DESIGN AND EVALUATION OF ENERGY-EFFICIENT MODULAR CLASSROOM STRUCTURES, PHASE II

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ABSTRACT

We are developing innovations to enable modular builders to improve the energy performance of their classrooms with a minimum increase in first cost. The Modern Building Systems' (MBS) classroom building conforms to the stringent Oregon and Washington energy codes, and at $18/S.F. (FOB the factory) it is at the low end of the cost range for modular classrooms. We are investigating daylighting, cross-ventilation, solar preheat of ventilation air, electric lighting controls, and down-sizing HVAC systems.

The work described in this paper is from the second phase of the project. In the first phase we redesigned the basic modular classroom to include energy efficiency features tailored to five distinct climates. Energy savings ranged from 6% to 49% with an average of 23%. Paybacks ranged from 1.3 yrs to 23.8 yrs, an average of 12.1. The initial work in Phase II (which added two more climates) has been to refine the designs for each of the seven climates and reduce payback periods.

In Phase II the number of baseline buildings was expanded by simulating buildings that would be typical of those produced by MBS for each of the seven locations/climates. A number of parametric simulations were performed for each energy strategy. Additionally we refined our previous algorithm for a solar ventilation air wall preheater and developed an algorithm for a roof preheater configuration. These algorithms were coded as functions in DOE 2.1E.

We were aiming for occupant comfort as well as energy savings. We performed computer analyses to verify adequate illumination on vertical surfaces and acceptable glare levels when using daylighting. We also used computational fluid dynamics software to determine air distribution from cross-ventilation and used the resulting interior wind speeds to calculate occupant comfort and allowable outside air temperatures for cross-ventilation.

To choose the final mix of energy strategies, we developed a method to compare incremental costs versus energy savings for all strategies at once. The results of parametric energy simulations were graphed against detailed cost information. This allowed us not only to easily see which broad strategies were most cost effective but also to choose the best configurations of the strategy.

Final results were obtained by simulating the strategies chosen from the cost/energy graphs. In some cases adjustments were made in the chosen strategies since the final performance is not readily predictable from parametrics of many systems.

RESEARCH CARRIED OUT

In Phase I we redesigned the basic unit to incorporate energy strategies including daylighting, cross-ventilation, solar preheating of ventilation air, and insulation. We also explored thermal mass but determined that it was not a cost-effective strategy in the five climates we examined. The basic unit before redesign consists of two 14'x64' modules that are put together on site to create two 28'x32' classrooms. Wall insulation is R11, roof insulation R30,

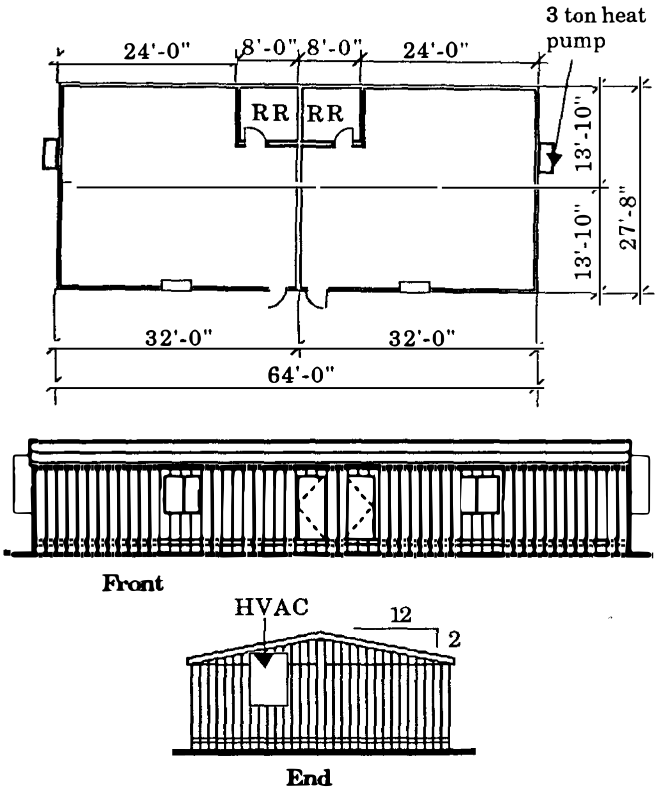

Fig. 1: Baseline Unit

and floors R19. Each classroom has one 4'x4' window, fluorescent lighting and one 3-ton heat pump; see fig. 1.

We tailored energy strategies for each of the five locations we explored: Fairbanks AK, Spokane WA, Astoria OR, Bakersfield CA, and Honolulu HI. The climates chosen reflect MBS's primary markets. Starting with a single baseline design that meets Oregon and Washington energy codes we achieved annual energy savings of 6% to 49% with simple paybacks of 1.3 years to 23.8 years. Fig. 2 shows the classroom unit design after Phase I.

In Phase II our goal is to improve payback periods. Our plan is to choose strategies for each climate that produce paybacks between 5 and 10 years. We have added Phoenix AZ and Miami FL to our study locations in order to make our results inclusive of the major climates in the United States, although MBS does not market in these areas. To make the results as accurate as possible, we created separate baseline buildings typical of the type of unit that MBS would actually ship to each location. We therefore repeated the Phase I simulations and cost analyses for the original five climates and added two more sets of analyses for the

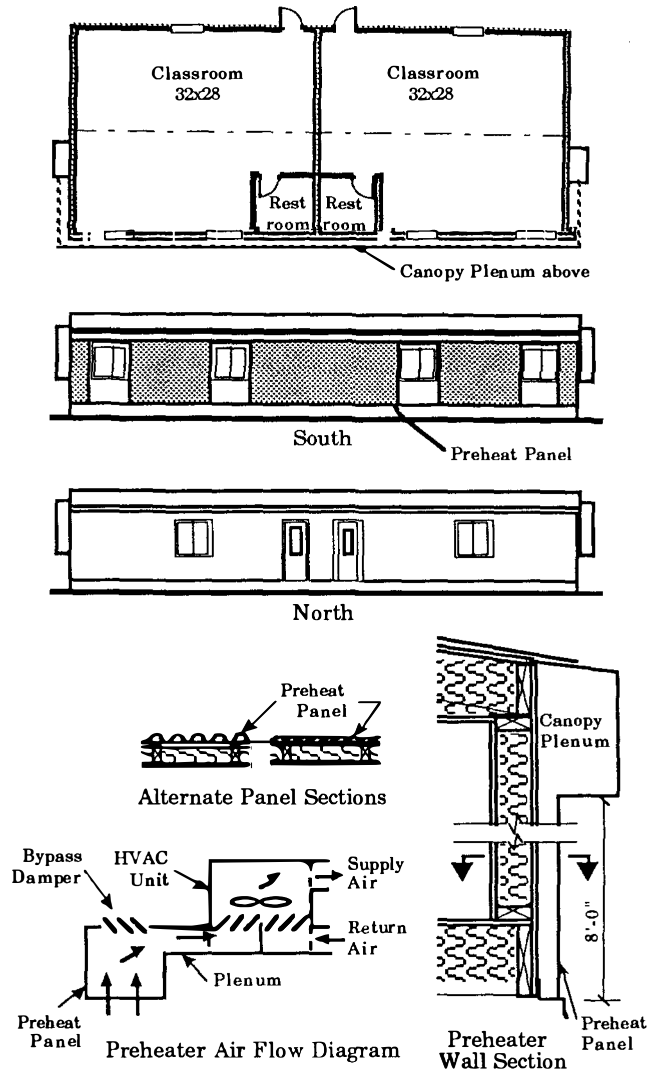

Fig. 2: Basic Unit with Energy Features, Phase I

new locations. For each climate we performed over 300 parametric simulations and cost analyses.

Another goal of Phase II is to address several occupant comfort issues, including visual comfort, and verify that cross-ventilation is effective in cooling all occupants of the rooms while not creating discomfort by introducing cold air at high velocities.

ENERGY STRATEGIES

Phase I results suggested that the cost-effectiveness of the solar vent air preheater was questionable in several climates.

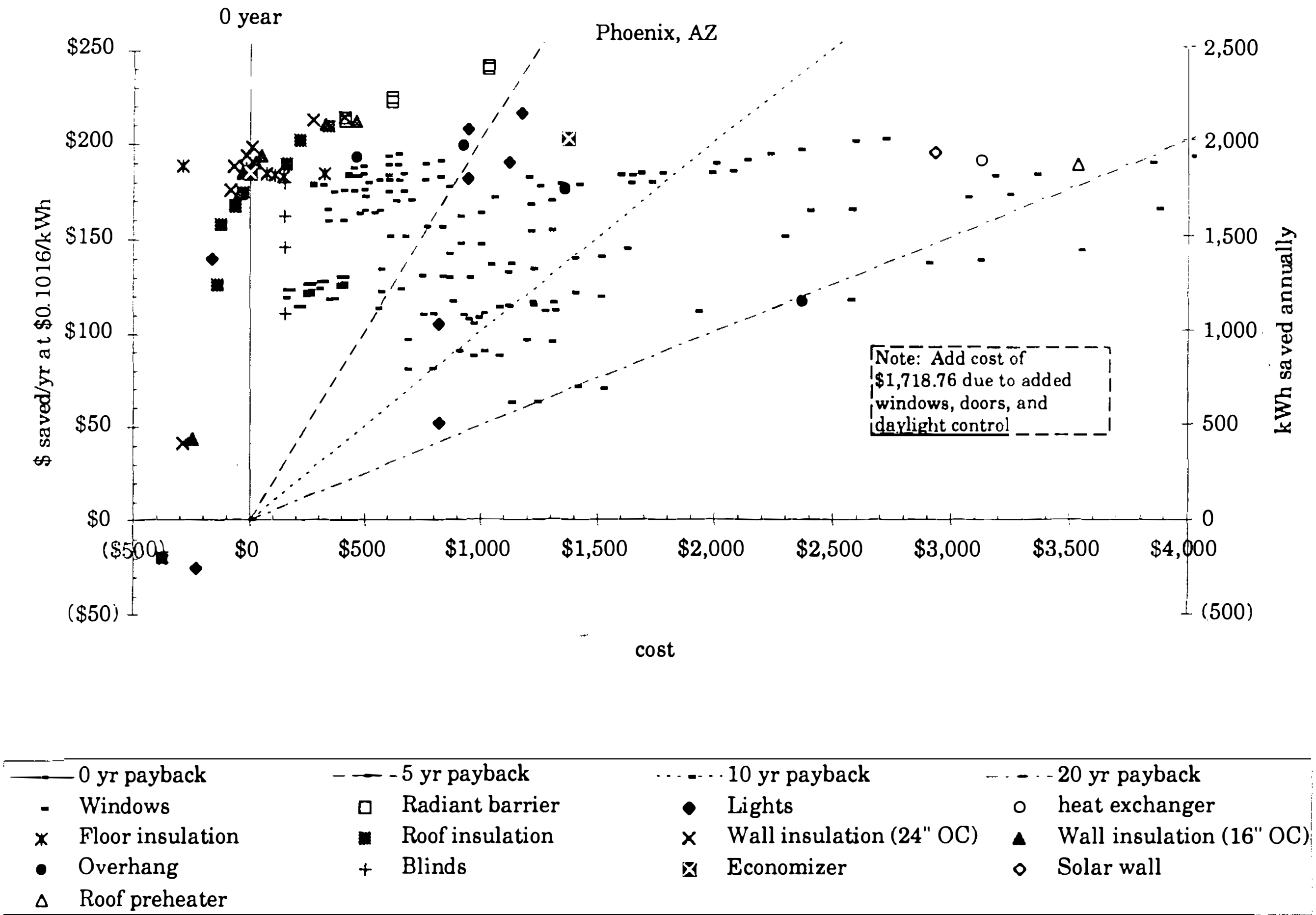

Fig. 3: Cost vs. Energy Graph

In Phase II therefore we refined our methods to determine its appropriateness. First we improved the simulation algorithm used for the wall-integrated preheater. The algorithm and FORTRAN code originally developed and included in our DOE 2.1E simulations did not take into account the effect of the preheater on conduction through the south wall. We refined the heat balance equations and integrated them into DOE 2.1, then validated our algorithms against empirical results obtained by others (Kutscher et al., 1993). In Phase I we had also identified a roof-integrated preheater as being potentially cost-effective in certain climates. We developed algorithms for this configuration; however, these could not be validated since we could not find any empirical data. Our intent was to validate these results with our own tests if the simulations appeared to warrant further development. We found in general that any preheater is an expensive strategy and not likely to meet our payback criteria. However, in the colder climates we will recommend wall preheaters to school districts with a longer term view of first cost vs. energy costs. Ultimately we decided not to pursue roof preheaters.

Lighting was the other major cost item from Phase I. During Phase I studies we looked only at more efficient systems with automatic daylight dimming and occupancy sensors. In this phase we also examined lower cost alternatives that might prove more appropriate in some climates.

Based on Phase I results, we felt that refining insulation decisions had a great potential to lower construction costs while reducing energy use, or that tradeoffs could be made against other strategies that would save more energy. We looked in greater detail at insulation configurations. Parametric simulations were performed for walls, roofs, and floors. We analyzed insulation thicknesses both greater and smaller than the baseline buildings and also looked at radiant barriers. We also performed simulations of many different window and glazing options.

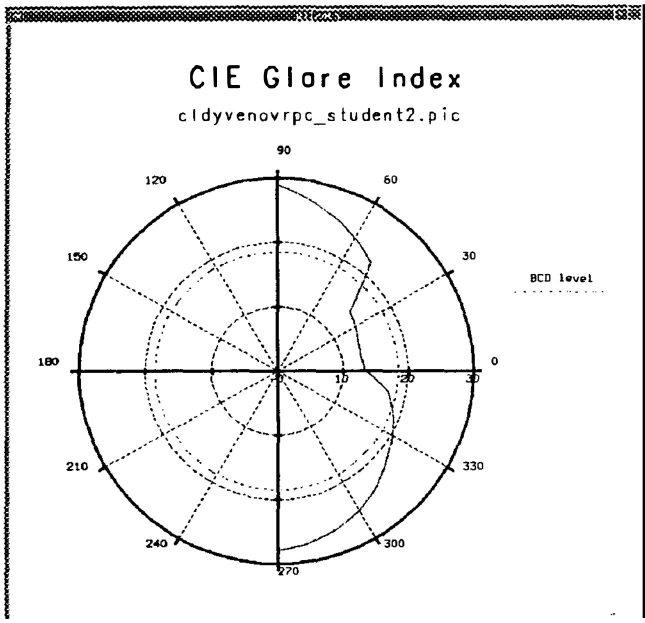

Fig. 4: Glare index plot

In this phase we have also looked into different HVAC systems and fuel choices.

All of the energy and cost analyses were plotted together for each location; see fig. 3. The horizontal scale is incremental construction cost over the base case, while the vertical axes are annual energy savings, both in dollars and kWh. The diagonal lines show 5, 10, and 20 year payback curves.

These graphs let us identify the most promising combinations of strategies and tradeoffs that would produce the best energy savings. We narrowed our explorations to a limited number of combinations to do integrated runs in order to obtain integrated performance predictions. Because of the great number of window parametrics, these were also graphed separately to facilitate analysis.

OCCUPANT COMFORT

Radiance (a Unix based ray-tracing software package from Lawrence Berkeley Laboratories) was used to evaluate illumination on vertical surfaces and glare from windows, and to determine the optimum window locations. Parametric simulations were performed for clear and cloudy days with several shading options. We used *Radiance* to produce polar plots of CIE glare indices for several locations in the room; see fig. 4. The radial lines are angles of vision, each from a given location in the classroom; the line marked 0 is

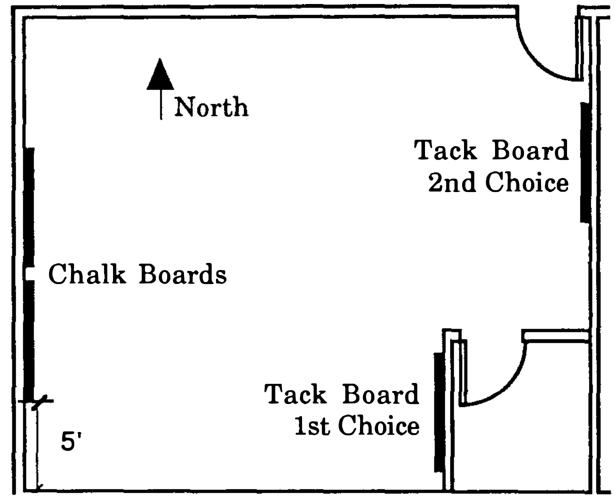

Fig. 5: Optimum chalk and tack board locations

looking straight towards the end wall. The circles marked 10, 20, and 30 are glare indices, and the irregular line shows the predicted performance.

We found that overhangs are not very effective at controlling glare, and that if other concerns do not argue for overhangs they could be eliminated. Operable shades are the most desirable means of eliminating glare, and while venetian blinds are not the best choice thermally they are the most cost-effective device and are also necessary for darkening rooms for media presentations. *Radiance* can also generate false-color renderings of a room's surfaces, showing illumination levels. From this we determined the best locations for chalk and tack boards; see fig. 5.

To evaluate air distribution from cross-ventilation, we used *Quick 'n' Simple*, a two-dimensional fluid dynamics simulation program by Scott Forbes and Gerald Recktenwald. We found we had acceptable cross-ventilation air distribution without introducing excessive wind speeds if the door was assumed to be used for venting; see figures 6 and 7. Outside air temperatures are adequate for cooling by natural ventilation for a percentage of the cooling hours in all of the climates so that HVAC equipment can be reduced in size or eliminated. Note that we assumed a nine-month school schedule that did not include the summer months.

In these comfort studies we parametrically varied window locations, and by examining all studies together we were able to determine the optimum window location for all criteria.

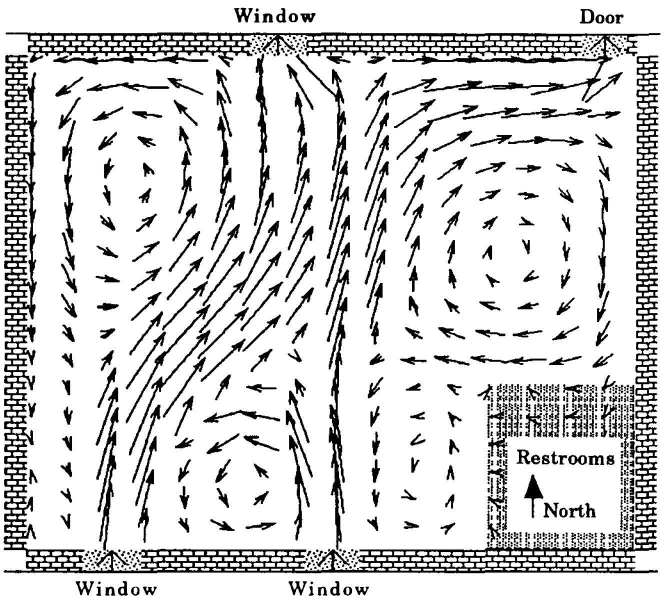

Fig. 7: Velocity vectors

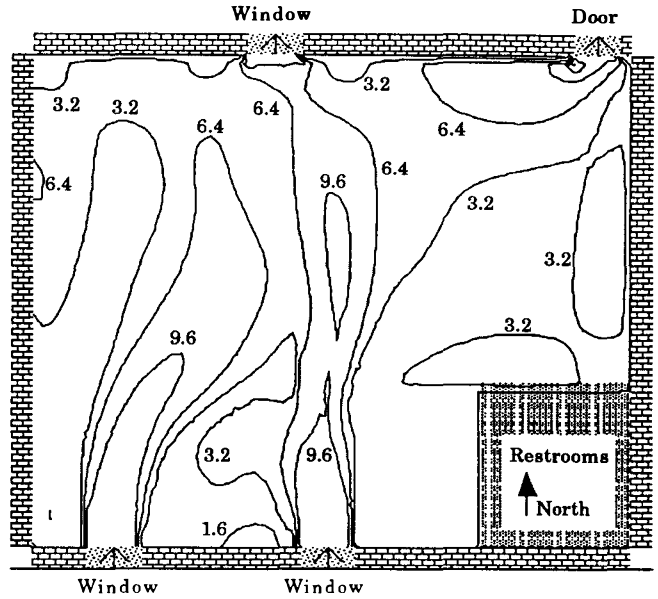

Fig. 8: Equal velocity contours

PRELIMINARY RESULTS

We have done a series of integrated simulations for Fairbanks thus far. While we have not yet decided on a final configuration, we have some examples of the types of savings and paybacks we are expecting. For instance, by increasing floor insulation from R19 to R30 and wall insulation from R19 to advanced framed R21; orienting the two 4' x 4' windows to the south and adding low-e coating (e=.1) and argon fill; improving the lighting to a higher efficiency T8 system without dimming; and keeping the electric heat pump currently used, annual savings of 1144 kWh or $142 could be achieved, a 4% savings. The simple payback for this is 3.4 years. If the heating system is changed from a heat pump to an oil furnace, this same configuration has annual savings of $1676 and costs less than the current building. This is a 47% energy cost savings. In Phase I we proposed adding four more windows to the double classroom unit in all locations. This is still true in Phase II except in Fairbanks where we will not add windows.

GENERAL FINDINGS

The following general conclusions can be made from the results of our analyses:

- Economizers are expensive and do not perform as well as other strategies.
- Walls framed with studs at 24" OC as opposed to 16" OC perform better and have a comparable cost.
- Doors with half lites are a cost-effective means of providing more daylight.
- Roof preheaters are too expensive and do not perform as well as wall preheaters.
- In cold climates the required ventilation air poses the most difficult load to reduce. Although heat exchangers and vent air preheaters perform well in these locations, their payback period is too long.
- In cold climates insulation levels should be maximized and less money spent on lighting systems.
- Overhangs do not appear to be a cost-effective shading strategy in hot climates. Interior operable shades are necessary for occupants to control glare and illumination levels anyway, and Venetian blinds are far less expensive than other solutions.
- In hot climates, eliminating the floor insulation improves energy performance and reduces cost. This is due to increased conduction losses through the floor during hot hours. There is some ground coupling aiding this heat transfer.
- Reducing insulation in hot climates reduces cost and is a good tradeoff for better and more expensive lighting systems.
- Radiant barriers are a good option in hot climates. They cost more but perform better than wall and roof insulations.

CONCLUSIONS

Our strategy of doing a great number of parametric simulations and cost analyses gives us confidence that we have fine-tuned the buildings. We spent considerable time setting up the DOE 2.1E input files to automate the parametric process. This was a time-consuming method, but ultimately it saved even more time by making it easy to batch process parametric runs without making a separate input file for each variation.

The enormous amount of data to analyze led us to develop the parametric energy vs. cost graphing method. This method makes the results far easier to interpret and is quite interesting in its own right. When first cost and operating cost are the primary drivers in the decision-making process, these graphs make all parametrics comparable.

ACKNOWLEDGEMENTS

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