating energy, 25% of the cooling energy, and 70% of the lighting energy could be saved in cool and temperate climates through learning, occupant and nature responsive controls.

For example, the 36% in heating energy savings from the 2010 Baseline of US commercial buildings with limited sensors, limited controllers and sloppy 7x24 operation could be cumulatively reduced:

- 7.7% through updated sensors, time of day operation, and no over/under start up times;
- 15.5% through night setback Δ5°F and weekend setback Δ2-7°F; and
- 36.1% through lower ambient settings & occupant controlled low watt task heating.

The 70% in lighting energy savings from the same 2010 baseline could be cumulatively reduced:

- 40% savings by daylighting when it met space requirements alone;
- 64% savings by adding occupant scene control to daylighting; and
- 71% total savings by Daylighting + Occupant Scene Control + Daylight Harvesting (possible through dimming controls).

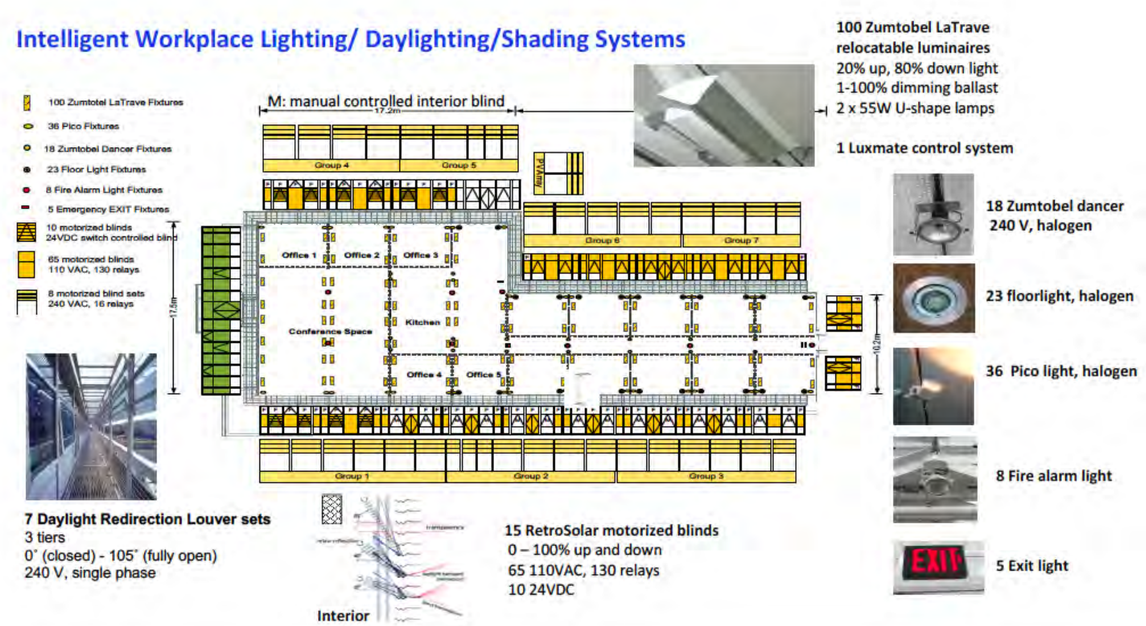

figure 4. The CMU Intelligent Workplace is a living and lived in laboratory for high performance building systems, the IoT, and human and nature responsive controls

The research also demonstrated that "control density is far more important than sensor density" and that the Internet of Things (IoT) offers a future where every node of service – every light fixture, air diffuser, heating or cooling coil, every plug – would support control optimization that integrates across environmental conditioning systems, and includes occupant & natural conditioning strategies. These advances are key to net zero energy, resiliency, as well as human health and performance.

CoBi: Bio-Sensing Building Mechanical System Controls for Sustainably Enhancing Individual Thermal Comfort

The CMU Intelligent Workplace has also been the testbed for numerous Master and PhD thesis projects including the path-breaking work on human bio-signals completed by Joonho Choi (Choi 2010, 2012). With IRB certified human subject testing of a host of bio-signals to control thermal conditions - skin temperatures from ten body locations, heart rate, heart rate variability, and sweat rate – the research identified the wrist as one of the most responsive body location relative to thermal sensation and comfort, given variations in seasons, BMI, MET and CLO conditions. When each individual's variation in wrist temperature is correlated to their thermal sensation votes and enabled to control air temperature, over 93% neutral sensation votes can be achieved, with 5.9 % energy savings for office cooling. This thesis helps to illustrate the importance of distributed controls for environmental systems and engaging occupants as sensors and controllers for energy savings and maximum user comfort, health and task performance.

Smart Phone Controls for the Internet of Things (IoT)

The potential of micro-zoning, of separating thermal and ventilation, of layering ambient and task conditioning, and of controlling every plug - is unlocked by the Internet of Things (IoT). Every node of service – every light fixture, air diffuser, heating or cooling coil, window, window shade, and even every plug – will support control optimization that integrates across environmental conditioning systems, and includes occupant and natural conditioning strategies. In 2010, the IW faculty began a long term collaboration with the students of Dr. Bernd Bruegge in the Institut for Informatik at the Technical University of Munich. Through this collaboration, the IW has been the laboratory for Bachelor, Masters and PhD thesis projects exploring the capabilities of smart phones to provide communication, expert feedback and consulting, and intuitive control (Peters 2012, 2016). These efforts have introduced wifi triangulation for IoT locations, gesture and voice control, innovative smart phone based occupancy sensors, environmental sensing, geo-fencing, smart plug data analytics and more (figure 5).

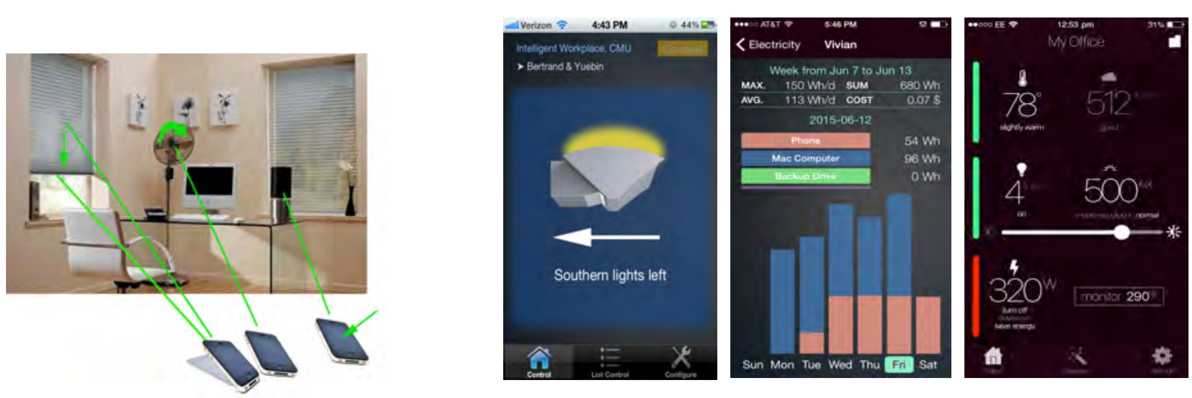

figure 5. Smart phones support intuitive gesture control of every fixture (left 2), provide energy use information (center) and readings of individual sensors and set points (right), (Peters, 2016)

Persistent Workplace Energy Savings and Awareness through Intelligent Dashboards

The importance of communication, feedback, expert consulting, and multiple levels of control are the basis of CMU's research into Intelligent Dashboards for Occupants (ID-O). The PhD thesis of *Ray Yun* explores the impact of nine critical interventions for behavioral change, structured in three sets: Instructional interventions – education, advice and self-monitoring; Motivational interventions – goal setting, comparison and engagement; and Supportive interventions – communication, control and reward (figure 6). With a focus on controlling plug loads, the fastest growing energy end use in commercial buildings, the nine-month controlled field experiment with 80 office workers at a leading green corporation in Pittsburgh revealed that occupant dashboards for controlling desktop technology, with ongoing energy communication and expert consulting generated by the occupants own data set, can generate up to 40% energy savings in plug loads (Yun, 2014).

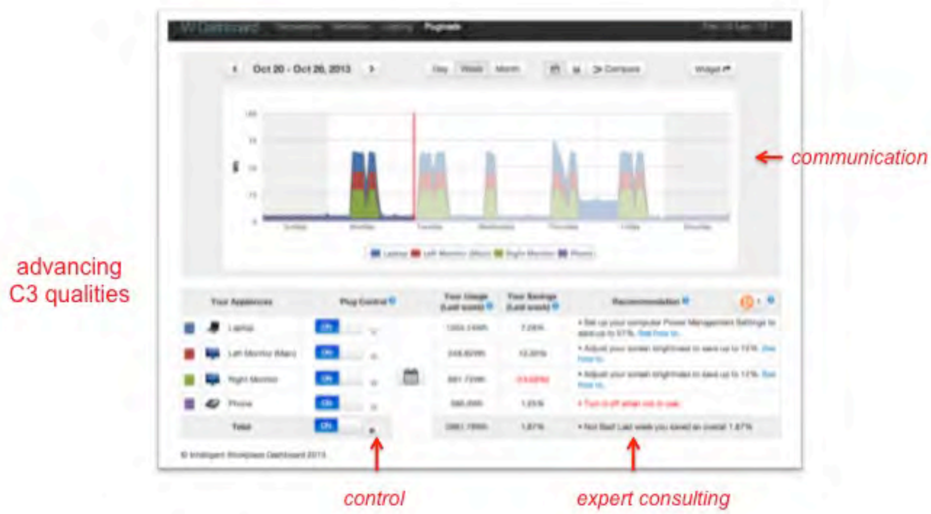

Figure 6 Desktop energy feedback and control dashboards for occupants yielded as much as 40% sustained savings from an already efficient workstation (Yun, 2014)

Occupant-oriented, mixed-mode, Energy+ predictive controls

In addition to engaging occupants directly, the power of occupancy and nature responsive building energy management (BEM) is also a critical development for the Internet of Things. The CBPD has been developing dynamic life-cycle building information models (DLC-BIM) into building energy models (BIM to BEM) focused on total building performance to ensure best practices in sustainable and green architecture. Jie Zhao completed a dissertation in 2015 demonstrating "Design-Build-Operate Energy Information Modeling for Occupant-Oriented Predictive Building Control", moving from controlled experimentation in the IW to a partnership with a newly awarded Living Building in Pittsburgh. This dissertation developed and demonstrated the concept of design-build-operate Energy Information Modeling infrastructure (DBO-EIM), which can be used at different stages of the building life-cycle to improve energy and thermal comfort performance (figure 7). Given the Pittsburgh weather context and current operation, the Occupant-oriented Mixed-mode EnergyPlus predictive control (OME+PC) system provided a 29.37% reduction in annual HVAC energy consumption. In addition, OME+PC enables building occupants to control their thermal environment through an internet-based dashboard, updating a design stage EnergyPlus model for use through the entire DBO-EIM process." (Zhao, 2015)

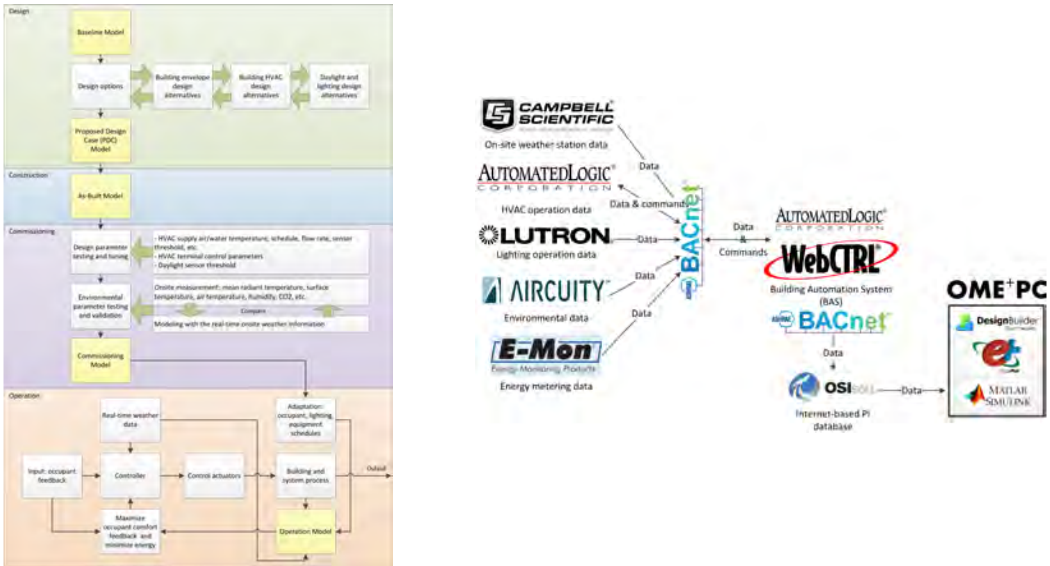

Figure 7 Design-build-operate Energy Information Modeling (DBO-EIM) infrastructure (left), and data collection and system integration architecture (Right) (Zhao, 2015)

Embracing Natural Conditioning

Erich Fromm used the term ‘biophilia’ to describe the psychological orientation of being attracted to all that is alive and vital. EO Wilson and Stephen Kellert, in their book ‘The Biophilia Hypothesis’ described biophilia as the links that human beings instinctively seek with other living systems (Kellert 1993). For those of us in the bricks and systems that define buildings, biophilia must include a passion for natural conditioning. Yet we know that advances in conditioning systems, sensors and controls are equally invaluable to our goals of intelligence, resiliency, health and productivity – especially in the warming and wildly fluctuating changes in our environment. Our future is in the marriage of the high tech and the low tech. First, we must pursue every possible hour of natural conditioning through environmental surfing for daylight, natural ventilation, night ventilation cooling, time lag cooling, passive solar heating, evaporative cooling and more. Then we must lightly introduce mechanical and electrical conditioning through mixed mode design. This demands no more heavy handed, pervasive overlighting or overcooling, and no more over-sealing, over-darkening our building facades. Instead, we must fully design for:

Mixed Mode: Daylight & Electric Light
Mixed Mode: Natural Cooling & Mechanical
Mixed Mode: Natural Ventilation & Mechanical
Mixed Mode: Outdoor & Indoor Work/Learn/Play/Heal

For each of these mixed mode solutions, the disciplines must collaborate from the earliest stages of design – to integrate structure, enclosure, mechanical, lighting, interiors and control systems that fully engage nature and the building occupants in a sustainable future.

CONCLUSION

Several decades of field and lab experiments at the Center for Building Performance and Diagnostics at Carnegie Mellon University have demonstrated that humans are good environmental sensors and humans are good environmental controllers, especially when given information, recommendations, and rewards. Occupants contribution to both energy savings and the highest level of individual satisfaction and delight is even greater when natural conditioning opportunities are introduced – daylighting, natural ventilation, night ventilation cooling, passive solar heating and more. Nature offers abundant, albeit variable, free energy sources for environmental conditioning. The future of intelligent buildings for resiliency, health and productivity depends on building systems that engage humans and nature to save energy and increase environmental quality.

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