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Optimal Control Strategies for Passive Heating and Cooling Elements Reduce Loads by Two-Thirds in the Adaptive Reuse of a San Francisco Bay Area Office

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ABSTRACT
Housing crises in urban centers and growing climate concerns are encouraging city planners and building owners to explore the conversion of commercial buildings into energy-efficient dwellings. Passive solar heating, shading, and natural ventilation are attractive in such adaptive reuse projects since they minimize operational energy, but they suffer from the perception of limited effectiveness, and passive heating is often disregarded entirely in cloudy climates. At the same time, passive heating has recently shown promise in the cloudy winters of western Oregon and upstate New York, allowing the San Francisco Bay area to provide an excellent opportunity for further exploration. Passive cooling measures, in turn, are essential to prevent overheating. This work investigates the conversion of a brick office space in Berkeley, CA into a residential loft, using movable insulation, operable windows, thermal mass, and shading to diminish the need for mechanical conditioning to the extent possible. To determine this extent, preliminary explorations in EnergyPlus were followed by Hooke-Jeeves and particle-swarm optimizations of control thresholds, following field-validated techniques for passive heating and cooling simulation. Optimized parameters included skylight tilt; schedules for movable insulation, shading, and natural ventilation; and thermal mass quantity, each required to minimize annual sensible heating and cooling energy while maintaining adaptive thermal comfort. With optimal control, over half of the heating need could be met by passive solar collection and storage; likewise, most cooling (~80%) could be accomplished passively if shading and natural ventilation were well-controlled. Without these controls, most of the benefit was lost. We therefore propose replacing the term “passive” with “well-controlled passive” to reflect the importance of controls in sensing conditions and adjusting movable elements to maximize the performance of these systems.

KEYWORDS
passive solar heating; passive cooling; controls; optimization; adaptive reuse

INTRODUCTION
The U.S. population devotes one-tenth of all energy consumed to the active heating and cooling of living spaces in buildings. This considerable quantity—nearly 10 quadrillion Btu per year—is derived largely from fossil fuels, emitting an estimated 500 million metric tons of CO_2 each year (EIA 2018). As climate concerns increase the pressure to design buildings with smaller carbon footprints (e.g. Nejat 2015), passive heating and cooling systems are regaining interest (Chan 2010), building on historic technical and conceptual explorations (e.g. Olgyay 1963; Givoni 1969) as well as centuries of vernacular development. Operable elements are often essential to passive systems, and recent efforts have compared operational strategies in natural ventilation (Schulze 2013), night ventilation of mass (Santamouris 2010), and shading (e.g. van Moeseke 2007), showing that controls can greatly improve their effectiveness. Numerical optimizations have also been applied to passive heating and cooling systems to inform choices of glazing orientation and type, wall composition, overhang depth, ventilation rate, etc., reviewed by Stevanović (2013). While these efforts have considered the presence vs. absence of operable elements

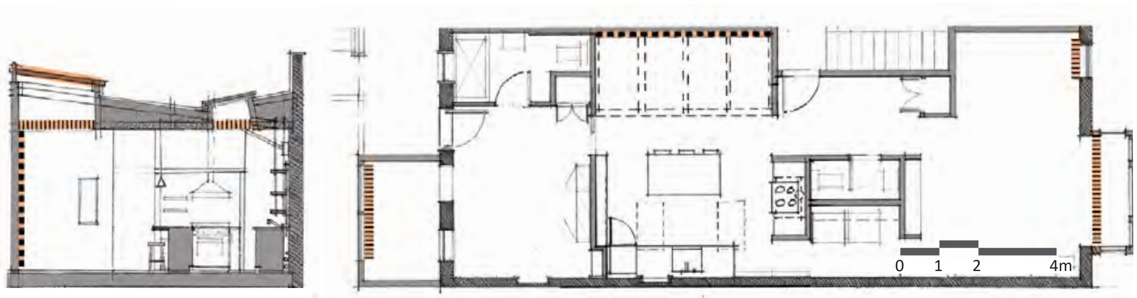

Figure 1. **Existing building** in (a) section and (b) plan, showing areas of investigation in orange, thermal mass in heavy dashes, and movable insulation in fine dashes.

as optimizable parameters, control thresholds have been pre-established in each case. To our knowledge, only Rempel (2015) has previously optimized threshold values themselves, and then only for cooling, without lower temperature limits. This work expands upon those findings by optimizing thresholds for passive heating and cooling simultaneously, incorporating upper and lower comfort limits throughout the year to predict the heating and cooling energy savings possible by these means. The renovation is planned for late 2018, and energy use will be monitored closely afterward, with the ultimate goal of providing compelling evidence that well-controlled passive systems have excellent performance potential in the Bay Area and similar climates.

METHODS

Simulations were conducted in EnergyPlus v8.7; windows and skylights were modeled in WINDOW 7.6 and referenced by EnergyPlus. Sensible heating and cooling loads were met by an Ideal Loads Air System, controlled by an adaptive comfort thermostat (Fig. 2a), to eliminate effects of mechanical system efficiency. Optimizations were conducted in GenOpt 3.1.1 using Hooke-Jeeves and particle-swarm optimizations for continuous and discontinuous variables, respectively, minimizing the annual sum of sensible heating + cooling energy.

Table 1. Baseline conditions and changes investigated

Parameter	**Baseline Condition**	**Changes**
Floor area	98.25m^2	-
Orientation	17° W of true south (i.e. 197°)	-
Roof assembly	Bitumen membrane o/ 75mm insul. board o/ 13mm pwd sheathing o/ 154mm batt insul. o/ 16mm gypsum board	-
Wall assemblies	N, S: adiabatic (party walls); E, W: 330mm solid brick (exterior); Porch: wood siding o/13mm pwd sheathing o/ 154mm batt insul. o/13mm pwd o/16mm gypsum board	-
Floor assembly	25mm Douglas fir o/19mm wood subfloor o/154mm batt insul. o/19mm gypsum board o/conditioned space	-
Thermal storage mass	None except for exterior brick walls	Mass wall
Window assemblies	E, W: Double clear, wood frame (7.8m^2, 1.0m^2); W porch: Double, alum. (3.9m^2); Sm skylights: Single, alum. (0.74m^2)	-
Skylight assembly	Acrylic dome, 7.2m^2: T_{vis}=0.53, SHGC=0.5, U=3.2 W/m^2K	Glazing, tilt
Movable insulation	None	Material, schedule
Infiltration	0.75 ACH	-
Natural ventilation	Operable E, W windows (2m^2); operable skylights (2m^2)	Temp. thresholds
Shading	None	Schedule
Internal gains	People = 2 adults; lighting power density = 1 W/m^2; equipment power density = 1 W/m^2	-

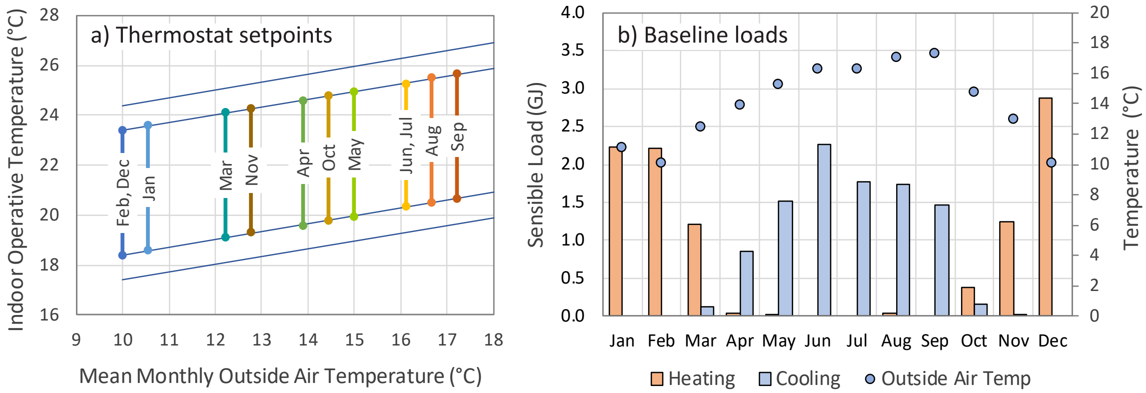

Figure 2. **Thermostat setpoints and resulting heating and cooling loads.** (a) Monthly heating and cooling setpoints, corresponding to the bounds of 90% acceptability in the adaptive thermal comfort zone (ASHRAE 2017); (b) Monthly sensible heating and cooling energy needed to raise or lower baseline-configuration air temperatures to thermostat setpoints.

RESULTS

The baseline building configuration (Fig. 1, Table 1) required 20.1 GJ of sensible heating and cooling energy annually to maintain conditions within the 90% acceptability limits of the adaptive thermal comfort zone (ASHRAE 2017), distributed between a heating season of October-March and a cooling season of April-September (Fig. 2b). Due to the large unshaded skylight, window heat gains were the greatest contributor to monthly cooling loads (Fig. 3), while infiltration and window heat losses contributed most to monthly heating loads. Because heat-recovery ventilation is generally not cost-effective in this climate, the infiltration target of approximately 0.75 ACH, consistent with provision of fresh air for four people, was not changed.

The first revision replaced the skylight's light-diffusing dome with double-clear uncoated glass (SHGC=0.67; U=3.5W/m²K; T_{vis}=0.72), tilted 40° above horizontal to receive the greatest possible solar radiation during the six-month heating season as estimated by the model of Perez (1990) (Fig. 4). This change did not in itself appreciably diminish the heating load, since thermal mass and movable insulation were not yet present to retain collected heat, but its effects were apparent in subsequent steps (Fig. 7a), and optimally-tilted glazing is generally necessary for excellent passive solar performance when cloud cover is a factor (Rempel 2013).

The second revision added movable insulation (*k*=0.03 W/mK) and shading (T_{vis}=0.3) to all glazing, reflecting the choice of inexpensive, physically manageable, commercially-available materials.

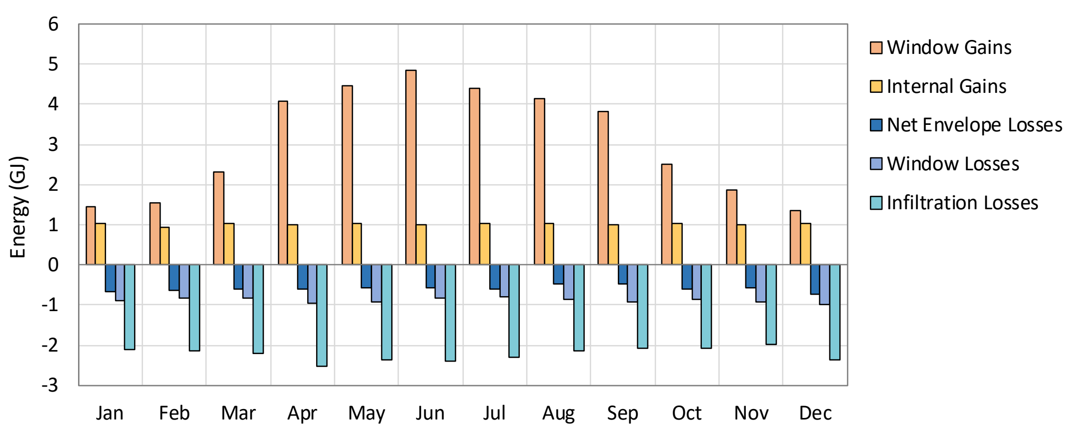

Figure 3. **Heat gain and loss pathways in the baseline configuration**, with prominent heat gains through the existing skylight and heat losses through windows and infiltration.

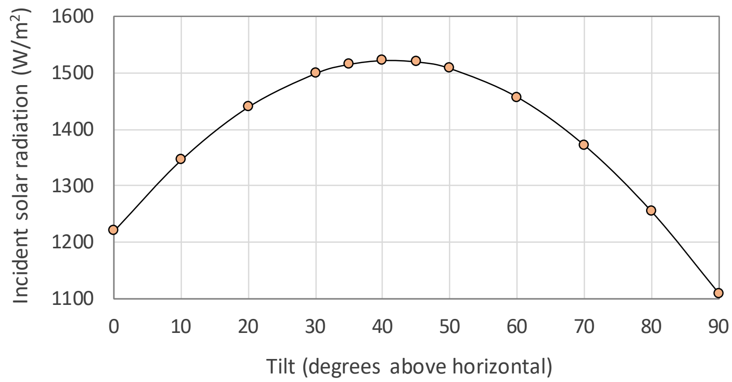

Figure 4. **Optimal tilt for solar-collecting glass,** shown by incident solar radiation during the heating season on surfaces of varying tilt to be approximately 40° above horizontal.

GenOpt was then used to find optimal hourly schedules for activation and retraction. Results showed, consistent with intuition from decades ago but contrary to recent assumptions (Stevanović 2013, van Moeseke 2007), that movable insulation was optimally activated hours before sunset in many months and often remained in place hours after sunrise; specific uninsulated hours depended on solar radiation utility (i.e. greater in Jan. than in Oct.) and heat loss vulnerability (i.e. greatest on Dec. mornings) (Fig. 5). Shading, similarly, was optimally activated well before the day's hottest hours and optimally retracted well before sunset, remaining retracted all night to promote cooling from glazed surfaces (Fig. 5). Together, these reduced the original heating load by about half and compensated for the cooling load introduced by the new skylight (Fig. 7a).

The third revision added thermal mass in the form of a brick wall north of the skylight (Fig. 1); its thickness was optimized alongside movable insulation and shading schedules due to strong interactions among these elements (Rempel 2015), yielding a final value of 25cm. The mass reduced annual loads only modestly (Fig. 7a), suggesting that seasonally-adjustable thermal mass (i.e. water or potted plants) should be explored. The fourth revision, in turn, sought optimal temperature thresholds, shown to be more effective than hourly schedules (Rempel 2015), for natural ventilation. These values, which reduced cooling loads by ~75% (Fig. 7a), fell within a surprisingly narrow range: above outside temperatures of ~25℃, and below indoor temperatures of ~23.5-24.5℃, natural ventilation had such a dramatic impact in this space, with amply-sized windows well-aligned to the prevailing wind, that overcooling easily resulted. This is evident, as well, in the appearance of small heating loads in April, May, and August (Fig. 6).

Table 2. Optimization parameters

Parameter	Range	Initial Step Size	Initiation Value	Result
Glazing tilt	0° - 90°	10°	n/a	Fig. 4
Movable insulation (Oct-Mar):				
time retracted (morning)	6:00 - 12:00	1:00	6:00	Fig. 5
time activated (evening)	15:00 - 20:00		15:00	
Shading (Apr-Sep):				
time activated (morning)	6:00 - 12:00	1:00	12:00	Fig. 5
time retracted (evening)	15:00 - 20:00		20:00	
Thermal mass thickness	0.01m - 0.3m	0.05m	0.01m	0.25m
Natural ventilation (Apr-Sep):				
indoor minimum temperature	16℃ - 30℃	10℃	26℃	Fig. 6
outdoor maximum temperature	20℃ - 38℃	10℃	26℃	

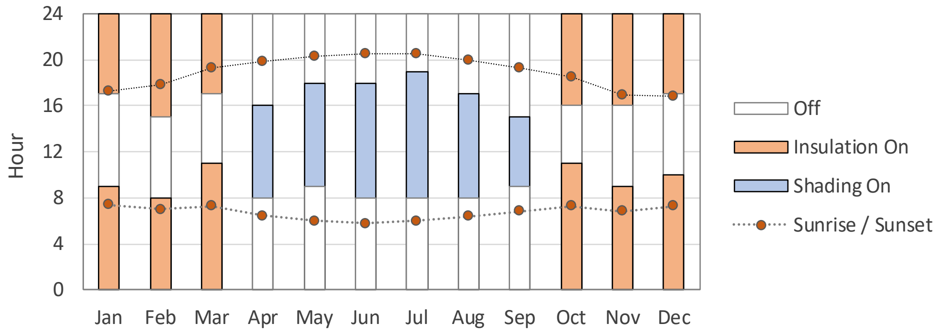

Figure 5. **Optimal hours for use of movable insulation** (orange bars) **and shading** (blue bars), as well as hours of full sunrise and full sunset (circles). Note nighttime retraction of shading.

DISCUSSION

Several useful observations emerge from these results. First, ideal thresholds for operation of movable elements are not necessarily intuitive, and despite accepted research practice (e.g. Ochoa 2008), they cannot be assumed. Here, movable insulation required activation of greater duration than the "nighttime" (sunset to sunrise) default found in EnergyPlus and other simulation engines; similarly, shading required activation hours before overheating occurred and also required removal at night. Where default activation settings exist, they must be overridden; likewise, effective manual operation by occupants cannot be assumed if thermal sensation and/or intuition are the only signals. Second, the penalties imposed by winter overheating and summer overcooling led to optimal thresholds that created small summer heating and winter cooling loads. If modest winter overheating and summer overcooling were permitted, which is not unrealistic given that mechanical heating is often made unavailable in the summer and vice-versa, these new loads would be reduced or eliminated. Third, it appears that even finer-grained optimizations would have been productive, particularly with respect to natural ventilation. The combination of summer overcooling penalties and ample operable window area, in this case, led to a high minimum indoor temperature threshold in May because so little time was necessary for natural ventilation to have sufficient cooling effect; optimizations that explore window area as well as sub-hourly timesteps might reveal better thresholds. The load reductions predicted here are therefore conservative, in the sense that they could be lowered even further, but optimistic in the sense that consistent, near-ideal operation is required to achieve them.

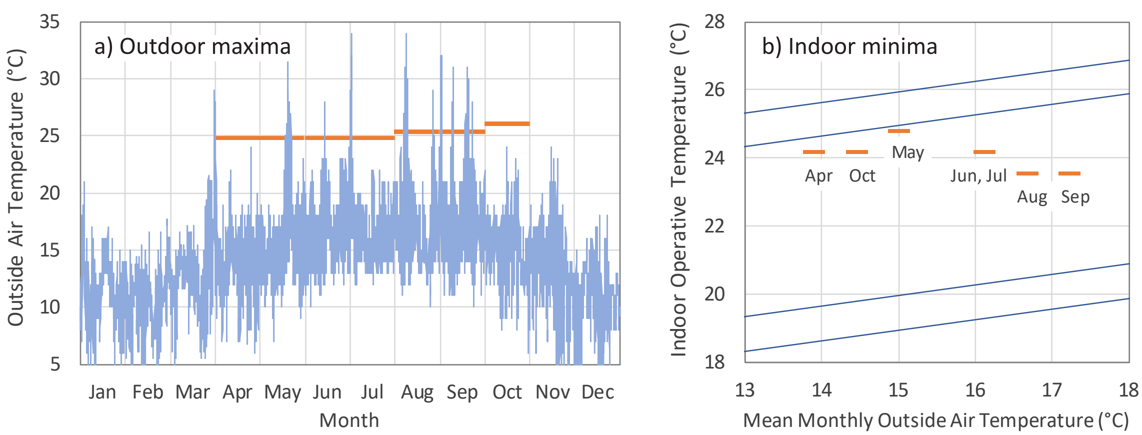

Figure 6. **Optimal temperature thresholds for natural ventilation control**. (a) Typical outdoor temperatures (blue; Oakland CA TMY3) and maximum values above which vents should be closed to avoid overheating (orange); (b) Adaptive thermal comfort zone (blue) and minimum indoor temperatures below which vents should be closed to avoid overcooling (orange).

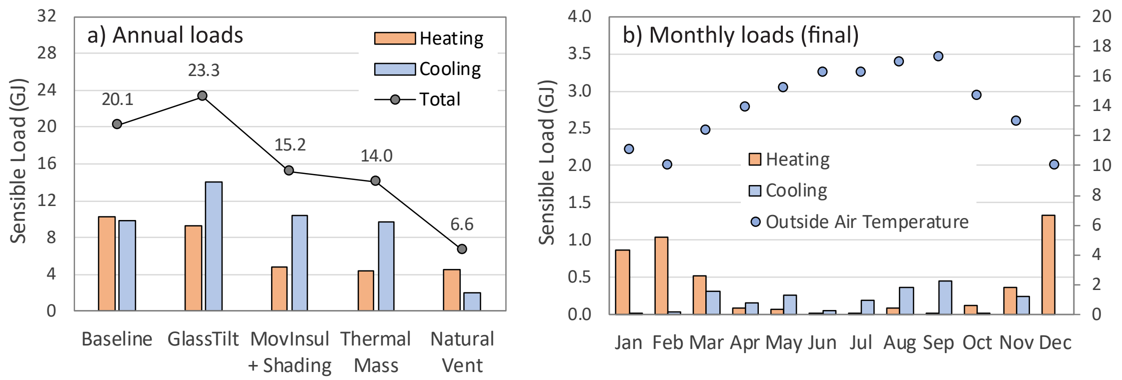

Figure 7. **Final loads with optimized controls.** (a) Annual loads at each stage, with final reductions of 56% (heating), 79% (cooling), and 67% (total); (b) Final loads by month (see Fig. 2b).

CONCLUSIONS

Together, the results above show the striking potential for well-controlled passive strategies to diminish space conditioning loads, even in a building with minimal insulation in a cloudy winter climate. In reducing the heating load by >50% and cooling load by ~80%, while maintaining adaptive comfort, the strategies that were identified challenge the perception that passive systems are difficult to control and, as a result, cannot contribute reliably to comfort. Instead, they suggest the opposite. While the load offsets found are specific to the building and climate studied, the value of well-operated elements is likely to be widespread in climates with significant diurnal and seasonal temperature variation, and the method for finding control thresholds is valid in general. Because the U.S. contributes disproportionately to the world's greenhouse gas emissions, the potential for well-controlled passive systems to meet such large fractions of heating and cooling demand, in a vital population center, is worth intense investigation and further development.

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