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Life Cycle Assessment of LEED vs. Conventionally Built Residential Units

Woo-Suk Chun

LIFE CYCLE ASSESSMENT OF LEED VERSUS CONVENTIONALLY BUILT RESIDENTIAL UNITS

THESIS

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AFIT/GEM/ENV/11-M09

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Abstract

The United States Air Force (USAF) constructed 1,028 LEED for Homes Silver and/or ENERGY STAR certified energy efficient homes at Biloxi, MS, in accordance with the USAF sustainable design and development policy. To analyze and compare these energy efficient homes to conventionally built homes, this study employed a hybrid LCA and energy simulation. These energy efficient homes have a 16% less environmental impact, consume 15% less energy, and save 2% in total life cycle cost while incurring a 1% cost increase in project construction compared to conventional homes. The simple payback period of the project to payback this initial 1% construction cost increase is 10 years. The most effective energy efficient measure implemented was increasing the air conditioning seasonal energy efficiency rating (SEER) while the least effective measure was increasing roof insulation R-value. Lastly, energy simulation results from the schematic design phase were statistically different compared to energy simulation results from the detailed design phase. By comparing the results of energy simulations from both design phases, simulation results from the detailed design phase were more accurate. The recommendation for a design team is to hold off on performing energy simulation until determining which energy efficiency measures to implement as permitted by the project timeline, cost, and other factors influencing the project.

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LIFE CYCLE ASSESSMENT OF LEED VERSUS CONVENTIONALLY BUILT RESIDENTIAL UNITS

I. Introduction

The goal of the United States Air Force's (USAF) sustainable design and development policy is to: "reduce the environmental impact and total ownership cost of facilities; improve energy efficiency and water conservation; and provide safe, healthy and productive built environments (Eulberg, 2007)." To achieve this goal, the USAF requires all vertical military construction (MILCON) be certifiable in Leadership in Energy and Environmental Design (LEED) Silver (Eulberg, 2007).

LEED can assist the USAF to design, construct, operate, and decommission high-performance buildings which can help reduce the environmental impact, improve overall energy efficiency, conserve water, and potentially improve the lives of building occupants. The LEED rating system measures overall performance of a building in five areas: sustainable site develoment, water savings, energy efficiency, material selection, and indoor environmental quality (USGBC, 2009). According to the U.S. Government Services Administration (GSA), 12 LEED GSA buildings consumed 26% less energy and had 33% less greenhouse gas (GHG) emissions compared to the average performance of U.S. commercial buildings (GSA, 2008). Newsham et al. (2009) reported that "LEED buildings used 18 - 39% less energy per floor area than their conventional counterparts. However, 28 – 35% of LEED buildings used more energy than their conventional counterparts (Newsham et al., 2009)." In the pursuit to accurately capture reduction of environmental impact and energy consumption, contrasting views justify the adoption of energy simulation and life cycle assessment (LCA) in the early stages of design.

Energy simulation is a method to provide whole building performance analysis (Hirsch, 2010). By using an energy simulation method, a design team can predict the building performance and evaluate design options to lower energy consumption. Energy simulation results can also serve as a baseline to determine whether the building is operating as designed. This research utilized two energy simulation tools: ESim and eQUEST (Hirsch, 2010; Kissock, 1997).

LCA analyzes the environmental impacts of a product or process throughout its entire life cycle (Horvath and Hendrickson, 1998). A typical LCA methodology consists of four steps:

1. Goal, project scope, and boundary definitions.
2. Inventory analysis involving estimates environmental burdens.
3. Impact assessment
4. Interpretation of the results subjected to sensitivity analysis and prepared for communication (Chester, 2008).

There are three common types of LCA available: process-based LCA, EIO-LCA, and hybrid LCA.

Project History

In 2006, the USAF awarded a $290 million MILCON contract to construct 1,028 residential homes at Keesler AFB, MS. The objective was to replace 1,820 military family homes, severely damaged or destroyed during Hurricane Katrina, using conventional construction. During construction, the USAF increased the project scope by $2 million to pursue ENERGY STAR certifications for all 1,028 homes and Leadership in Energy and Environmental Design (LEED) for Homes Silver certifications for 736 residential units. This required several design changes. Eleven types of single family dwelling units and 17 types of duplex units using a mixture of 14 different floor plans exist. The size of units ranges from 1,705 ft^2 ($158m^2$) to 4,200 ft^2 (390 m^2).

Research Objectives

The purpose of this thesis was to analyze energy efficient homes and compare them to conventional homes. We conducted energy simulations and a hybrid LCA, incorporating information obtained from energy simulations and construction data (i.e. design, total project cost), to address the following research objectives:

- Quantify environmental impact and energy consumption differences between energy efficient and conventionally built homes.
- Analyze individual energy efficiency measures to quantify the energy reduction contribution.
- Compare energy simulation results from schematic design and detailed design.

Methodology

Using results from energy simulation and data extracted from USAF facility maintenance instructions and construction documents, a hybrid LCA was used to quantify and compare the environmental impact of energy efficient homes built at Keesler AFB to conventionally built homes. To quantify the energy reduction contribution of individual energy efficiency measures, we identified seven prominent energy efficiency measures, varied the values of these measures, and analyzed the individual effect of measures on the total energy consumption of the house. Lastly, using two different energy simulation tools available, eQUEST and ESim, energy simulations at different phases of design were statistically analyzed.

Preview

This thesis follows the scholarly article format. The following chapter is the manuscript, which was submitted to the *Energy and Buildings Journal*. Chapter 2 includes an abstract, introduction, literature reviews on energy simulation and life cycle assessment, project history, objectives, methods, results and discussions including limitations and future research topics, and conclusions as prescribed by the peer review journal. Chapter 3 summarizes the article and offers a final discussion with pertinent findings.

II. Life Cycle Assessment of LEED vs. Conventionally Built Residential Units

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Abstract

The United States Air Force (USAF) constructed 1,028 LEED for Homes Silver and/or ENERGY STAR certified energy efficient homes at Biloxi, MS, in accordance with the USAF sustainable design and development policy. To analyze and compare these energy efficient homes to conventionally built homes, this study employed a hybrid LCA and energy simulation. These energy efficient homes have a 16% less environmental impact, consume 15% less energy, and save 2% in total life cycle cost while incurring a 1% cost increase in project construction compared to conventional homes. The simple payback period of the initial 1% construction cost increase is 10 years. The most effective energy efficient measure implemented was increasing the air conditioning seasonal energy efficiency rating (SEER) while the least effective measure was increasing roof insulation R-value. Lastly, energy simulation results from the schematic design phase were statistically different compared to energy simulation results from the detailed design phase. By comparing the results of energy simulations from both design phases, simulation results from the detailed design phase were more accurate. The recommendation for a design team is to hold off on performing energy simulation until determining which energy efficiency measures to implement as permitted by the project timeline, cost, and other factors influencing the project.

Keywords: LEED; Life cycle assessment; EIO-LCA; Hybrid LCA; Residential buildings; Energy simulation; eQUEST; ESim

1. Introduction

1.1. Background

The United States government is the world's largest volume-buyer of energy related products (SAF/IE, 2009). Figure 1 shows that the Department of Defense (DoD) consumes 91% of all federal energy consumption and of the four services, the United States Air Force (USAF) consumes 64% while 12% is attributed to facility operations (SAF/IE, 2009). As an effort to reduce energy consumption for facility operations, the USAF requires all vertical military construction (MILCON) be certifiable in Leadership in Energy and Environmental Design (LEED) Silver (Eulberg, 2007).

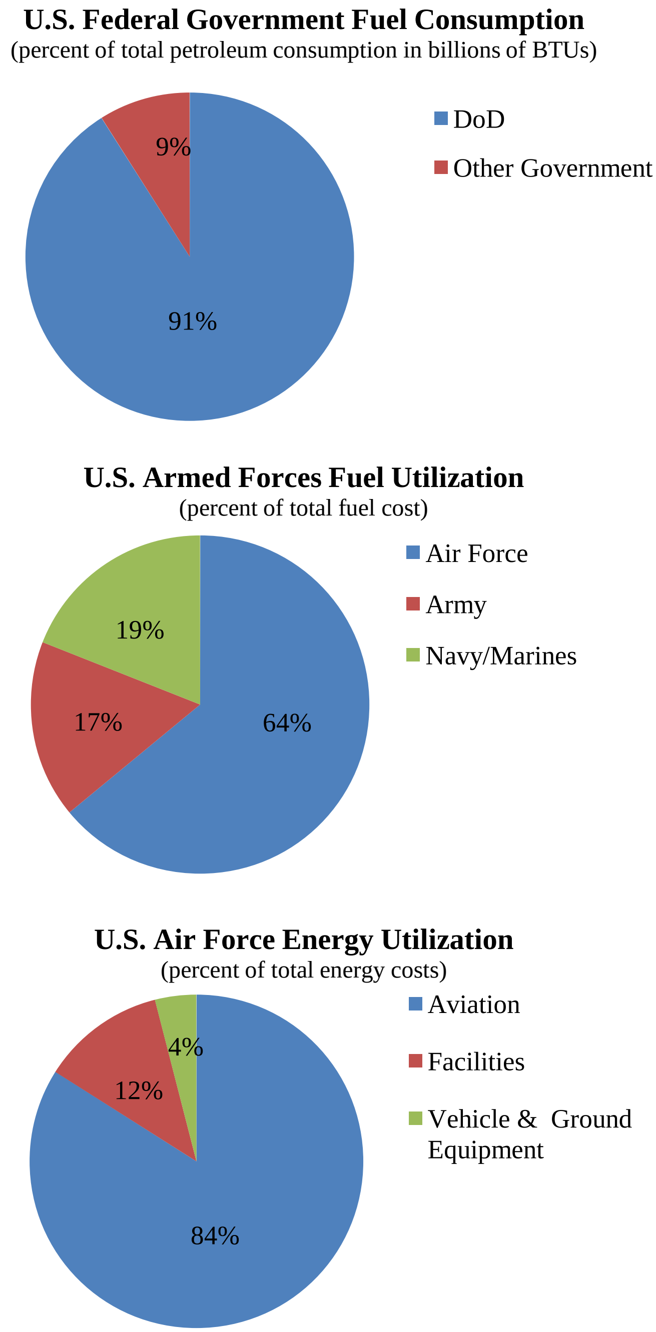

Figure 1. U.S. Government Energy Snapshot (SAF/IE, 2009)

The LEED rating system measures overall performance of a building in five areas: sustainable site develoment, water savings, energy efficiency, material selection, and indoor environmental quality (USGBC, 2009). According to the U.S. Government Services Administration (GSA), 12 LEED GSA buildings consumed 26% less energy and had 33% less greenhouse gas (GHG) emissions compared to the average performance of U.S. commercial buildings (GSA, 2008). Newsham et al. (2009) reported that "LEED buildings used 18 - 39% less energy per floor area than their conventional counterparts. However, 28 – 35% of LEED buildings used more energy than their conventional counterparts (Newsham et al., 2009)." In the pursuit to accurately capture reduction of environmental impact and energy consumption, contrasting views justify the adoption of energy simulation and life cycle assessment (LCA) in the early stages of design.

1.2. Energy Simulation

Energy simulation is a method to provide whole building performance analysis (Hirsch, 2010). By using an energy simulation method, a design team can predict the building performance and evaluate design options to lower energy consumption. Energy simulation results can also serve as a baseline to determine whether the building is operating as designed. This research utilized two energy simulation tools: ESim and eQUEST (Hirsch, 2010; Kissock, 1997).

1.2.1. ESim

ESim employs computational algorithms which are based on "fundamental thermodynamic, psychrometric and heat-transfer calculations. However, data input requirements are the minimum necessary to model the major energy flows, control systems, and equipment" (Kissock, 1997). Due to limited data input requirements, ESim cannot model non-conditioned zones in a building and ESim automatically assumes that a building is a box shape, so information available during the schematic design phase is sufficient. Raffio et al. (2006) used ESim to simulate energy consumption of an energy efficient house at the University of Dayton and found that the house consumed 52% to 58% less energy compared to a conventionally built house.

1.2.2. eQUEST

eQUEST combines “the wizard,” for building model creation and energy efficiency measure analysis, and a “detailed interface” which links to the DOE-2.2 simulation engine (Hirsch, 2010). “The wizard” of eQUEST allows users to input detailed design information and define a floor layout. Zhu et al. (2009) employed eQUEST to simulate energy consumption of a zero energy house and a conventional house in Las Vegas, NV. The data show that a radiant barrier and a water-cooled air conditioner are major contributors to the energy savings while an insulated floor slab and thermal mass walls are not effective for energy conservation (Zhu et al., 2009).

1.3. Life Cycle Assessment

LCA analyzes the environmental impacts a product or process throughout its entire life cycle (Horvath and Hendrickson, 1998). LCA provides three types of analytical results: (1) inventory analysis which estimates the negative environmental impacts; (2) impact analysis which estimates the stress caused by these burdens on humans and nature; and (3) improvement analysis which identifies areas where improvements are possible (Horvath and Hendrickson, 1998). A LCA methodology typically consists of four steps:

1. Goal, project scope, and boundary definitions
2. Inventory analysis involving estimates environmental burdens
3. Impact assessment

4. Interpretation of the results subjected to sensitivity analysis and prepared for communication (Chester, 2008)

There are three common types of LCA available: process-based LCA, EIO-LCA, and hybrid LCA.

Process-based LCAs can produce detailed results where a specific product or process can be compared; however, a process-based LCA tends to be time extensive and expensive. Also, the researcher conducting a process-based LCA subjectively determines the boundary. The EIO-LCA model uses economic input-output matrices and industry sector level environmental and resource consumption data to assess the economy-wide environmental impacts of products and processes (Hendrickson et al., 1997). The EIO-LCA results allow systems-level comparisons. The EIO-LCA can be repeated because it uses publicly available data; however, the results of the EIO-LCA analysis represent the impacts from a change in demand for an industry sector. Also, the EIO-LCA models are incomplete in as much as a limited number of environmental effects are included. Lastly, the data used to produce the EIO-LCA can be old and incomplete ("Economic Input-Outpt Life Cycle Assessment," 2009; Hendrickson et al., 2006). Because of the complex nature of construction, a process-based LCA and the EIO-LCA are not the best methods. Therefore, this research utilized a hybrid LCA model which incorporates the advantages of both LCA methodologies.

1.4. Project History

In 2006, the USAF awarded a $290 million MILCON contract to construct 1,028 residential homes at Keesler AFB, MS. The objective was to replace 1,820 military family homes, severely damaged or destroyed during Hurricane Katrina, using conventional construction. During construction, the USAF increased the project scope by $2 million to pursue ENERGY STAR certifications for all 1,028 homes and Leadership in Energy and Environmental Design (LEED) for Homes Silver certifications for 736 residential units. This required several design changes. Eleven types of single family dwelling units and 17 types of duplex units using a mixture of 14 different floor plans exist. The size of units ranges from 1,705 ft^2 ($158m^2$) to 4,200 ft^2 (390 m^2).

1.5. Objectives

We conducted energy simulations and a hybrid LCA, incorporating information obtained from energy simulations and construction data (i.e. design, total project cost), using these homes. The following research objectives were addressed:

- Quantify environmental impact and energy consumption differences between energy efficient and conventionally built homes.
- Analyze individual energy efficiency measures to quantify the energy reduction contribution.
- Compare energy simulation results from schematic design and detailed design.

2. Methods

2.1. LCA

Using results from energy simulations and data extracted from USAF facility maintenance instructions and construction documents, the hybrid LCA was used to quantify and compare the environmental impact of energy efficient homes built at

Keesler AFB to conventionally built homes. The proposed hybrid LCA method consists of following steps:

1. Derive an input-output LCA model
2. Extract the most important pathways for the construction sectors
3. Derive case specific LCA data for the building and its components
4. Substitute the case specific LCA data into the input-output model (Treloar et al., 2000)

The life-cycle of this project was divided into three phases: construction, use, and disposal following the EIO-LCA conducted for U.S. residential buildings by Ochoa et al. (2003). The construction phase included raw material acquisition, material manufacturing, and construction of homes. The use phase included remodeling, home improvement, heating, cooling, lighting, daily electrical consumption other than lighting, and hot and cold water consumption. Lastly, the disposal phase included demolition, recycling, and disposal of construction debris (Ochoa et al., 2003). Table 1 summarizes the LCA types conducted for each phase.

Table 1. LCA Types

<table>
<tr><th colspan="2">Phase</th><th>LCA Types</th></tr>
<tr><td colspan="2">Construction</td><td>EIO-LCA</td></tr>
<tr><td rowspan="2">Use</td><td>Operations</td><td>Case specific LCA based on energy simulation results</td></tr>
<tr><td>Maintenance & Repair</td><td>EIO-LCA</td></tr>
<tr><td colspan="2">Disposal</td><td>EIO-LCA</td></tr>
</table>

We calculated the total environmental impact and energy consumption using the original contract cost for the construction phase of conventional homes. For the construction phase of energy efficiency homes, we used the modified contract cost to determine the total environmental impact and energy consumption.

The use phase was divided into two major components: operations and maintenance/repair. To calculate the operations cost, we used eQUEST to simulate energy consumption (both electricity and natural gas) assuming a life of 60 years. The electricity and natural gas costs of Biloxi MS in 2002 were 7.28 cents per kWh and $7.76 per 1,000cfm, respectively (EIA, 2010a, 2010b). The annual maintenance and repair cost of these homes was determined to be 1% of the total construction cost in accordance with USAF facility maintenance instructions for both conventional and energy efficiency homes.

Lastly, the disposal cost was calculated to be 1% of total life time cost of the project based on past studies for both conventional and energy efficiency homes (Kannan et al., 2007). The EIO-LCA tool used in this study is based on the U.S. economy annual input-output from 2002. All monetary values were brought back to 2002 by using 3% annual inflation rate following the EIO-LCA conducted for U.S. residential buildings by Ochoa et al. (2003).

2.2. Sensitivity Analysis

A house is a system of systems. Various components of a home interact closely with each other to influence the total energy consumption during operations. Using eQUEST's energy efficiency measure analysis tool, we varied the values of major energy efficiency measures implemented to make Keesler homes energy efficient and quantified the individual effect of measures on the house. Table 2 outlines the most prominent energy efficiency measures adopted and analyzed for this study.

Table 2 Housing characteristics

Characteristics	Conventional	KEESLER AFB Housing Profile LEED for Homes/ENERGY STAR
Structural Framing	2"x4" @ 16" (0.05m x 0.10m @ 0.41m) on center (O.C.) wood frame	2"x6" @ 16" (0.05m x 0.15m @ 0.41m) O.C. wood frame
Wall Insulation	R-value: 11 h·ft^2·ºF/Btu (1.94 K·m^2/W) Unfaced Batt Insulation	R-value: 19 h·ft^2·ºF/Btu (3.35 K·m^2/W) Unfaced Batt Insulation
Roof Insulation	R-value: 21 h·ft^2·ºF/Btu (3.70 K·m^2/W)	R-value: 30 h·ft^2·ºF/Btu (5.28 K·m^2/W)
Roof Color	Dark	Light
Infiltration (ACH*)	0.68	0.35
Cooling (SEER**)	10 Btu/W·hr	16 Btu/W·hr
Heating (HSPF***)	6.8 Btu/W·hr	9.2 Btu/W·hr

* ACH: Air changes per hour
** SEER: Seasonal energy efficiency rating
*** HSPF: Heating seasonal performance factor

2.3. Schematic design vs. detailed design

LEED recommends that project teams pursuing LEED certification adopt energy simulation early in the design phase. The question is "how early?" Does energy simulation conducted in the schematic design phase provide a similar energy profile as energy simulation in the detailed design phase of construction? Using two different energy simulation tools available, eQUEST and ESim, energy simulations at different phases of design were statistically analyzed.

3. Results and Discussions

3.1. LCA

To quantatively analyze and compare the environmental impacts of Keesler's energy efficienct homes to conventionally built homes, we utilized a hybrid LCA by incorporating results from energy simulations and data obtained from construction documents and Air Force facility operation instructions. For energy simulation, the accuracy of an energy consumption behavior (energy consumption profile) of a building depends on the accuracy of the building characteristic inputs. Also, the building occupant behaviors must be taken into consideration because they can greatly affect the consumption profile. Collecting historical energy consumption data is crucial to accurately simulate the energy consumption profile while taking into account occupant energy consumption behaviors. Regretfully, Keesler AFB did not collect energy consumption data. One quick way to validate the energy simulation model was to compare the average end use intensity (EUI) of conventional homes. From the energy simulation, the average EUI of conventional homes is 7.2 $kWh/ft^2{\cdot}yr$ (280 $MJ/m^2{\cdot}yr$) with a standard deviation of 0.25 $kWh/ft^2{\cdot}yr$ (10 $MJ/m^2{\cdot}yr$). This is comparable to the 7.6 $kWh/ft^2{\cdot}yr$ (294 $MJ/m^2{\cdot}yr$), value reported by RWL Analytics (2007) as the average EUI of newly constructed homes using electrical heating system in 2006.

Figure 2 shows that the construction phase economic activity represents 65% of total life cycle economic activity for conventional homes with support infrastructure. The global warming potential (GWP) and energy consumption during construction phase are 20% and 22%, respectively. The economic activity of the use phase (operations, maintenance, and repair) is relatively small compared to the construction phase, 34%, but GWP and energy consumption of the use phase represent major portion of the total GWP and energy consumption 79% and 78%, respectively. Lastly, the disposal phase economic activity, GWP and energy consumption are negligible.

Figure 2 also shows that energy efficient homes with support infrastructure follow a similar trend. The construction phase economic activity represents 67% of total life cycle economic activity. The GWP and energy consumption during the construction phase are 24% and 27%, respectively. For the use phase, the economic activity is 32%, while GWP is 75%, and energy consumption is 73%. Lastly, the disposal phase economic activity, GWP, and energy consumption are negligible. Note that the use phase constitutes a large portion of GWP and energy consumption and any economically feasible steps taken to reduce energy consumption and GWP during the use phase can have great impacts.

Ochoa et al. (2003), conducted an EIO-LCA of the U.S. residential sector for 1997 and found that within three phases, the use phase (54% of economic activity) is the largest consumer of energy (93%) and the largest GWP (92%)" (Ochoa, et al., 2003). A process-based LCA conducted by Scheuer et al. (2003) reported similar results where the use phase energy consumption accounted for 94% of life cycle primary energy consumption. The results from past studies are slightly different from this study's findings and the primary difference is the project scope. Unlike the previous two studies, this study included support infrastructures like access roads and utility mains.

Adjusting the construction costs, by excluding the support infrastructure costs, reduces the differences significantly. Figure 2 shows the economic activity of conventional homes represents 49% of the total construction phase, while the GWP and energy consumption during construction phase are 12% and 13%, respectively. For the use phase, the economic activity is 50%, while GWP is 88%, and energy consumption is 87%. The disposal phase still plays a minor role. For energy efficient homes without support infrastructure, the construction phase economic activity represents 52% of total life cycle economic activity. The GWP and energy consumption during construction phase are 14% and 16%, respectively. For the use phase, the economic activity is 47%, while GWP and energy consumption are 85% and 84%, respectively. The disposal phase economic activity, GWP, and energy consumption are negligible. The results for energy efficient homes are similar to results reported by Blanchard and Reppe (1998), who found that the construction phase represents 16% of total life cycle energy of an energy efficient home where the use phase represents 83%.

Overall a 1% increase in construction cost resulted in a 2% reduction of overall total life cycle cost, 16% GWP reduction, and 15% reduction in total energy consumed. The GWP and energy consumption fall short of the 33% GHG reduction and 18-39% energy reduction reported in previous studies (GSA, 2008). These differences may be due to different LEED certification approaches that the USAF took compared to LEED certified buildings. Additionally, the simple payback period of initial two million dollar investment to build energy efficiency homes is 10 years.

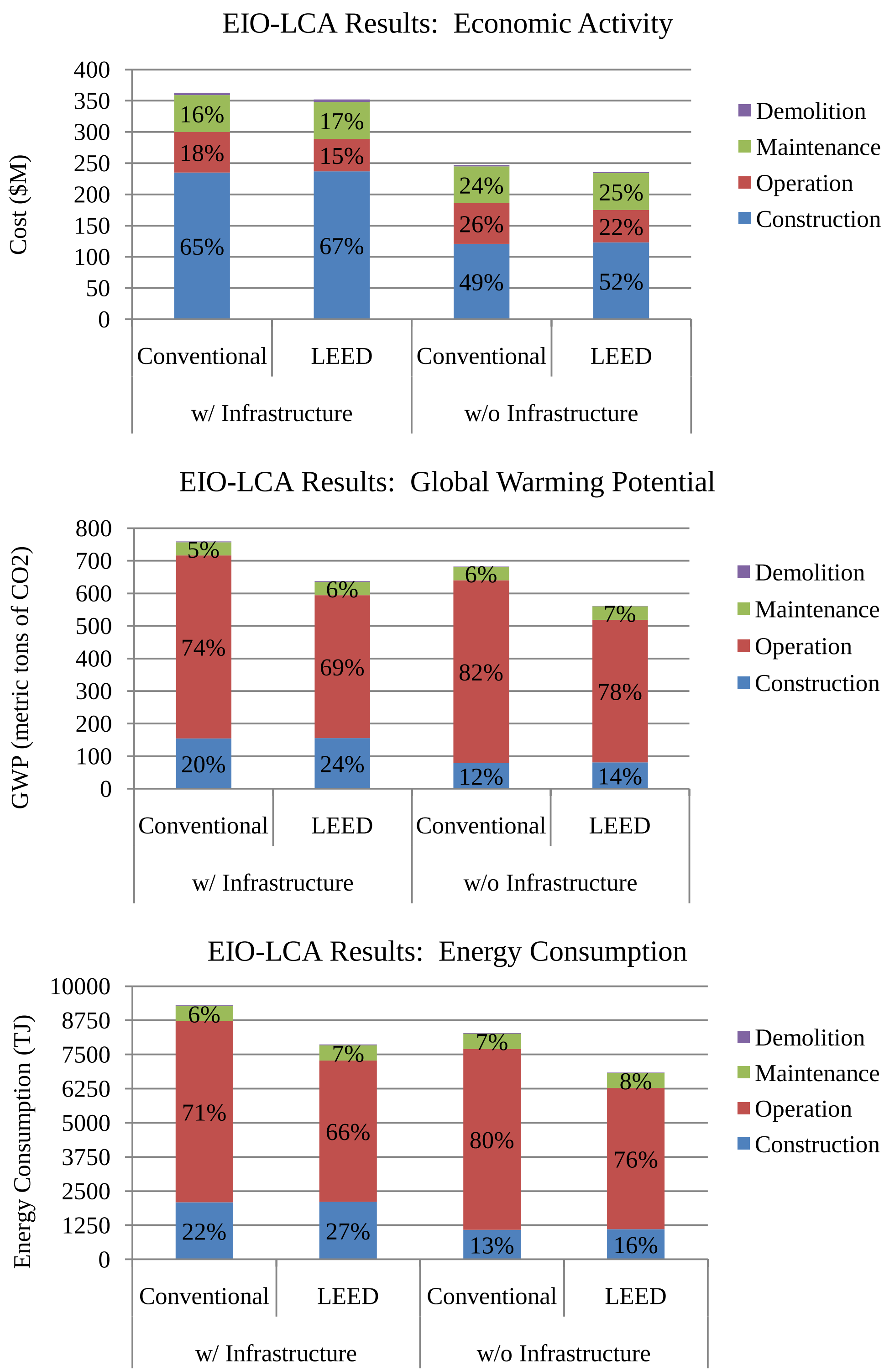

Figure 2. LCA results, with and without support infrastructure, comparison of total economic activity, environmental impact and energy consumption

3.2. Effectiveness of Energy Efficiency Measures

Construction budgets are limited and design teams often face decisions on which energy efficient measures to implement. By analyzing the effect of readily adopted energy efficient measures, design teams can prioritize the measures available to minimize the energy consumption. Figure 3 shows the individual effects of several major energy efficiency measures implemented during the construction phase and the effect of adjusting cooling and heating temperature set points. The measure with the greatest impact is cooling temperature set points. Changing cooling set points from 68°F (20°C) to 80°F (27°C) reduced the EUI by 10%. However, the occupants' cooperation to adjust cooling set points higher cannot be guaranteed. A measure implemented during the construction phase with the greatest impact is increasing cooling system efficiency. Changing an air conditioning unit with SEER 10 to an air conditioning unit with SEER 23 resulted in an 8% EUI reduction. The least effective measure implemented during the construction phase is increasing the thermal resistivity (R-value) of a roof. This measure, with an increase in R-value from 21 $h \cdot ft^2 \cdot {}^oF/Btu$ (3.7 $K \cdot m^2/W$) to 60 $h \cdot ft^2 \cdot {}^oF/Btu$ (11 $K \cdot m^2/W$) only reduced EUI by 2%. Affected by warm weather year-around, increased efficiency of a heating system and decreasing heating temperature set points from 80°F (27°C) to 68°F (20°C) do not have as great an energy consumption reduction as cooling system changes. However, these measures still result in 6% and 3% reduction of EUI, respectively.

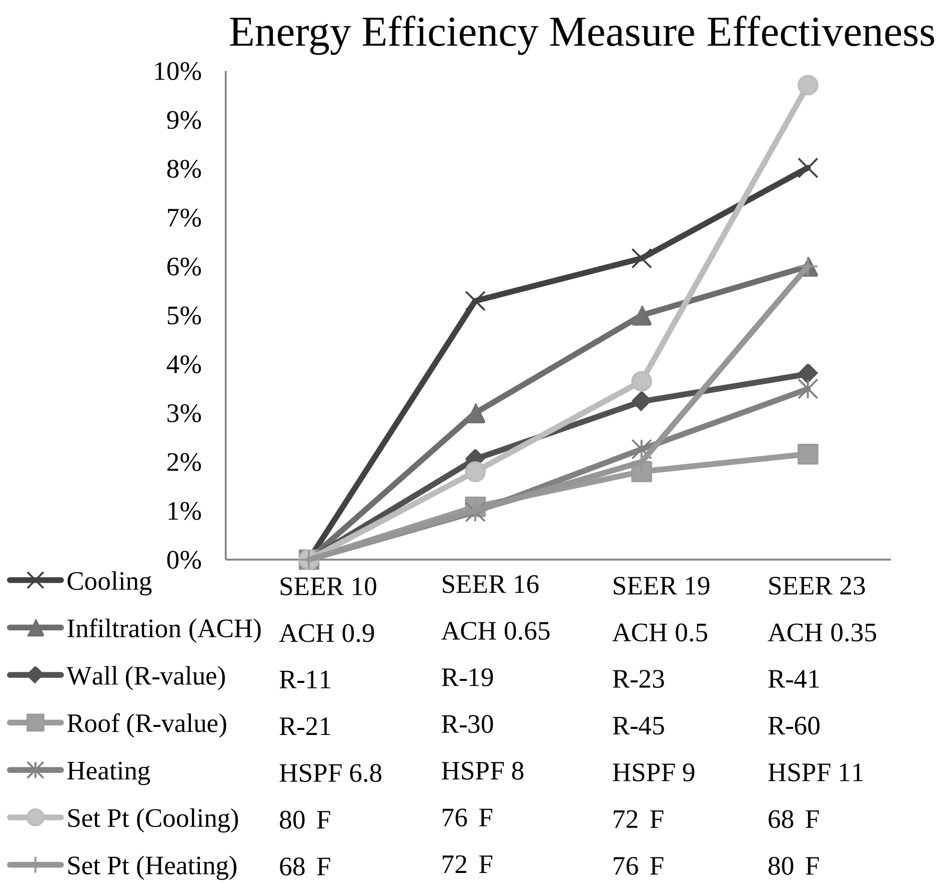

Figure 3. Effectiveness of energy efficiency measures implemented

3.3. Energy simulation using schematic design vs. detailed design

The assumptions made to differentiate the design stages were: (1) a floor layout is not clearly defined, and (2) building's exterior shape has not been clearly defined during the schematic design phase. Following these assumptions, ESim can simulate energy consumption in the early design stage, but eQUEST requires more information available in the later design stage where the floor layout is clearly identified and the building's exterior shape has been defined. Using ESim, the average EUI is 6.3 kWh/ft^2·yr (250 MJ/m^2·yr) with a standard deviation of 0.29 kWh/ft^2·yr (11 MJ/m^2·yr). Using eQUEST, the average EUI was 6.0 kWh/ft^2·yr (230 MJ/m^2·yr) with a standard deviation of 0.27 kWh/ft^2·yr (10 MJ/m^2·yr).

Before we compared the EUIs, the Shapiro-Wilk test was used to test the normality of the data. The Shapiro-Wilk test indicated that the EUIs calculated using schematic design and detailed design are not normally distributed, but instead, both EUIs were bimodally distributed. The Levene's test was also used to test the homogeneity of variances assumption. The Levene's test also indicated that the EUIs do not have equal variance. Since the EUIs calculated are not normally distributed nor have the homogeneity of variances, we employed the Wilcoxon signed rank test to compare the median EUIs instead of the mean EUIs. The Wilcoxon signed rank test reports that the p-value is less than 0.0001, which indicates that the median EUI from the schematic design is statistically different from the median EUI calculated using detailed design. Despite relatively similar values of EUIs, the bimodally distributed EUIs have very different median EUIs. The main reason for the bimodal distribution in EUIs is the design. While examining the data collected, we have noticed that there were two different types of design. The first type had houses designed in generally square shapes. However, the second design type was more of rectangular shape with very long side exterior walls and very narrow front and back exterior walls. This difference in the house shape resulted in the bimodal distribution of EUIs where the square shape houses generally had lower EUIs.

LEED recommends design teams simulate energy consumption in the early design phase, but the timing of conducting energy simulations must be adjusted based on the objectives of simulating energy consumption. The statistical difference suggests that the design team hold off on conducting energy simulation until the design is at the final stage if the intent is to quantify energy savings and develop a building's energy performance baseline. However, the design teams should simulate energy consumption in the early design phase as LEED recommends if the intent is to modify designs based on energy simulation results. This is consistent with work by Feng et al. (2008) demonstrating how rework timing affects the entire project by delaying the final plan and work in order to resolve unknowns; therefore, the overall time required for negative rework decreases.

3.4. Limitations and future research topics

Historical energy consumption data can help calibrate the energy simulation to create a more realistic energy consumption profile. A lack of historical energy data of Keesler homes limited the strength of the energy simulation used in this study. We were able to compare the EUI with published data, but it is highly recommended that energy consumption data of Keesler homes be collected to further strengthen the energy simulation. Also, the weather data used in this study was limited to Biloxi, MS. By limiting the location of this study, the LCA and sensitivity analysis results can only represent Biloxi, MS. Selecting different cities around the U.S. to study the effect of different weather patterns on the LCA and sensitivity analysis will be appropriate. Lastly, many different approaches exist for LEED certification. It is appropriate to analyze different LEED certification approaches and their effect on the total life cycle cost, environment, and total energy consumption.

4. Conclusions

The decision to build LEED and/or ENERGY STAR homes at Keesler AFB resulted in a 16% environmental impact reduction, 15% energy consumption reduction and 2% total life cycle cost reduction. The 16% environmental impact reduction and 15% energy consumption reduction fall short of results in previous studies; however, this study reinforces a claim that LEED certified homes do save energy and reduces the environmental impact while reducing the total life cycle cost.

The most effective energy efficient measure implemented was increasing air conditioning SEER while the least effective measure was increasing roof insulation R-value. Prioritizing the impact of energy efficiency measures provides guidance to the maintenance team at Keesler AFB to offer additional attention to more effective measures. Also, the prioritized list allows design teams to maximize energy efficiency efforts by adopting measures with greater impact first. However, the most effective measure of all is to educate occupants to adjust cooling set points to a higher temperature.

Lastly, energy simulation results from the schematic design phase were statistically different when compared to energy simulation results from the detailed design phase. The recommendation to a design team is to hold off on performing energy simulation until the design is at final stage.

References

The references of this article are combined with the thesis following the appendixes.

III. Conclusion

This chapter readdresses the research findings in relation to the research objectives outlined in Chapter 1. Future research topics are then discussed. Finally, a summary of the thesis is presented to wrap up the thesis.

Reviews of Findings

Three research objectives outlined in Chapter 1 were; (1) quantify environmental impact and energy consumption differences between energy efficient and conventionally built homes; (2) individually analyze implemented energy efficiency measures; and (3) compare energy simulation results from schematic design and detailed design. The discussion below provides a summary of the findings.

Energy efficient homes built at Biloxi, MS, have a 16% less environmental impact, consume 15% less energy, and save 2% in total life cycle cost while incurring a 1% cost increase in project construction compared to conventional homes. From a hybrid LCA, energy efficient homes' use phase (32% of economic activity) is the largest consumer of energy (73%) and the largest GWP (75%) and any economically feasible steps taken to reduce energy consumption and GWP during the use phase can have great impacts.

The most effective energy efficient measure implemented was increasing air conditioning SEER, followed by reducing the infiltration. The least effective measure was increasing roof insulation R-value. However, the most effective measure of all is to educate occupants to adjust cooling set points to a higher temperature.

Lastly, LEED recommends design teams simulate energy consumption in the early design phase. Using eQUEST and ESim, energy simulations at different phases of design, were statistically analyzed. The average EUI calculated using information available using schematic designs is 6.3 $kWh/ft^2 \cdot yr$ (250 $MJ/m^2 \cdot yr$) with a standard deviation of 0.29 $kWh/ft^2 \cdot yr$ (11 $MJ/m^2 \cdot yr$). The average EUI calculated using information available using detailed designs is 6.0 $kWh/ft^2 \cdot yr$ (230 $MJ/m^2 \cdot yr$) with a standard deviation of 0.27 $kWh/ft^2 \cdot yr$ (10 $MJ/m^2 \cdot yr$). Despite relatively similar values of the EUIs, that the median EUI from schematic design is statistically different from the median EUI calculated using detailed design.

Significance

The delivery of energy efficient buildings is one way for the USAF to achieve it's sustainable design and development goal, especially to reduce environmental impact and energy consumption. Energy simulation and LCA can be overlooked to speed up the process during the design phase; however, LCA and energy simulation can provide quantitative understanding of the economical and environmental impact of a facility. Additionally, LCA and energy simulation can help measure the effectiveness of an energy efficient facility compared to a conventional facility. The results of energy simulation can also help the facility maintenance crews optimize the building performance.

We have conducted a sensitivity analysis on various components of houses built in Biloxi, MS. The analysis helps discern the effect of an individual system to a facility in this region. The analysis can help focus limited resources during the construction and use phase to maximize both energy and environmental reduction. Lastly, the statistical comparison of EUIs calculated using schematic designs and detailed designs can help determine the better timing of energy simulations, thereby leading to a more accurate assessment of an energy efficient building.

Future Research

This research was limited on several aspects. These limitations offer opportunities for future research. A lack of historical energy data for Keesler homes limited the strength of the energy simulation used in this study. Collecting energy consumption data to further calibrate the energy simulations can provide in-depth understanding of the effects of energy efficient homes. Also, the weather data used in this study was limited to Biloxi, MS. Selecting different cities around the U.S. to study the effect of different weather patterns on the LCA and sensitivity analysis will be appropriate. Lastly, many different approaches exist for LEED certification. It is appropriate to analyze different LEED certification approaches and their effect on the total life cycle cost, environment, and total energy consumption.

Summary

This research analyzed LEED for Homes Silver certified homes using energy simulation and a hybrid LCA and compared the results to conventionally built homes. The purpose of this research was to understand the impact of energy efficient homes on the environment, the effectiveness of energy efficiency measures, and differences in energy simulation results in relation to different design phases.

The decision to build LEED and/or ENERGY STAR homes at Keesler AFB resulted in 16% environmental impact reduction, 15% energy consumption reduction, and 2% total life cycle cost reduction. The most effective energy efficient measure implemented during the construction phase was increasing air conditioning SEER while the least effective measure was increasing roof insulation R-value. Lastly, energy simulation results from the schematic design phase were statistically different when compared to energy simulation results from the detailed design phase.

Appendix A: Detailed Mathematical Calculations for EIO-LCA Methodology

The entire appendix is copied from http://www.eiolca.net/Method/eiolca%20math.pdf

("Economic Input-Outpt Life Cycle Assessment," 2009)

Combining life cycle assessment and economic input-output is based on the work of Wassily Leontief in the 1930s. Leontief developed the idea of input-output models of the U.S. economy and theorized about expanding them with non-economic data. But the computational power at the time limited uses of the Economic Input-Output method that required matrix algebra.

From the Input-Output accounts a matrix or table **A** is created that represents the direct requirements of the intersectoral relationships. The rows of **A** indicate the amount of output from industry *i* required to produce one dollar of output from industry *j*. These are considered the direct requirements – the output from first tier of suppliers directly to the industry of interest.

Next, consider a vector of final demand, **y**, of goods in the economy. The sector in consideration must produce **I**×**y** units of output to meet this demand. At the same time **A**×**y** units of output are produced in all other sectors. So, the result is more than demand for the initial sector, but also demand for its direct supplier sectors. The resulting total output, **xdirect**, of the entire economy can be written

xdirect = (I + A)y

This relationship takes into account only one level of suppliers, however. The demand of output from the first-tier of suppliers creates a demand for output from *their* direct suppliers (i.e., the second-tier suppliers of the sector in consideration). For example, the demand for computers from the computer manufacturing sector results in a demand for semiconductors from the semiconductor manufacturing sector (first-tier). That in turn results in a demand from the electricity generation sector (second-tier) to operate the semiconductor manufacturing facilities. This demand continues throughout the economy. The output demanded from these second-tier sectors and beyond is considered indirect output.

The second-tier supplier requirements are calculated by further multiplication of the direct requirements matrix by the final demand, or **A**×**A**×**y**. In many cases, third and fourth or more tiers of suppliers exist, resulting in a summation of many of these factors so that the total output can be calculated as:

X = (I + A + AA + AAA + …)y

where **X** (with no subscript) is a vector including all supplier outputs, direct and indirect.

The expression **(I + A + AA + AAA + …)** can be shown to be equivalent to **(I-A)-1**, which is called the total requirements matrix or the Leontief inverse. The relationship between final demand and total output can be expressed compactly as:

X = (I-A)-1y or Δ X = (I-A)-1Δy

where the latter expression indicates that the EIO framework can be used to determine relative changes in total output based on an incremental change in final demand. Typically, the values in the matrices and vectors are expressed in dollar figures (i.e., in the direct requirements matrix, **A**, the dollar value of output from industry *i* used to produce one dollar of output from industry *j*). This puts all items in the economy, petroleum or coal or electricity, into comparable units.

The economic input-output analysis can then be augmented with additional, noneconomic data. One can determine the total external outputs associated with each dollar of economic output by adding external information to the EIO framework. First, the total external output per dollar of output is calculated from:

Ri = total external output / Xi

where Ri is used to denote the impact in sector *i*, and Xi is the total dollar output for sector *i*.

To determine the total (direct plus indirect) impact throughout the economy, the direct impact value is used with the EIO model. A vector of the total external outputs, Bi, can be obtained by multiplying the total economic output at each stage by the impact:

Δbi = RiΔX = Ri(I-A)-1Δy

where **Ri** is a matrix with the elements of the vector Ri along the diagonal and zeros elsewhere, and **X** is the vector of relative change in total output based on an incremental change in final demand. A variety of impacts can be included in the calculation – resource inputs such as

Assumptions

The EIO-LCA method is a linear model. Thus, the results of a $1,000 change in demand or level of economic activity will be 10 times the results of a $100 change in demand.

The results represent impacts through the production of output by the sector with increased demand. For the most part then, the use phase and end-of-life phases are not directly included in the results. However, additional analyses using the EIO-LCA method can model these life cycle stages.

For example, modeling a $1 million increase of demand from the industry sector that produces automobiles represents the impacts from materials extraction, materials manufacturing, parts manufacturing, assembly, transport of good between these stages, as well as product design and testing of vehicle models - all activities prior to the final vehicle from the assembly line getting driven out the manufacturing facility gates. That analyses of $1 million in the automobile manufacturing sector does not include impacts from the fuel used to drive the car during its useful life or the impacts of salvaging parts or landfilling materials from an end-of-life vehicle. One could estimate the upstream impacts from the fuel consumption with the EIO-LCA method by doing an analysis for an increase in demand from the petroleum manufacturing sector. Emissions from the use phase would need to be estimated using other methods.

Many assumptions go into creating the impact vectors (the values for the environmental effects and materials consumption). Most data that we use are categorized by industry sectors using the North American Industry Classification System (NAICS) or other generic categories (e.g., the USDA categorizes farms by crop type). These data do not directly map onto the IO sectors in the economic models. We allocate values using weighted averages, or information from data sources or other publications. See the documentation associated with the model of interest for information on specific assumptions made in creating the impact vectors.

The IO models used for the various EIO-LCA models represent economies of a single nation. Imports and exports, though, are a major part of any economy's transactions. Imports are implicitly assumed to have the same production characteristics as comparable products made in the country of interest. Thus, if a truck is imported and used by a U.S. company, the environmental effect of the production of the truck is expected to be comparable to those made in the U.S. To the extent that overseas production is regarded as more or less of an environmental concern, then the results from the EIO-LCA model should be modified by adding additional transportation and logistics (e.g., for overseas delivery) as well as possibly adjustment for different production processes.

Uncertainty

We are uncertain as to all the uncertainty in the EIO-LCA models available on the site. Here are some of the most important:

- **Old Data:** The data associated with each model are representative of the year of the model. Thus, data for the 1997 U.S. Benchmark model are from 1997, including the economic input-output matrix and the associated environmental data. Care should be taken in using a model to replicate current conditions. The changes in these data over time vary widely. Economic input-output coefficients for stable industries (e.g., steel making, which has had similar processes for years) may be similar to past coefficients; however EIO coefficients for rapidly changing industries (e.g., computer manufacturing, which has rapid development of products and processes) may be very different over time. Similarly, environmental data can change over time due to changes in process efficiency, regulations for pollutants, or production levels.

- **Uncertainty Inherent in Original Data:** All data incorporated into an EIO-LCA model is originally compiled from surveys and forms submitted by industries to governments for national statistical purposes. The uncertainty in sampling, response rate, missing/incomplete data, estimations to complete forms, etc. from the original data remain as underlying uncertainty in the EIO-LCA models. See the model documentation for references to the original data sources and refer to the documentation provided with the original data source for more information of uncertainty within a given data source.
- **Incomplete Original Data:** Related to the uncertainty in the original data sources, some data used in the EIO-LCA models are incomplete, in that they underestimate the true values. A good example of this is toxic release data. In the U.S., only facilities which emit above a certain threshold of toxics or which fall into certain industry classifications are required to report their toxic emissions. So, the actual value of toxic emissions reported is known to be lower than the actual level of emissions. See the model documentation for references to the original data sources and refer to the documentation provided with the original data source for more information of uncertainty within a given data source.
- **Aggregated Original Data:** As mentioned above, most data are categorized in a way that does not directly correspond to the economic input-output sectors used in the IO matrix. For example, electricity use for commercial buildings is aggregated by the type of building (e.g., office space, retail space, etc.), not by sector (e.g., engineering consulting offices, accounting, etc.). We make assumptions to allocate aggregated data to the most appropriate sector. See the model documentation for more information about how aggregated data is allocated.
- **Aggregation of Sectors:** The results of an EIO-LCA analysis represent the impacts from a change in demand for an industry sector. Depending on the model chosen, an industry sector represents an collection of several industry types, and this aggregation leads to uncertainty in how well a specific industry is modeled. For example, in the U.S. models, one sector represents Power Generation and Supply, which would include coal-fired plants with high levels of CO2 and particulate emissions as well as hydropower plants with virtually no CO2 or particulate emissions. The results for impacts from the Power Generation and Supply sector thus represent the "average" impacts for generating electricity. (Yet, we like to point out that the U.S. models designate one sector entirely for Tortilla Manufacturing, so the impacts for making tortillas are well-represented.) Non-U.S. models are more aggregated, with up to only 100 sectors representing all industries. See the model information for the number of sectors represented in the economy of a given model.

Other Issues and Considerations

As an LCA tool, the EIO-LCA models are incomplete as only a limited number of environmental effects are included. The EIO-LCA models use as the basis for data only those data which are publicly available (i.e., no proprietary data is included, all data sources are provided). While industry specific data is available for a number of environmental effects, we do not have data for impacts such as habitat destruction, non-hazardous solids wastes, or non-toxic pollutants to water. Some data used in earlier models (e.g., fertilizers) are no longer collected at the national level due to efforts to minimize reporting burden of companies. Other sources and LCA methods will need to be consulted to account for a full range of environmental impacts.

The EIO-LCA method, models, and results represent the inventory stage of the LCA. The results estimate the environmental emissions or resource consumption associated with the life cycle of an industry sector, but do not estimate the actual environmental or human health impacts that these emissions or consumption patterns cause. For example, the U.S. models estimate the emissions of particulates to the air, but do not estimate the increased number of hospitalizations or deaths due to these emissions.

Each EIO-LCA model uses economic data as the user-defined parameter of analysis. Each model uses the currency of the country of origin (i.e., U.S. models should have $US as input, Germany model should have € as input, etc.). Similarly, the monetary values represent the value of the currency in the year of the model. So, the 1997 U.S. Benchmark model is based on 1997 U.S. dollar values. If current prices are used, they should first be converted to the model year with an appropriate economic index. The Statistical Abstract of the United States provides historical price indexes for the U.S. for the overall economy and for major commodity groups such as food, energy, and transportation.

> For example, if you found prices for hospitalization for 2006 but wanted to use the 2002 U.S. Benchmark model, you would need to convert the prices. The Statistical Abstract of the United States lists the consumer price index for medical care in 2006 as 336.2 and in 2002 as 285.6. Dividing the 2002 medical CPI by the 2006 medical CPI results in a ratio of 0.85. All 2006 prices should be multiplied by 0.85 for use in the model.

Another consideration is the correct use of producer versus purchaser prices. Most of the economic input-output models that form the basis for the EIO-LCA models represent the producer prices - the price a producer receives for goods and services (plus taxes, minus subsidies), or the cost of buying all the materials, running facilities, paying workers, etc. The purchaser price includes the producer price plus the transportation costs of shipping product to the point of sale, and the wholesale and retail trade margins (the profit these industries take for marketing and selling the product). For many goods, the producer prices can be far less than what a final consumer would pay (e.g., the producer price for leather goods in U.S. is approximately 35% of the final purchaser price). For many services, where no goods are transported and wholesale/retail trade is limited, the producer price and purchaser price are often the same (e.g., barber shops and childcare).

Limitations of the EIO-LCA Method and Models

The factors that make the EIO-LCA method an efficient and robust tool also limit its use for life cycle assessment.

First, the results of an EIO-LCA analysis represent the impacts from a change in demand for an industry sector. Depending on the model chosen, an industry sector represents a collection of several industry types, and this aggregation leads to uncertainty in how well a specific industry is modeled. For example, in the U.S. models, one sector represents Power Generation and Supply, which would include coal-fired plants with high levels of CO2 and particulate emissions as well as hydropower plants with virtually no CO2 or particulate emissions. The results for impacts from the Power Generation and Supply sector thus represent the "average" impacts for generating electricity. Similarly, a sector such as the Electronic Computer Manufacturing sector produces hand-held computers (PDAs), laptops, desktops, workstations, and mainframe computers. Since making these products requires similar processes, they are grouped together in a single sector. So, the method is limited in its ability to model the effects of "producing one laptop" but is good at modeling the effects of the Electronic Computer Manufacturing sector as a whole. (We like to point out that the U.S. models designate one sector entirely for Tortilla Manufacturing, so the impacts for making tortillas are well-represented.) Non-U.S. models are more aggregated, with up to only 100 sectors representing all industries. See the model information for the number of sectors represented in the economy of a given model.

Second, as an LCA tool, the EIO-LCA models are incomplete in as much as a limited number of environmental effects are included. The EIO-LCA models use as the basis for data only that which is publicly available. While industry specific data is publicly available for a number of environmental effects, we do not have data for impacts such as habitat destruction, non-hazardous solids wastes, or non-toxic pollutants to water. Some data used in earlier models (e.g., fertilizers) are no longer collected at the national level due to efforts to minimize reporting burden of companies. Other sources and LCA methods will need to be consulted to account for a full range of environmental impacts.

Third, the EIO-LCA method, models, and results represent the inventory stage of the LCA. The results estimate the environmental emissions or resource consumption associated with the life cycle of an industry sector, but do not estimate the actual environmental or human health impacts that these emissions or consumption patterns cause. For example, the U.S. models estimate the emissions of particulates to the air, but do not estimate the increased number of hospitalizations or deaths due to these emissions. Again, other sources and LCA methods will need to be consulted to account for translating the inventory results from an EIO-LCA analysis into impact on the environment.

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1. Type of Product:

CD-ROM

2. Operating System/Version:

Windows

3. New Product or Replacement:

NEW

4. Type of File:

Database

5. Language/Utility Program:

Adobe Acrobat Reader 9, Microsoft Office Excel 2007, and eQUEST 3-64

6. # of Files/# of Products:

N/A

7. Character Set:

8. Disk Capacity:

660MB

9. Compatibility:

PC

10. Disk Size:

4 3/4"

11. Title:

GEM/ENV/11/M09 Thesis Data and Data Analysis Results

12. Performing Organization:

AFIT
2950 Hobson Way

13. Performing Report #:

14. Contract #:

n/a

15. Program Element #:

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16. Sponsor/Monitor:

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27. Abstract: USAF constructed 1,028 LEED homes, at Biloxi, MS. These energy efficient homes have a 16% less environmental impact, consume 15% less energy, and save 2% in total life cycle cost while incurring a 1% cost increase in project construction compared to conventional homes. The most effective energy efficient measure implemented was increasing the air conditioning SEER while the least effective measure was increasing roof insulation R-value. Lastly, energy simulation results from the schematic design phase were statistically different compared to energy simulation results from the detailed design phase.						
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41. Playback Speed:	**42. Video:** N		**43. Text:** N	**44. Still Photos:** N		**45. Audio:** N
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14. ABSTRACT
The United States Air Force constructed 1,028 energy efficient homes at Biloxi, MS. To analyze and compare these energy efficient homes to conventionally built homes, this study employed a hybrid LCA and energy simulation. These energy efficient homes have a 16% less environmental impact, consume 15% less energy, and save 2% in total life cycle cost while incurring a 1% cost increase in project construction compared to conventional homes. The simple payback period of the project to payback this initial 1% construction cost increase is 10 years. The most effective energy efficient measure implemented was increasing the air conditioning seasonal energy efficiency rating (SEER) while the least effective measure was increasing roof insulation R-value. Lastly, energy simulation results from the schematic design phase were statistically different compared to energy simulation results from the detailed design phase. By comparing the results of energy simulations from both design phases, simulation results from the detailed design phase were more accurate. The recommendation for a design team is to hold off on performing energy simulation until determining which energy efficiency measures to implement as permitted by the project timeline, cost, and other factors influencing the project.

15. SUBJECT TERMS
LEED; Life cycle assessment; EIO-LCA; Hybrid LCA; Residential buildings; Energy simulation; eQUEST; ESim

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