1.2. Thermal Envelope Optimization

Purpose

The purpose of this study was to answer the research question: “What is the optimal lifecycle thermal envelope system by space type?” The contribution that envelope improvements can make toward achieving net zero energy is highly dependent on the mix of end-use loads in the building, the physical characteristics of the building, and the climate.

Research Question

What is the optimal lifecycle thermal envelope system by space type?

Because of the diverse usage patterns in military buildings at Fort Carson and other bases, we assumed that the optimal envelope features may vary significantly based on several characteristics:

- Magnitude of internal heat gains (people and equipment)
- Timing of internal heat gains
- Heating and cooling set points
- Hours of operation
- Ventilation rates
- Surface area to volume ratio

This study investigated the most cost-effective envelope features for each of five major building types on the base, in order to determine the appropriateness of specifying a single set of envelope characteristics for all new Fort Carson buildings. Because we focused on a single subsystem, we did not determine the optimal envelope design needed to achieve Fort Carson's net zero energy goal. Whole-building optimization would be necessary for such an analysis, as described in the context of retrofit projects in Net Zero Retrofit Optimization.

Space Types

- Headquarters office building (HQ)
- Dining Facility (DFAC)
- Company Operations Facility (COF)
- Tank and Equipment Maintenance Facility (TEMF)
- Barracks

Methods

To answer this research question, we evaluated the performance of a variety of envelope components, including their impact on conductive heat gains and losses, air leakage, solar heat gains, daylighting, and thermal comfort. Space types included in the evaluation are those found in the following facilities for the newly constructed 4th Brigade LEED Gold facilities:

The methodology included the following steps:

1. Select a set of envelope characteristics spanning a range of performance from levels specified by standards from ASHRAE 90.1-2007 to Passivhaus.
2. Assess tested air barrier performance versus wall construction type.

3. Model each facility to determine the energy savings for each envelope improvement. Conditioned and semi-conditioned zones were analyzed separately.

4. Work with the U.S. Army Corps of Engineers (USACE) and the Design-Build teams to collect first cost information to include in the lifecycle assessments.

5. Perform lifecycle cost analysis of all measures to determine the optimal combinations for each building type.

Baseline Models

NREL obtained the USACE Construction Engineering Research Laboratory (CERL) models for five building types that will serve as the starting point for optimizing envelope design (USACE 2011). The ASHRAE 90.1-2007 models for the Colorado Springs climate location were used as the baseline for this study. Google Sketchup representations of the five buildings are shown in Figure 4 through Figure 8. Three of the models were developed by NREL (Dining Facility [DFAC], Company Operations Facility [COF], and Tactical Equipment Maintenance Facility [TEMF]), and the other two were developed by Big Ladder Software (Headquarters [HQ] and Barracks). Window-to-wall ratio (WWR) and skylight-to-roof ratio (SRR) are also provided for each building type.

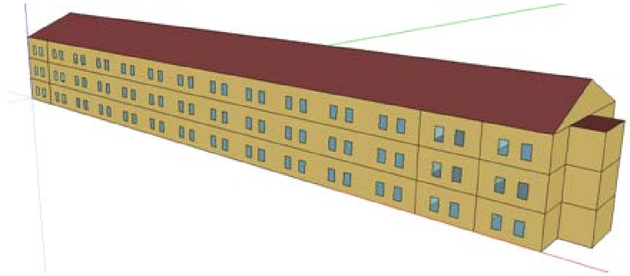

Figure 4 Barracks model (WWR=9%, SRR=0%)

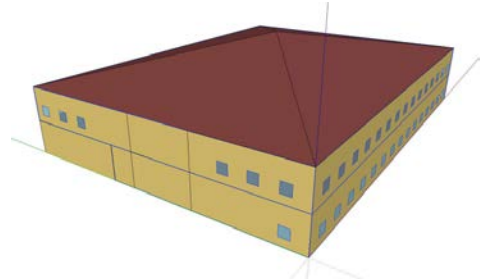

Figure 5 Brigade HQ model (WWR=7%, SRR=0%)

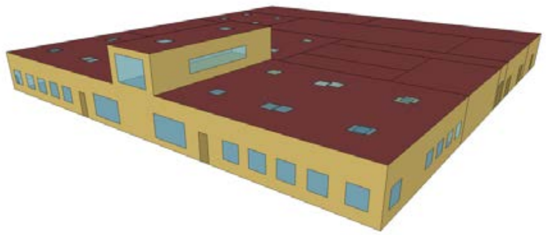

Figure 6 Dining Facility (DFAC) model (WWR=11%, SRR=0.6%)

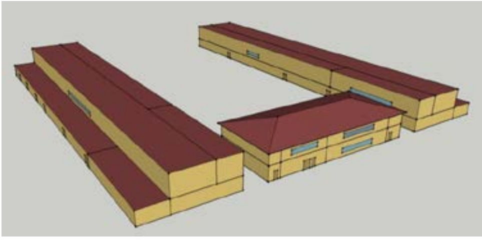

Figure 7 Company Operations Facility (COF) model (WWR=3%, SRR=0%)

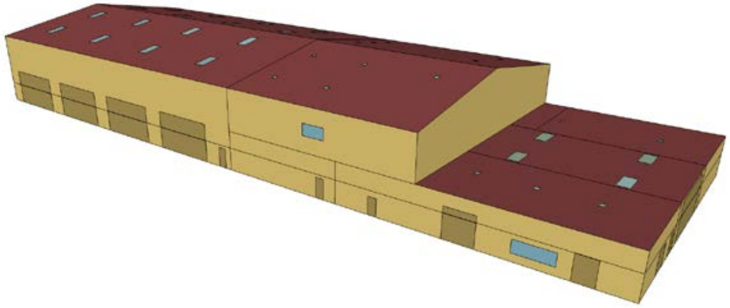

Figure 8 Tactical Equipment Maintenance Facility (TEMF) model (WWR=1%, SRR=3%)

NREL attempted to create OpenStudio models of the five building types using the EnergyPlus models developed for CERL, in order to utilize the same optimization capabilities used for the Net Zero Energy Retrofit task (See Net Zero Retrofit Optimization). Because the models were in a relatively old version of Energy Plus, and not all features of Energy Plus are supported by OpenStudio, there were a large number of conversion errors. We were unable to rectify these conversion issues in a reasonable amount of time, so we decided to proceed with a parametric optimization using EnergyPlus, along with run management features of OpenStudio.

NREL overcame some conversion issues while upgrading the five baseline models to the latest version of EnergyPlus. We also needed to prepare all baseline models for the parametric runs by making adjustments to assembly naming conventions, geometries, and material properties to ensure consistent application of the envelope measures in each building type.

We identified zone groupings in each of the five building types for which optimized envelope assemblies would be developed. Zones with similar heating and cooling set points were grouped together. In addition, zones that were likely to be vacant during troop deployments were identified, allowing the application of reduced ventilation rates, lower heating set points, and higher cooling set points.

The baseline models were used to examine the end-use breakdowns of energy use in each building type. These end-use breakdowns are shown in Figure 9 through Figure 13.

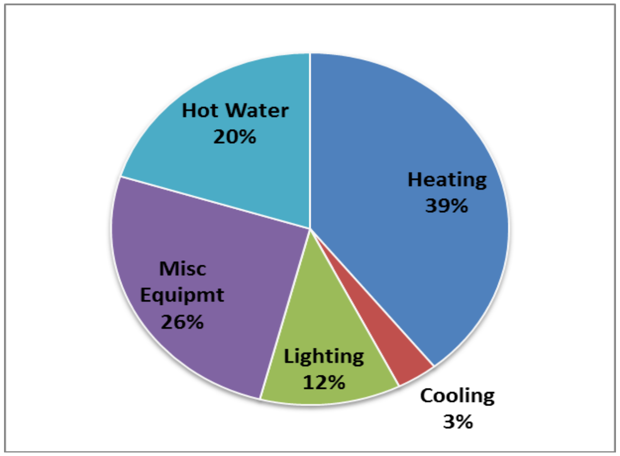

Figure 9 Barracks energy end-use breakdown

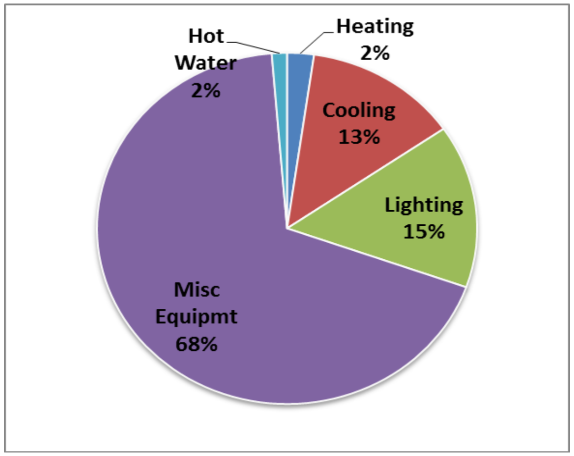

Figure 10 Brigade HQ energy end-use breakdown

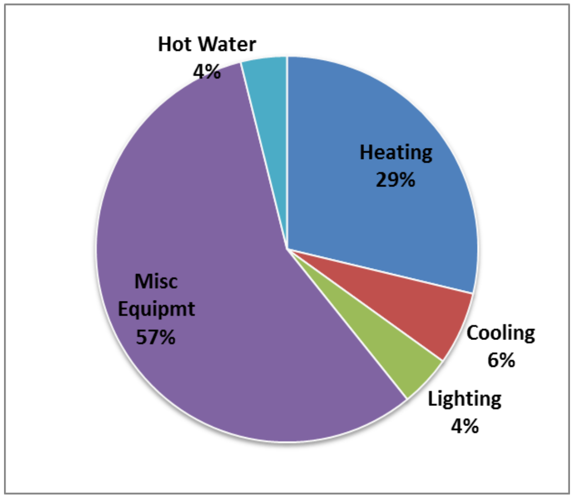

Figure 11 DFAC energy end-use breakdown

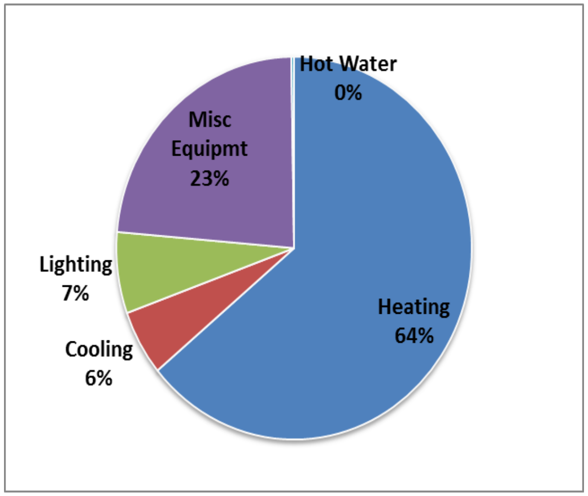

Figure 12 COF energy end-use breakdown

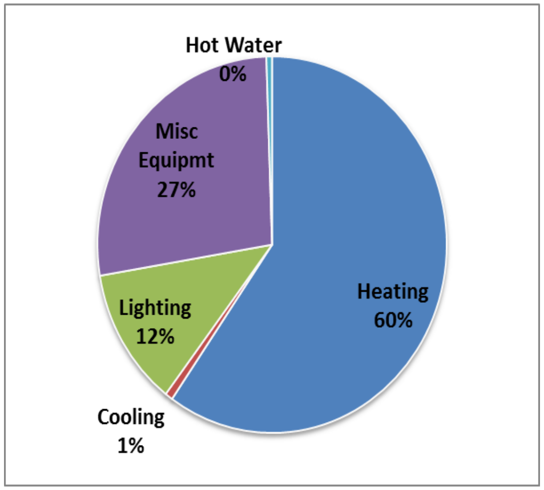

Figure 13 TEMF energy end-use breakdown

The Brigade HQ building model was dominated by equipment loads because a large data center was present.

Several important observations were made based on the end-use breakdowns of the five building types:

- The Brigade Headquarters building model was dominated by equipment loads because a large data center was present. As a result, the heating load calculated by the baseline model was very small, and the cooling load was relatively large. Expectations for significant energy savings resulting from added insulation and a tighter envelope should be tempered for buildings with such large internal heat gains.

- The DFAC model also had large internal heat gains due to cooking activities, but these loads occurred primarily during the day when meals are served. Greater opportunities exist for energy savings due to envelope improvements.

- The heating loads in the COF and TEMF models are relatively large, suggesting these building types are very good candidates for envelope upgrades. However, they also have large semi-conditioned spaces with lower heating set points, where envelope improvements may not be as cost-effective.

Measures Considered

Envelope components in the analysis included **wall construction, roof construction, window assemblies**, and **special interior zoning when troops are deployed**. We did not investigate basement or slab measures, which were deemed less likely to produce significant energy savings. We also did not study alternate building geometries or window placement, because the complexity of such analysis was outside the scope of this project. We also did not consider daylighting control measures such as clerestories or electrochromic windows, because those topics are addressed in the lighting optimization study (See Lighting System Performance).

Envelope analysis components included wall construction, roof construction, window assemblies, and special interior zoning when troops are deployed.

We performed a literature review to identify candidate envelope assemblies, including those analyzed in the draft report for the Military Construction (MILCON) Energy Efficiency and Sustainability Study of Five Army Buildings (USACE 2011). This report documented energy savings and cost projections for envelope types ranging from code minimum to Passivhaus levels. We noted a gap between insulation values for Passivhaus and what was referred to as the Army Whole Building Design Guide (WBDG), designated as Option 0 in the analysis. We decided to use the MILCON options for ASHRAE 189.1, WBDG, and Passivhaus, and fill in the gap with a few additional options. Recognizing that certain envelope design constraints are mission-critical (physical layout of zones, window blast/fire resistance, minimum view window area), we accepted the basic design features of the MILCON baseline models and focused on insulation levels, window coatings, and air sealing measures.

Specifications for the envelope measures were primarily taken from the MILCON study where available. Insulation levels for most of the additional wall and roof construction measures were interpolated between MILCON values. Precast concrete wall specifications were based on NREL experience with other projects. Infiltration values were obtained based on the recent USACE air barrier study conducted for buildings with various wall constructions at Fort Carson. Window properties were taken from the 2009 ASHRAE Handbook of Fundamentals. Thermostat setback and setup for the deployment zoning analysis was based on schedules for unconditioned spaces in the baseline models.

The final measure specifications used in the envelope optimization study are summarized in Table 1 through Table 4.

Table 1 Alternate wall constructions considered

Wall Efficiency Level	Wall Assembly	Wall Insulation R value*	Leakage rate cfm/ft^2 @ 0.3 in w.g.
ASHRAE 90.1-2007	2x4 Steel Framing, 2" EPS	13+7.5 ci	0.25
ASHRAE 189.1-2011	2x4 Steel Framing, 3" EPS	13+10 ci	0.25
Option 0	2x4 Steel Framing, 2" Polyiso	13+12.5 ci	0.25
Option 1	2x4 Steel Framing, 4" EPS	13+15 ci	0.25
Option 2	2x4 Steel Framing, 4" EPS, Tighter	13+15 ci	0.11
Option 3	Prefab Wall, Precast Concrete, 8" EPS	0+30 ci	0.05
Passivhaus	2x6 Steel Framing, 8" EPS, Tighter	19+30 ci	0.11

*Stated wall R-values are nominal, and do not include the effects of thermal short circuits, compression, or other impacts on installed R-value

Table 2 Alternate roof constructions considered

Roof Efficiency Level	Roof Assembly	Roof Insulation R value
ASHRAE 90.1-2007	IEAD, 4" Polyiso	20
ASHRAE 189.1-2011	IEAD, 5" Polyiso	25
Option 0	IEAD, 6" Polyiso	30
Option 1	IEAD, 8" Polyiso	40
Option 2	IEAD, 10" Polyiso	50
Passivhaus	IEAD, 11" Polyiso	55

Table 3 Alternate window assemblies considered

Window Efficiency Level	Window Assembly	Required Window U value	Required Window SHGC
ASHRAE 90.1-2007	Double, LowE, AlumNoBrk	0.55	0.40
ASHRAE 189.1-2011	Double, LowE, Bronze, AlumWBrk	0.45	0.35
Option 0	Double, LowE, AlumWBrk	0.42	0.39
Option 1	Double, LowE, Vinyl	--	--
Passivhaus	Triple, LowE, Vinyl	0.18	0.49

Table 4 Deployment status options

Unit Deployment Status	Heating Set Point (°F)	Cooling Set Point (°F)	Ventilation Rate (cfm)
Home Station	70	75	100%
Deployed	55	80	0

We considered the results of the Pacific Northwest National Laboratory (PNNL) interviews and surveys, which indicated that passive design measures, with minimal need for occupant intervention, were the most appropriate given the other important priorities of Army personnel. We originally planned to perform infrared imaging and other types of short-term envelope and thermal comfort testing to evaluate the envelope performance of existing buildings at Fort Carson, but resource constraints made this level of testing impractical.

We obtained peer reviews of our candidate envelope assemblies from the GSA team as well as a few members of the NREL Commercial Buildings Team and Mortenson Construction to verify the appropriateness of the measures for the building types under consideration. Several additional options were added based on these review comments.

Cost Inputs

Initial cost estimates for the envelope options were assembled from four sources. The primary cost estimates were provided by our partners at Mortenson Construction, who obtained quotes for most of the measures from their subcontractors. Alternate cost data sources were identified as a check for reasonableness, and to fill any gaps where Mortenson was unable to provide data. These alternate sources included the following:

- USACE air sealing cost data obtained from Fort Carson contractors

- Military Construction (MILCON) Energy Efficiency and Sustainability Study of Five Army Buildings (USACE 2011)
- Technical Support Document: Strategies for 50% Energy Savings in Large Office Buildings (Leach et al, 2010)
- RSMeans Building Construction Cost Data 2012 (R.S. Means, 2012)
- NREL's Opt-E-Plus cost library (NREL 2010)

The final incremental cost data used in the analysis are summarized in Table 5 through Table 7.

Table 5 Incremental wall construction costs

Wall Assembly	Incremental Cost ($/ft^2)
2x4 Steel Framing, 2" EPS	$-
2x4 Steel Framing, 3" EPS	$0.43
2x4 Steel Framing, 2" Polyiso	$0.95
2x4 Steel Framing, 4" EPS	$0.85
2x4 Steel Framing, 4" EPS, Tighter	$2.25
Prefab Wall, Precast Concrete, 8" EPS	$20.25
2x6 Steel Framing, 8" EPS, Tighter	$2.95

Table 6 Incremental roof construction costs

Roof Assembly	Incremental Cost ($/ft^2)
IEAD, 4" Polyiso	$-
IEAD, 5" Polyiso	$0.40
IEAD, 6" Polyiso	$0.80
IEAD, 8" Polyiso	$1.50
IEAD, 10" Polyiso	$2.20
IEAD, 11" Polyiso	$2.55

Table 7 Incremental window assembly costs

Window Assembly	Incremental Cost ($/ft^2)
Double, LowE, AlumNoBrk	$-
Double, LowE, Bronze, AlumWBrk	$4.80
Double, LowE, AlumWBrk	$1.80
Double,LowE, Vinyl	$5.00
Triple, LowE, Vinyl	$8.30

We did not attempt to estimate the cost of designing buildings where certain thermal zones can be isolated when troops are deployed. Modifications to the heating, ventilation, and air conditioning (HVAC) system would be necessary, along with additional interior walls and doors with a reasonable level of insulation and air tightness. This constitutes an uncommon set of features, and we were unable to locate relevant cost data. However, the potential energy savings justifies further research to evaluate cost-effectiveness.

Analysis Approach

NREL developed a Ruby script file that generated and ran EnergyPlus files for each envelope option in each of the five building types. The Ruby script utilized the run management features of OpenStudio to perform the modeling in an efficient manner, and allowed straightforward changes to the application of measures when necessary. EnergyPlus output data was loaded into a spreadsheet, which performed net present value (NPV) analysis of individual envelope construction types, as well as the optimal package for each building type. “Optimal” in this context refers to the option with the highest NPV among the choices that were considered.

Results and Lessons Learned

NREL performed net-present value analysis of all envelope options that were considered for the five building types, two of which included separate analysis of conditioned and semi-conditioned spaces (TEMFs and COFs). Optimal wall constructions, roof insulation levels, and window assemblies were identified based on maximum net present value in the corresponding building type over a **30-year project period using the standard 4% nominal discount factor** established by the U.S. Army. These optimal envelope features, along with their corresponding first cost and NPV, are summarized in Table 8 to Table 11. NREL also estimated the potential energy cost savings for designing the buildings with special zoning capability that would allow a significant temperature setback and reduction in ventilation for most of the building when troops are deployed, as shown in Table 11.

Table 8 Optimal wall constructions

Building Type	Wall Construction	Incremental First Cost	30 Year NPV vs. ASHRAE 90.1 2007
Barracks	2x4 Steel Framing, 4" EPS, Improved Air Barrier	$58,700	$90,100
HQ	2x4 Steel Framing, 2" EPS	$0	$0
DFAC	2x4 Steel Framing, 4" EPS	$7,670	$529
COF (Conditioned)	2x6 Steel Framing, 8" EPS, Improved Air Barrier	$60,000	$214,000
COF (Semi-conditioned)	2x4 Steel Framing, 4" EPS, Improved Air Barrier	$75,100	$128,000
TEMF (Conditioned)	2x4 Steel Framing, 4" EPS, Improved Air Barrier	$16,500	$30,600
TEMF (Semi-conditioned)	2x4 Steel Framing, 4" EPS, Improved Air Barrier	$30,700	$42,700

Table 9 Optimal roof constructions

Building Type	Roof Construction	Incremental First Cost	30 Year NPV vs. ASHRAE 90.1 2007
Barracks	Insulation Entirely Above Deck, 4" Polyisocyanurate	$0	$0
HQ	Insulation Entirely Above Deck, 4" Polyisocyanurate	$0	$0
DFAC	Insulation Entirely Above Deck, 4" Polyisocyanurate	$0	$0
COF (Conditioned)	Insulation Entirely Above Deck, 6" Polyisocyanurate	$18,300	$10,200
COF (Semi-conditioned)	Insulation Entirely Above Deck, 4" Polyisocyanurate	$0	$0
TEMF (Conditioned)	Insulation Entirely Above Deck, 4" Polyisocyanurate	$0	$0
TEMF (Semi-conditioned)	Insulation Entirely Above Deck, 4" Polyisocyanurate	$0	$0

Table 10 Optimal window assemblies

Building Type	Window Construction	Incremental First Cost	30 Year NPV vs. ASHRAE 90.1 2007
Barracks	Triple Pane, Low-E, Vinyl Frame	$20,900	$234
HQ	Double Pane, Low-E, Aluminum Frame without Thermal Break	$0	$0
DFAC	Double Pane, Low-E, Bronze Coating, Aluminum Frame with Thermal Break	$5,160	$4,200
COF	Triple Pane, Low-E, Vinyl Frame	$18,300	$1,810
TEMF	Double Pane, Low-E, Aluminum Frame without Thermal Break	$0	$0

Table 11 Impact of relaxed thermostat settings and reduced ventilation rates during troop deployments

Building Type	Annual Cost Savings	Annual Energy Savings
Barracks	$12,508	14%
HQ	$2,955	4%
DFAC	$7,799	4%
COF	$25,047	23%
TEMF	$5,254	12%

No single measure is optimal in all five building types.

The results of the individual measure analyses illustrated several important points:

- No single measure is optimal in all five building types.
- Using the assumed first cost estimates, roof improvements beyond code were generally not cost-effective.
- The optimal envelope constructions were the same for conditioned and unconditioned spaces in the TEMF, but slightly higher insulation was recommended for conditioned spaces in the COF.
- Interior zoning during troop deployment appears to be a very high impact measure in buildings with large heating loads (Barracks, COF, TEMF). It is important to note that the energy savings for this study does not include reductions in lighting and plug loads, which are assumed to occur whether or not special zoning is in place. This analysis only includes the effects of reduced ventilation and more relaxed thermostat settings.

The optimal wall, roof, and window designs for each building type were next combined into a single package, and re-analyzed to capture any interactive effects. The results for these optimal packages are summarized in Table 12.

Table 12 Energy savings of optimal envelope packages versus ASHRAE 90.1-2007

Building Type	Energy Savings	Incremental First Cost	Annual Energy Savings	30 Year NPV	Simple Payback
Barracks	15.8%	$79,700	$7,650	$83,000	10 yrs
HQ	0.0%	$0	$0	$0	N/A
DFAC	0.3%	$12,800	$601	$88	21 yrs
COF	24.8%	$168,000	$24,600	$353,000	7 yrs
TEMF	21.8%	$47,200	$5,660	$72,700	8 yrs

The results indicate that very large whole-building energy savings can be achieved cost-effectively for the COF, Barracks, and TEMF, by improving the envelope construction beyond code. However, no improvements were recommended for the HQ building beyond code. As mentioned earlier, the large data center in the HQ model produced such large internal heat gains, that very little supplemental heating was necessary. As a result, reducing heat losses through the thermal envelope was often counterproductive, increasing the cooling energy use more than it reduced heating energy. Large internal heat gains also resulted in minimal cost-effective improvements for the DFAC.

Recommendations

Whole-building energy savings up to 25% can be achieved in new buildings at Fort Carson with NPV over $300,000 and a simple payback as low as 7 years.

The results of the envelope study provide several important insights that should be considered for future new construction projects at Fort Carson:

- Whole-building energy savings up to 25% can be achieved in new buildings at Fort Carson with NPV over $300,000 and a simple payback as low as seven years.
- Improving air-tightness is generally higher impact than increasing insulation levels.
- Savings can be very significant for thermal zoning and ventilation setback when troops are deployed
- Designers should consider using envelope constructions adapted to the unique attributes and usage patterns of each building type. For example, buildings with smaller internal gains per square foot should be targeted for envelope improvements before buildings with relatively high internal gains. Also, semi-conditioned spaces may not benefit from envelope upgrades as much as fully conditioned spaces.

- Envelope improvements are an essential component of net zero energy design for buildings with large heating loads associated with the thermal envelope (infiltration, conduction) that must be met by the HVAC system, but should not be the primary focus for buildings that are dominated by internal gains from equipment.

There may be many non-economic reasons to select packages based on the energy efficiency goals of the Army.

There are a few limitations to the application of the envelope study results that should be noted:

- "Optimal" packages in the context of this study are based on the highest NPV relative to a code minimum building, using fuel costs that track with inflation. There may be many non-economic reasons to select packages that are not strictly optimal from an economic standpoint, based on the energy efficiency goals of the Army for a particular project. Societal impacts such as source energy, greenhouse gas emissions, and reduced dependence on limited fossil fuel sources, may be important considerations. Envelope improvements can also protect against unexpected increases in fuel prices, and can greatly improve the uniformity of temperatures in a building, creating a more comfortable work environment for occupants.

- Optimal envelope features may change if part of a larger package of improvements. For the most part, higher insulation levels and reduced air infiltration measures are independent of each other, and have no systems interactions. But many envelope improvements will be less cost-effective when bundled with HVAC efficiency improvements that reduce the amount of energy needed to meet envelope loads. At the same time, equipment downsizing may be possible when envelope loads are reduced, resulting in higher cost-effectiveness. Because these positive and negative interactive effects are common with energy efficiency projects, the optimal envelope design may depend on the efficiency of other building systems.

- Optimal envelope packages are likely to be dependent on building geometry. This study focused on representative building types at Fort Carson, but other building characteristics (e.g., surface area to volume ratios, window-to-wall ratio, solar exposure) could produce different results.

- NPVs of window enhancements are highly dependent on window orientation, heating/cooling loads, and daylighting controls.

- Cost data is highly variable, both over time and from site-to-site. It may be possible for Fort Carson to obtain materials at a lower cost than we assumed. If that is the case, more aggressive packages of envelope improvements may become optimal. Similarly, higher energy prices resulting from resource scarcity can also increase the economic value of investments in envelope improvements.

- This study was limited to the Colorado Springs area. As a result, the optimal packages may not apply to other Army bases in other locations. However, the key lessons learned are still relevant as general guiding principles.

- The analysis was performed in the context of new construction. The energy savings may be significantly higher for existing buildings with building envelopes that do not meet ASHRAE 90.1 requirements, or that experience performance degradation over time. However, envelope improvements are generally much more costly for existing buildings because installation costs are higher and incremental purchase costs cannot be used unless the envelope components are at the end of their useful life, or a major renovation is planned that requires replacement of major building envelope assemblies. As a result, the optimal envelope designs discussed in this section are relevant for very deep retrofits, but are unlikely to be cost-effective for more common energy-driven retrofit scenarios. A separate analysis should be performed in the context of retrofits.