DESIGN AND EVALUATION OF ENERGY EFFICIENT MODULAR CLASSROOM STRUCTURES

Sarah Bernhard, G.Z. Brown, John Briscoe, Jeff Kline,
Pawan Kumar, Zhunqin Wang
Energy Studies in Buildings Laboratory
Department of Architecture
University of Oregon
Eugene, OR, 97403, U.S.A.

Donald Rasmussen, Kenneth Rasmussen, James Stanard
Modern Building Systems, Inc.
P.O. Box 110
9493 Porter Road
Aumsville, OR 97325, U.S.A.

Abstract

The objective of our investigations was to develop innovations that would enable modular builders to improve the energy performance of their classrooms without increasing their first cost. The Modern Building Systems' 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. Therefore the objective we set for ourselves was challenging. We proposed to investigate daylighting, cross-ventilation, solar preheat of ventilation air, and thermal storage as ways to reduce energy use.

Simple paybacks range from 1.3 years in Honolulu to 23.8 years in Astoria, OR. Therefore in the five climates we investigated in Phase I we came closest to achieving our objective of increasing energy performance without increasing the first cost of the unit in the Honolulu climate. We were able to do this in Honolulu because a preheater was not required, and we were able to save money by eliminating the economizer unit, using cross-ventilation, and reducing insulation in the envelope.

Our second best performing climate was Fairbanks with a simple payback of 7.7 years. In this case we were able to eliminate the heat pump and economizer by using cross-ventilation, thereby reducing cost.

Our third best performing climate was Bakersfield, California, which had a simple payback of 10.3 years. Spokane had a simple payback period of 17.2 years. The major cost increases in Spokane are in the preheater and lights, with a modest increase in windows. Astoria had the worst payback period of almost 24 years with most of the increased cost being in the preheater, windows, and lighting. The savings from the preheater are modest.

In Phase II of this project, by combining the strategies of improved electrical light-switching, perimeter insulation, shading, window sizing, preheater configuration and location and HVAC locations, we expect to reduce simple payback periods to 0 years in Honolulu, Hawaii; less than 2 years in Bakersfield, California; 3 years in Astoria, Oregon; 4 years in Fairbanks, Alaska; and 8 years in Spokane, Washington.

Research Carried Out

Our Phase I work plan had six tasks: collect data, develop the baseline building, establish a universe of design possibilities and prepare computer models, generate design alternatives, analyze costs, and select the design.

The baseline building (figure 1) is 28' x 64' and has the following energy-related specifications: walls R11, floors R19, roof R30, (2) aluminum frame slider type windows U.85, (2) insulated steel doors, 2' x 4' recessed four-tube fluorescent light fixtures - 50 fc, and (2) 3-ton heat pumps with economizer and programmable thermostat.

We analyzed the heating and cooling loads of the baseline modular classroom building with its long side facing south in five different climates: Astoria, Oregon; Bakersfield, California; Fairbanks, Alaska; Honolulu, Hawaii; and Spokane, Washington using two programs – Energy Scheming 2.0 and DOE 2.1E. Each climate presents a different challenge to mitigate the energy consumption of the classroom.Using Energy Scheming 2.0 we looked at net gains and losses over a 24-hour period for typical days for each climate in March, June, September and December. The climates selected are consistent with the Modern Building Systems' (MBS) market area. They also represent cold, temperate, oceanic, and warm, dry climate zones that exist elsewhere in the U.S.; therefore, the ideas developed for our specific climates have application in other parts of the U.S.

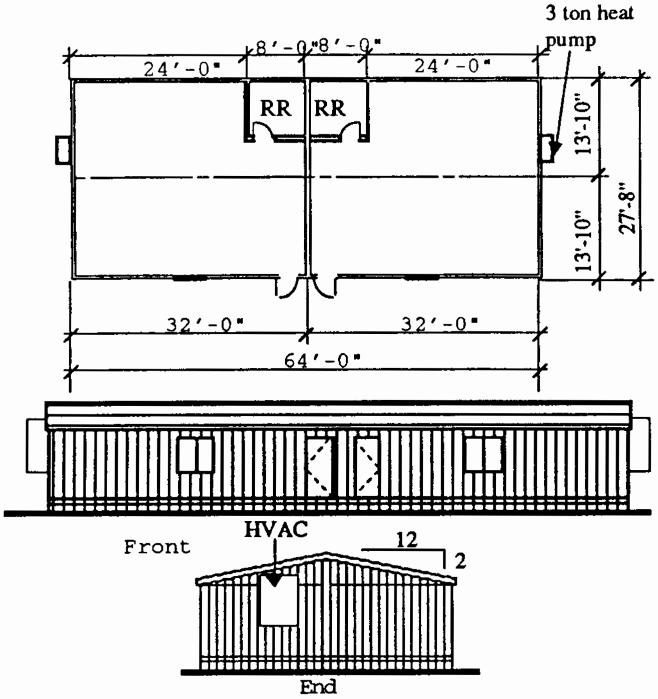

Fig. 1, Baseline Building

Physical and Psychological Criteria

Working with an education consultant, we completed a review of classroom design literature. That review revealed that many schools in use today were built decades ago with different pedagogical goals than are now common, and have adapted poorly to contemporary needs (Branch, 1994). Whereas schools were once intended to help students achieve expertise in a specific vocation through data memorization, the school of the late twentieth century should actively educate the "knowledge worker," that is, the person who is educated to think broadly and analytically and to effectively manipulate large quantities of information (Sanoff, 1994). In addition, people exhibit individual differences in learning style, all of which are now considered valid. Dunn, Pizzo and Hanna (1983) concluded "that learning style is biological and has its basis in the structure of the individual's neural organization and personality" (National Task Force, 1983, in Florida, 1993, p. 25) These "multiple intelligences" (Gardner, 1983) should be accommodated by an equitable instructional environment.

Educational infrastructure must respond to rapidly changing student populations, and increased needs for instructional space are often met by relocatable classroom structures. However, these structures are often poorly received both by users and the community. While schools choose modular transportable classrooms in order to quickly acquire affordable classroom space, neighboring residents often consider such structures to be eyesores, and parents frequently judge these buildings to be substandard educational facilities (Florida, 1993). A study of students and faculty at the University of California at Davis identified the greatest problem with the quality of classrooms as aesthetics (Babey, 1991). This shortcoming may be especially true of relocatable classroom structures, which have been characterized as monotonous and uninspiring, due largely to lack of aesthetic attention (Educational Facilities Laboratories, 1964).

In order to produce a healthy learning environment, we developed criteria both physically and psychologically in the following areas: Thermal comfort and air quality, noise control and acoustic environment, illumination, windows, adaptability, user-friendliness, size, materials, and aesthetics.

Cost Baseline

Detailed cost break-downs of time and materials for the baseline module were developed as shown in figure 2.

Div. #1	General requirements	$1654
Div. #6	Wood/ plastic (floors, walls, roof)	$11537
Div. #7	Thermal and moisture	$3657
Div. #8	Doors and windows	$977
Div. #9	Finishes	$4064
Div. #10	Specialties	$112
Div. #15	Mechanical	$5780
Div. #16	Electrical	$4429
	Total	$32,211
	$/SF	$17.97

Site Work and Transportation		Total Cost
Astoria	$6,113	$38,323
Bakersfield	$12,302	$44,512
Fairbanks	$25,034	$57,244
Honolulu	$30,541	$62,751
Spokane	$8,431	$40,623

Fig. 2, Baseline Module Cost Break-downs

Energy Baseline

The Energy Scheming runs confirmed our hypothesis that ventilation air was a primary cause of energy use, particularly during cold months when that air must be heated to comfortable temperatures before entering the classroom.

In addition to cross-ventilation, we also modeled the passive strategies of daylighting (with photo controlled continuous dimming) and thermal mass. The thermal mass simulations did not show a substantial contribution in either heating or cooling. In cold months, increased solar gain and internal gain was insufficient to offset losses due to fresh air requirements, and therefore there was little opportunity to store heat for later use. In hot months, the mass available was insufficient to meet a substantial amount of the cooling load.

The use of daylighting significantly reduced the electric lighting load without seriously compromising the overall u value of the envelope in many of the climates. At the conclusion of the *Energy Scheming* studies we determined that mass was not a viable strategy, but daylighting, solar preheating of ventilation air, and cross-ventilation had potential to cost effectively reduce energy use.

Adjustments to the Energy Baseline

To more accurately predict annual energy use, we switched from *Energy Scheming* to *DOE 2.1E.* In order to verify the accuracy of our baseline simulation, we compared the simulation's fuel use predictions to fuel use records collected for an Astoria, Oregon, classroom building. As shown in figure 3, our prediction was within less than 1% of actual fuel use indicating that our computer model was representative of our modular classroom building.

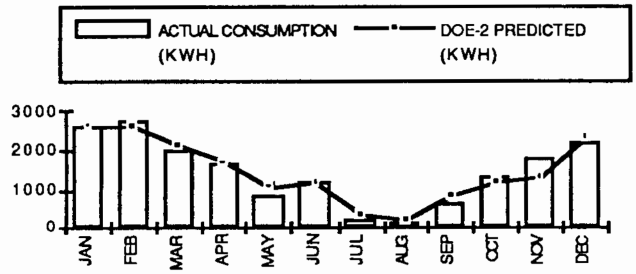

Fig. 3, Baseline Simulation

Universe of Design Possibilities

We next developed a morphological matrix of architectural design options based on rules of thumb for window, and a preheater area and mass area. We evaluated 10 configurations, with varying window placements, orientation, and preheater areas, etc. A sample of our analysis is shown in figure 4. The upper-left corner of the matrix shows the orientation of the building with walls and roof spread out around the plan. The vertical axis shows the considerations – glazing area, cross-ventilation area, etc. The horizontal axis shows a range of daylight factors and the area required of each consideration. Each cell in the matrix shows the square footage of the building element that exists given a daylight factor and a certain morphology (upper left). For example, in figure 4 at the intersection of cross-ventilation and 2% daylight factor, there is 90 S.F. of inlet and outlet required for cross-ventilation. However, the rule of thumb (right column) says that a minimum of 179 S.F. of inlet/or outlet is required, so, the cross-ventilation window area is inadequate for that morphology. The cell is greyed to indicate a failure to meet the rule-of-thumb requirements. When all the morphologies were compared, the ones with the least grey were the best performers. The morphology with North and South windows and the long side facing North and South met the most criteria and was selected for further study.

Long Side North and South - Windows North and South, equally distributed

N ↑ 		Characteristics 2% Daylight Factor	4% Daylight Factor	6% Daylight Factor	Rule-of-Thumb Reqmts
Glazing Area	N S E W	90 sf 90 sf 0 sf 0 sf	179 sf 179 sf 0 sf 0 sf	269 sf 269 sf 0 sf 0 sf	179 sf for 2% DF
Cross Vent Area	Inlet Outlet	90 sf 90 sf	179 sf 179 sf	269 sf 269 sf	179 to 717 sf 179 to 717 sf
Mass Area		1293 sf	1114 sf	960 sf	2688 to 5376 sf
Night Vent Area	Inlet Outlet	90 sf 90 sf	179 sf 179 sf	269 sf 269 sf	54 to 108 sf 54 to 108 sf
Preheater Area		1331 sf	1242 sf	1152 sf	250 to 500 sf, (south facing)
Shear Wall Lengths	Short: E W Long: N S	 25'+1 door 25'+1 door 41.5' 41.5'	 25'+1 door 25'+1 door 19' 19'	 25'+1 door 25'+1 door 0' 0'	20' 42'
Cost	Roof Floor Wall Windows Doors	NC NC -148 sf +148 sf NC	NC NC -326 sf +326 sf NC	NC NC -506 sf +506 sf NC	Equal or lower total installed cost
Transportation Dimensions	Width Length Height	13'-10" 64' 11'-10"	13'-10" 64' 11'-10"	13'-10" 64' 11'-10"	16' (14' CA) 66' 12'-8"

Note: Shaded values do not meet Rule-of-Thumb requirements.

Figure 4, Morphological Matrix Analysis M = Mass area, P= Preheater area, S=Shear wall lengths, C= Cost

Computer Models

We next developed computer code to simulate the preheater based on performance data supplied by Conserval Engineering Inc. and incorporated that code into DOE 2.1E. After doing a regression analysis of the performance of the solar wall based on the data provided by the manufacturer, we arrived at the following performance equation: $\Delta T = aI + b$, where,

$$a = 0.39157 + 0.03138\,(F) - 0.19575\,(F)^{1/2}$$

$$b = 6.62503 + 0.27785\,(F) - 0.75707\,(F)^{1/2}$$

I = Insolation on the vertical wall in Btu/hr S. F.

where,

F is the flow rate in cfm/S.F. of the solar wall.

The preheater area is calculated based on the assumption that there is 8'0" of clear wall height available below the air plenum (see figure 5). Also the area of the wall below the window is not taken into consideration while calculating the available preheater area. During the operating hours of the preheater all the conduction loss occurring through the area of the south wall behind the preheater is captured by the incoming air. For the purpose of simplifying the algorithm, this phenomenon has not been taken into consideration. In order to perform the simulation, the solar insolation on the south wall calculated by the loads program is stored as a variable in the preheater FORTRAN code and read back during the system's calculations when the main preheater algorithm is executed.

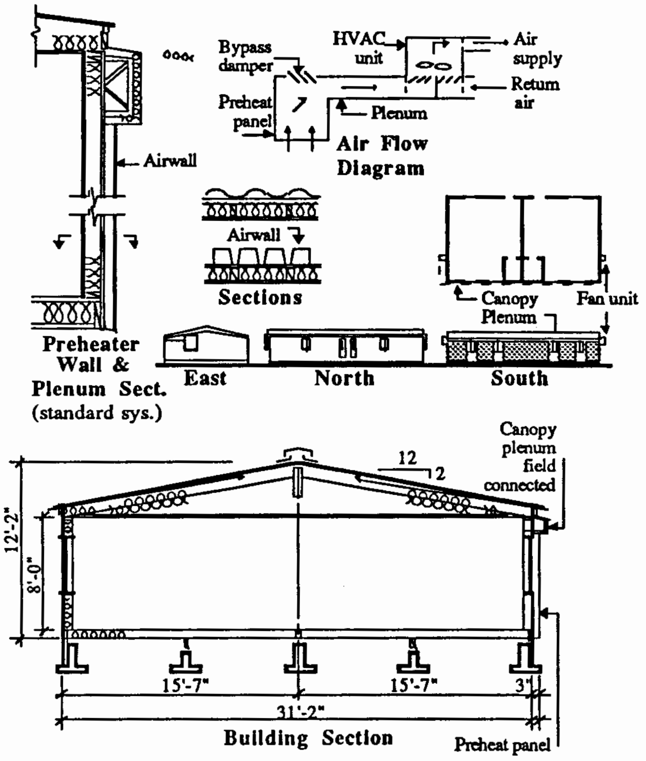

Fig. 5, Baseline Unit with Energy Features

Design Alternatives

Using the morphological analysis, we selected designs for further investigation. As our studies evolved during this phase we explored numerous whole building ideas and many component configurations. The "baseline with energy features" option was developed in the most detail (see figure 5).

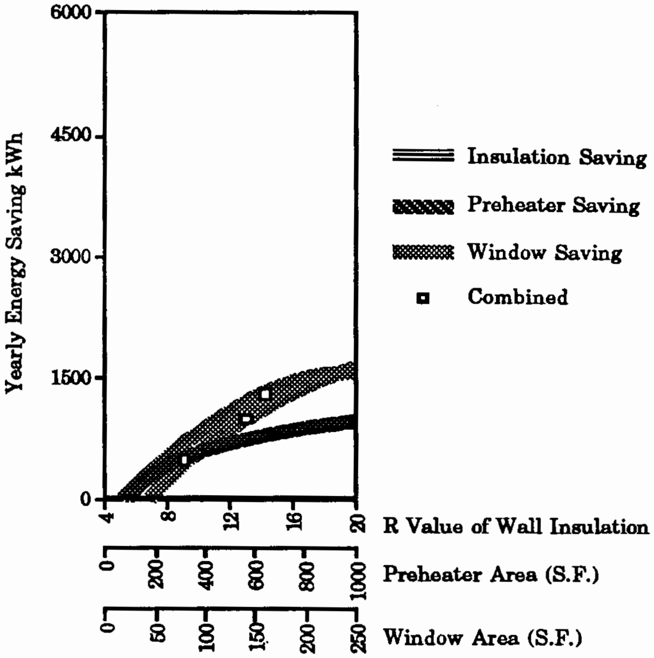

Fig. 6, Yearly Energy Savings for Astoria

We conducted parametric studies of windows, insulation, and preheaters in the five different climates using DOE 2.1E which allowed us to understand HVAC requirements in each case. We analyzed the parametric simulations to develop specific energy strategies and identified optimal window and preheater areas and insulation levels for each climate and traded off elements such as south facing windows and south facing preheaters based on the magnitude of energy reduction potential of each element. Final simulation of the base line unit with energy features, based on the optimal window and preheater areas and insulation levels, were performed for each the five different climates. Detailed cost estimates were then completed for each climate and both energy and cost compared to the baseline.

Findings

Simple paybacks range from 1.3 years in Honolulu to 23.8 years in Astoria, OR. Therefore in the five climates we investigated in Phase I we came closest to achieving our objective of increasing energy performance without increasing the first cost of the unit in the Honolulu climate. We were able to do this in Honolulu because a preheater was not required, and we were able to save money by eliminating the economizer unit, using cross-ventilation, and reducing insulation in the envelope. We had a $988 increase in first cost and an annual energy savings of $763.

Our second best performing climate was Fairbanks with a simple payback of 7.7 years. In this case we were able to eliminate the heat pump and economizer by using cross-ventilation, thereby reducing cost.

Our third best performing climate was Bakersfield, California, which had annual savings of $467 and a simple payback of 10.3 years. Spokane had a simple payback period of 17.2 years. The major cost increases in Spokane are in the preheater ($3057) and lights ($2204), with a modest $434 increase in windows. Astoria had the worst payback period of almost 24 years with most of the increased cost being in the preheater ($2809), windows ($898), and lighting ($2204). The savings from the preheater are modest with the "knee" of the curve occurring at a low panel area.

Conclusions and Recommendations

We did not reach the level of payback in all climates that we desired with the resources we had available for this research. However, we have achieved enough understanding about potential energy savings and further cost reductions for these modular classrooms to be able to make some projections about later phases of this research.

Our best payback period occurred in Honolulu, and we believe we can reduce this further by increasing the window size from 4'x4' to 6'x4'. This will increase cost by about $39 dollars per window but save about 375 KWh per year. We will also save building cost by using alternative switching for the electrical lighting. The switching methods we will evaluate include manual, occupancy off-manual-on and stepped. We will determine energy savings from these methods by using statistical data that verifies actual expected use rather than theoretical use. We also believe there will be new less-expensive dimmable ballast widely available in the market by the time we build our prototypes in the second year of Phase II. We expect to save at least 50% of the $2204 cost increase estimated for the lighting system. With these changes the building actually becomes less expensive to build than the baseline unit and uses less energy.

We expect to be able to reduce the cost of the baseline with energy features in Bakersfield by using a perimeter insulated foundation system and by using alternative switching for the electrical lighting as described for Honolulu. The preheater is our largest cost increase, but we expect to reduce its costs by refinements to the control system. We also hope that component testing of the preheater in Phase II will reveal fabrication opportunities that will also save cost. Because of Bakersfield's relatively low latitude and consequently higher sun altitudes we believe it will be possible to get fair preheating performance from a roof-integrated preheater. Because of the way the roof is currently constructed, we can integrate a preheater at approximately 85% of the cost of the preheater on the vertical wall. Moving the preheater to the roof will also eliminate the current conflict between south glazing and the preheater allowing us to increase window area and improve performance. Alternatively we could eliminate the preheater altogether and compensate for the loss in performance by increasing the window area. We did not simulate shading in Bakersfield, which may be a very cost-effective strategy for reducing the cooling load peak and therefore potentially decreasing the size of the heat pump. With these changes we could reduce the simple payback to less than two years.

In Astoria, unfortunately, the high fixed costs of the plenum connection to the HVAC system and related controls make small preheater areas economically unattractive, although we could expect to save some of these costs by locating the furnace in the center of the building as mentioned in the Fairbanks description. We will probably eliminate the preheater for Astoria in Phase II. It is important to note that the utility costs at $.06 per KWh are relatively low and that the preheater might be worthwhile in similar climates with higher electricity rates. We can increase the savings for our electric lighting control system by increasing the window area from 4'x6' windows to 5'x6' windows (an increase of $14 per window) and improving their thermal performance with vinyl frames and argon fill (an increase of $55 per 6'x5' window). We will also explore alternate switching as outlined in the Honolulu description. Enlarging and improving the windows would cost approximately $69 per window. For six windows the increase in cost will be $414. The increase in performance due to the windows will offset the decrease in performance caused by eliminating the preheater at a savings of $2809. With these changes the total cost increase will be $678, and the simple payback will be reduced to about 3.9 years. With the savings from a perimeter insulating system the simple payback would be 2.7 years.

In Fairbanks we can reduce the cost of the preheater duct system by locating one furnace in the center of the building rather than having the two HVAC units located on both ends of the building, which is currently the case. The annual savings from daylighting is the lowest of all the climate studies due to two factors: low ambient illumination levels and heat loss through glazed areas. We expect to cost effectively improve the window/daylight performance by increasing the thermal performance of the windows by using a better frame and argon fill. The additional cost of these windows is modest at about $30 per 2'x4' window . Because the percent of time that daylighting is used is small compared to the other climates, a simpler switching system such as that described for Honolulu, will probably be the most cost effective. We also think that horizontal skylights may be very cost effective if heat loss can be controlled because of the potential increased illumination with less opening and little need for shading. We also hope to decrease the cost for the preheater using methods described for Bakersfield. Refinements to the preheater simulation to account for increased gain due to snow reflecting more sunlight to the panels will more accurately show the value of the preheater. The overall performance of the Fairbanks classroom building can be substantially improved by increasing the overall envelope R value. In a scenario that used just an occupancy switching system the total increase in cost would be $1797 with a payback of 3.4 years.

Compared to Astoria, in Spokane the energy savings from the preheater are substantial, and whether it should be eliminated will require careful consideration. If the preheater were eliminated (saving $3057) and the windows were increased from 6 - 2x4 windows (50 SF) to 6 - 4x6 (144 SF) windows with vinyl frames, argon fill and low-e coatings (for a total cost increase for windows of $642), and if the increase in windows resulted in an increase in savings equal to that lost by eliminating the preheater, the simple payback would be 7.8 years . Alternatively, the preheater could be retained and the electric lighting control system simplified or eliminated because of low utilization thus reducing the cost by as much as $2204 with a decrease in annual savings of not more than 500 KWh per year. As described for other climates, we would expect to reduce cost by using a perimeter insulated foundation system. It is also probably a cost-effective strategy to increase envelope insulation levels in Spokane.

With a conservative estimation of the cumulative changes mentioned above we would expect to achieve simple paybacks of 0 years in Honolulu, less than 2 years in Bakersfield, 4 years in Fairbanks, 3 years in Astoria, and 8 years in Spokane.

In Phase II as a result of refinement of the design and optimization of manufacturing we hope to further reduce or eliminate payback period.

Acknowledgments

This project has been supported by the National Renewable Energy Lab, Small Business Innovative Research/U.S. Department of Energy.

References

(1) Babey, E. (1991, March 26). The classroom: Physical environments that enhance teaching and learning. Washington, DC: American Association for Higher Education.

(2) Branch, M. A. (1994, June). Tomorrow's schoolhouses: Making the pieces fit. Progressive Architecture, pp. 77-83.

(3) Dunn, R., Pizzo, J.S., & Hanna, S. (1983, August). Sound: One learning style characteristic.

(4) Educational Facilities Laboratories. (1964). Educational school facilities. New York: Author. (ERIC Document Reproduction Service No. ED 066 846)

(5)The Florida Center of Community Design and Research. (1993, November 16). The use of relocatable classrooms in the public school districts of Florida. (A research report for the Florida Department of Education, Office of Educational Facilities). Tampa: University of South Florida.

(6) Gardner, H. (1983). Frames of mind: The theory of multiple intelligences. New York: Basic Books.

(7) National Task Force. (1983). National task force defines learning styles operationally and conceptually. Learning Styles Network Newsletter 4(2), p. 1.