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Sarah E. Schanck
Rowan University

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MODELING ATYPICAL BUILDING USE WITH COMMERCIALLY AVAILABLE BUILDING SIMULATION SOFTWARE

by

Sarah Schanck

A Thesis

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Thesis Chair: William Riddell, Ph.D.

Dedications

This thesis is dedicated to Richard Schanck and Dan Collins.

Dad, you have always been an inspiration. You constantly encourage me to try new things and to never settle for "good enough". You are the reason I wanted my Master's Degree.

Dan, you have been constant support through this journey. You are especially skilled at finding my motivation when I misplace it. You are one of the major reasons I completed my Master's Degree.

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I would not have been able to complete this work without assistance and encouragement from a number of people. While a comprehensive list is not possible, I would like to thank a few people here.

William Riddell for letting me know about this opportunity and guiding me through it. The engineering secretaries, specifically Regina Baumgartner, Barbara Wynn, and Michelle Schwaiger, for helping with paperwork and for having can-do attitudes most every day. Samantha Valentine for laying the groundwork for me to take over after her and handling occasional requests for odd pieces of information. The clinic students that worked on this project, for doing energy audits and asking 'dumb' questions that led to additional correction factors and better audit results. Sam DelPidio and Phillip Fiore, armorers for the National Guard, for allowing me frequent access to their armories.

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Abstract

Sarah Schanck
MODELING ATYPICAL BUILDING USE WITH COMMERCIALLY AVAILABLE BUILDING SIMULATION SOFTWARE
2015-2016
William Riddell, Ph.D.
Master of Science in Mechanical Engineering

National Guard armories are audited to provide recommendations for future energy reduction measures. The annual energy consumption of a New Jersey National Guard Armories cannot be modeled directly with commercially available building simulation software, due to discrepancies between the modeling capabilities of the software and the reality of the armory. A building simulation software, eQUEST, was chosen for use in this project. Discrepancies between eQUEST inputs and reality were identified and correction factors developed to minimize the effect of each discrepancy on predicted energy consumption, with the end goal of accuracy between predicted and actual energy consumption. In addition, an alternative heating scenario was simulated using a corrected eQUEST model in combination with a heat transfer model to examine the effects on energy consumption, CO_2 emissions, and cost. It was determined that space heater use in occupied rooms in combination with reduced use of the central heating system results in reduced energy consumption, CO_2 emissions, and cost when not more than 30% of the building is occupied.

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Chapter 1

Introduction

Energy audits are an inspection of energy consumption habits within a building. An audit team examines utility bills, lights, plug loads, the HVAC system, and the building envelope to gather data. These data are used to create one or more models of energy consumption in the building. After these models are verified against actual building consumption, potential methods to reduce energy consumption are modeled to quantify savings from the implementation of each method. Once savings for an Energy Conservation Measure (ECM) are quantified, a financial analysis is performed to determine whether that measure is worth implementing. The worthwhile ECMs are recommended to building owners, along with details about the financial and material investment each measure requires.

The National Guard

New Jersey Department of Military and Veteran Affairs (NJ DMAVA) is a federal entity that owns and maintains buildings for the New Jersey National Guard, primarily armories. It runs or helps the state run forty-eight National Guard buildings totaling 2.5 million square feet. The total annual energy consumption for these buildings is equivalent to 160,500 MMBTU at a cost close to $3.2 million. The Energy Independence and Security Act of 2007 (EISA) requires that all federal agencies reduce their energy intensity 30% by 2015 from a fiscal year 2003 baseline [1]. Additionally, EISA requires that 25% of all square footage owned by a federal agency must be audited each year. To fulfill the first requirement, NJ DMAVA needs recommendations for measures that will reduce energy consumption, preferably reducing annual costs concurrently. These recommendations are developed through detailed energy audits performed on each building, which count towards the second EISA requirement.

Of the forty-eight New Jersey National Guard buildings DMAVA supports, twenty-six are armories with a total area of 1.4 million square feet. Annual armory energy consumption is approximately 85,480 MMBTU, at a cost of about $1.4 million. Individual area for each armory ranges from 11,000 to 184,000 square feet. Average armory size is 57,700 square feet. These armories share many characteristics, some of which set armories as unique from any other type of building. Armories are mixed-use buildings, a combination of office space, vehicle garage, and storage. They are typically constructed from brick and cinderblock, one story tall, with a handful of daily occupants. In addition, there are drill events, training for the National Guard unit or units stationed at that armory. These occur one weekend each month and can involve more than one hundred extra people in the armory.

Energy Audits for New Jersey National Guard Armories

DMAVA has an agreement with the Civil Engineering Department at Rowan University for undergraduate engineering students to perform energy audits on National Guard buildings. Energy audits of non-armory buildings are not discussed in this work. A multi-disciplinary team of undergraduate engineering students, led by a graduate engineering student, constitute the audit team. Undergraduate team members are typically on the project for a single semester.

There are several factors that complicate the completion of energy audits on National Guard Armories. A minor, but relevant, issue is turnover of undergraduate students each semester. Students new to the project must be taught how to perform an audit before they can do so. In addition, their inexperience sometimes leads to setbacks, though these are minimized by oversight from both a graduate student and several engineering professors with ample energy audit experience. However, more significant is the creation of an accurate model of energy consumption. Reasons for error include insufficient data collected during the audit team's walkthrough of the armory, occupancy that does not occur weekly, a high percentage of part-time occupants with individual offices, lack of long-term consumption information, and occasional deployment of occupants.

Building simulation software typically assumes uniform weekly use of the building for the simulated year. Each National Guard Armory hosts a monthly drill weekend and a yearly drill week for the unit or units stationed at that armory. This is regular non-weekly use of the building that cannot be directly modeled in commercially available building simulation software. Most armories have non-constant occupancy, with a relatively high percentage of part-time occupants for an office building. Some officers split their workweek between two armories, so they must be considered part time occupants when either of these armories is being audited. Recruiters are rarely in their office every weekday, so they should also be counted as part time occupants. Another difficulty is lack of long-term information. Occupants can switch or leave armories suddenly, leaving a lack of knowledge about recent history of occupancy in the building. In addition, occupants rarely pay much attention to their energy consumption habits. This is detrimental during utility bill analysis, when the audit team interviews occupants about their energy consumption habits in an attempt to understand the cause of any abnormal consumption in the few years prior to the audit. Lack of information about consumption during this time increases the difficulty of modeling consumption for this time period when utility bills are available.

Occasionally, the unit stationed at an armory is deployed. Several officers from another armory work out of the otherwise empty armory a few days per week, for an occupancy less than 20% of normal. This can be modeled after careful analysis, but the situation brings up the possibility of a specific energy reduction strategy that would not work for a fully occupied armory. The Army Facilities Management Report proposes an alternate heating and cooling option for under-utilized buildings. Section III, Chapter 22-12 b (2) of the Army Facilities Management Report, revised March 28, 2009, discusses the use of supplemental heating and cooling systems [2]. These supplemental systems are allowed when cost effective energy reductions can be achieved through their use in combination with reduced use of the primary conditioning systems. Unit air conditioners are already standard in most armories instead of central air in the summer. Thus, the energy and cost savings resulting from using space heaters in the winter should be examined for low occupancy buildings.

These complications present issues that must be resolved for an accurate energy audit to occur. It is proposed that the discrepancies between the model of energy consumption and actual energy consumption in an armory can be resolved through the application of correction factors to select inputs in each model. In addition, it is proposed that an alternate heating plan of reduced central heating in combination with space heater use can be modeled and evaluated for implementation in low occupancy armories.

Scope of This Work

The end goal of performing energy audits on New Jersey National Guard Armories is to provide supported recommendations for energy and cost savings to the National Guard for their buildings. To do so, detailed models of energy consumption in a building are created and used as the numerical basis for evaluating each potential recommendation. From these models, the impact of each Energy Conservation Measure (ECM) can be evaluated.

However, many buildings cannot be modeled directly, due to limitations on what can be modeled in a building simulation program or in a spreadsheet model. The simplifying assumptions that allow non-expert users to use building simulation software such as eQUEST also limit the breadth and detail of a modeled building. Elimination of some assumptions is possible but undesirable, as these simplifying assumptions are essential for new users to understand and use the program. To work around the limitations inherent in the program, it was proposed that a specific input in the program could be altered to account for a specific discrepancy. Upon testing, it was found that this produced acceptable results, i.e. increased the accuracy of predicted energy consumption compared to reported consumption from the utility bills. Thus, the same process of input alteration to account for a specific discrepancy between the model and the bills was repeated for numerous discrepancies, described above and otherwise. These input alterations are labeled as corrections factors, as they are correcting the model to better reflect reality.

Correction factors are applied in an iterative process, with the accuracy of the model calculated after each iteration. Once the model is deemed sufficiently accurate, it becomes a baseline that can be used to predict energy savings resulting from a proposed change to the building. Most of the proposed Energy Conservation Measures (ECM's) can be calculated directly from the models, by altering the relevant input to reflect the proposed change. These proposed changes include measures such as altering light bulb wattage to model bulb replacement and altering temperature setpoints to model the installation and use of programmable thermostats.

However, one ECM requires additional modeling. For low-occupancy buildings where occupants are clustered in a single part of the building, it is proposed that the use of space heaters in that part of the building can be more cost effective and energy efficient than heating the whole building. Energy savings from reducing the overall building temperature can be modeled directly in eQUEST. Calculating the energy requirements for space heaters to heat the occupied part of the building requires a separate heat transfer model, based on building characteristics and regional seasonal temperature data.

Once all potential recommendations have been evaluated, the audit team assembles the best set of Energy Conservation Measures to recommend to NJ DMAVA. The relevant supporting evidence, including data records, calculations, and a financial analysis, are compiled into a cohesive document. This report is submitted to the Energy Manager of NJ DMAVA and used to validate the expenditure of money to implement the recommended ECMs.

Chapter 2

Literature Review

In 2013, the United States consumed 97,533.5 trillion BTUs of energy [3]. From an end-use perspective, commercial buildings account for 18% of electricity consumed in the United States, and residential and commercial buildings together account for 40%, as shown in Figure 1 below [3]. Reducing total electricity production by 1% will prevent 20.39 million metric tons of CO_2 from being emitted each year, the equivalent of 4.292 million passenger vehicles not driving at all each year [4], [5]. This study focuses on energy consumption in buildings to identify opportunities for savings.

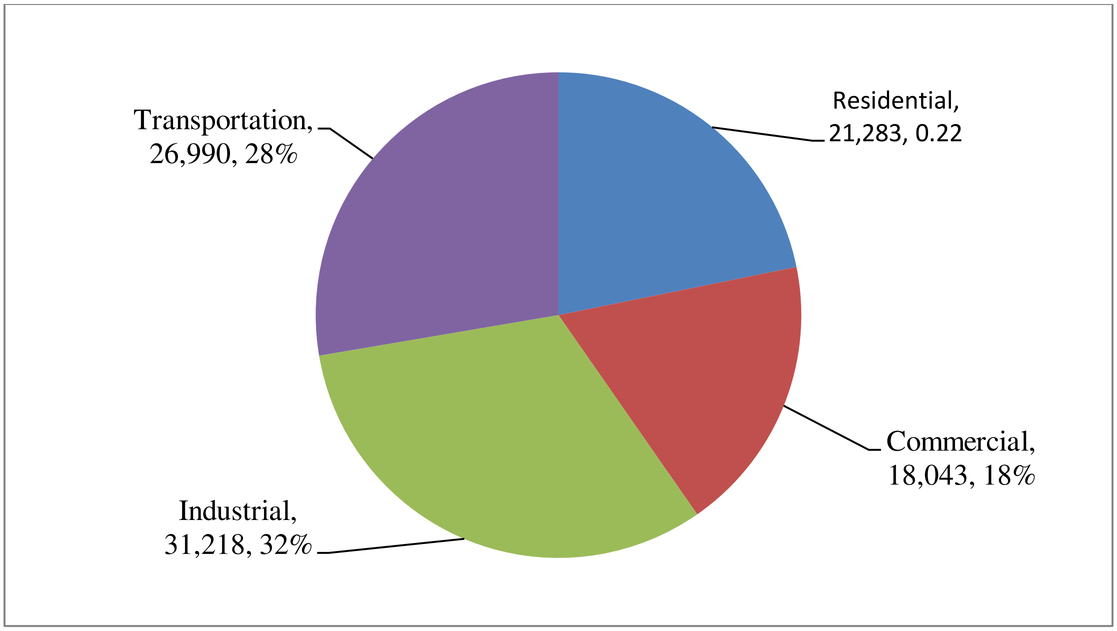


Figure 1. Total end use consumption in the United States in 2013, in trillion BTUs.

There are several points in a building's lifespan when energy use can be evaluated, primarily during design and during occupation. Before a building is constructed, almost anything can be altered or replaced, so there is a high degree of flexibility in the design. Pacheco, et al [6] concluded that a building's orientation, shape, and compactness (ratio of surface area to volume) have the greatest impact on total energy consumption of a building. However, the practicality of a study performed during the design phase is limited, because the energy use model cannot be validated until the building is constructed and in use throughout an entire year. Several studies showed that actual consumption tends to be twice the predicted value [7], [8], [9]. This is the result of a disconnect between predictive models and energy consumption habits of occupants. This limitation can be minimized by examining energy consumption habits in buildings similar to the one being modeled and through discussions with future occupants about their expected consumption patterns [10]. This process allows the modeler to more closely match modeled occupant-controlled consumption to expected actions of the occupants. During the occupation of a building, alterations tend to be more difficult and expensive, though the actual energy consumption can be measured, increasing the accuracy of the model built at this point.

Modeling the building during both design and occupation is the best compromise. The divide between ease of altering the design and ease of gathering accurate data makes it more effective to study different aspects of the building at different times. Li, et al. [11] divided their analysis into building envelope, internal electrical loads, and building service systems. This literature review follows their division; each section will be addressed one at a time, including features of the section, related studies, and an effective time to study it.

The building envelope includes walls, windows, doors, and any surfaces separating conditioned indoor air from the external environment. While not directly responsible for electrical consumption, it has a strong impact on heating and cooling demands [12]. Sozer [12] compared three building designs for a hotel in Turkey using eQUEST. The first model was of a Turkish hotel built in 1992, when there were no regulations about energy performance in buildings. The second model altered the building envelope to meet the ASHRAE 2004 standard. The third model altered the building envelope from the second model to incorporate additional passive design strategies, such as balconies for shading, double paned windows, and reduced window area. The ASHRAE model resulted annual energy consumption 34% lower than current building and the passive design model resulted in annual energy consumption 40% lower than the current building. This section of the building is better studied in the design phase, as retrofits and modifications to the building structure can be expensive and will interfere with use of the building. Dall'o and Sarto [13] studied school complexes in Italy and found that it is less expensive and more convenient to build a new building than to enhance buildings older than forty years to a high level of energy efficiency. Kossecka and Kosny [14] studied the configuration of wall materials within the building envelope, and found that the order and thickness of each material has an impact on the overall effectiveness of the wall. Mahdy and Nikolopoulou [15] compared varying window specifications across the lifetime of identical buildings in three climate zones and found that reflective single paned glass is the most cost-effective type of window for all the climate zones studied. The desired window-to-wall ratio varies with the climate, as does the desired overhang (to limit direct sunlight on window glass). As concluded in the studies above, the orientation, shape, compactness, window-to-wall ratio, wall material, order and configuration of wall materials, overhang above windows, and window specifications should be all examined when designing the envelope of a building.

Internal electrical loads include anything that consumes electricity and is plugged into an outlet. These include, but are not limited to, office equipment, printers, computers, kitchen appliances, dryers, and unit room heating/cooling equipment such as fans, space heaters, and window air conditioning units. Lighting is sometimes included in this category, but according to Li, et al. [11], it should be included in building services. Energy consumption resulting from internal electrical loads is highly dependent on occupant behaviors. Hoes, et al. [10] concluded that user behavior has a larger impact than thermal processes like heating and cooling on consumption within a building. Bonte, et al. [7] compared predicted consumption to actual energy consumption for given buildings, and found that most conventional modeling predictions underestimate the actual consumption by a factor of two because they do not properly account for occupant-driven consumption. Because of this, electrical loads are best examined after the building is in use, when consumption can be measured and the model adjusted accordingly. From this model, suggestions can be made to reduce electrical consumption. Because of the wide scope of this area, few studies are comprehensive; instead focusing on a single aspect of it. Menezes [16] studied appliance loads and created new benchmark values of energy consumption for those appliances. This is significant because new appliances consume different amounts of electricity than older appliances, and electrical loads are becoming a larger percentage of building-wide energy consumption as energy consumption from HVAC systems and lighting is reduced.

Building service systems include building-wide services such as heating, ventilation, and cooling (HVAC) systems, vertical transportation (elevators and escalators), and lighting. HVAC systems have been subject to many studies and modeling efforts because they have a large impact on energy consumption and can be complex to model accurately. Lighting and HVAC systems should be examined both during the design phase and the occupancy phase. Before it is installed, the HVAC system must be sized to match the building [17], but exact energy consumption is driven by the demand for heating and cooling from the occupants. Building services like the HVAC system are not identical from building to building. The rated size of the system is related to the size and use of the building [18], thus the system should be matched to the expected needs of the building.

Once a building has been evaluated and modeled, decisions about the desired level of energy efficiency or an energy reduction goal should be set before deciding on specific Energy Conservation Measures (ECMs) to implement. These goals can range from keeping with standard practice, applying energy efficient measures, obtaining certification, to achieving zero energy status. These are listed in order of general energy savings, though this is not a strict progression. A building can be more energy efficient than a certified building and not be certified because certification was not applied for. Menassa [19] examined eleven LEED certified Navy buildings and found that the majority of them consumed more electricity than the national average for similar buildings. This could be due to some of the buildings qualifying for certification without actually making changes to the energy consumption of the building. In addition, there is a lack of agreement regarding the definition of 'zero energy building' [20]. Marszal, et al.

compared twelve definitions of ‘zero energy building’ and concluded that common practice is to look at a building's annual net energy use, calculated as consumption minus onsite generation [20]. This ignores any energy expended in construction or destruction of the building.

One of the reasons there are so many definitions of 'zero energy building' is because different regions of the world have individual energy efficient standards for their buildings. A universal standard is impractical, as different climate zones require different regulations to achieve the same intensity of energy use. Some governments have passed laws to limit future energy consumption of buildings, such as the Energy Independence and Security Act (EISA), passed in 2007 in the United States and the Energy Performance of Buildings Directive (EPBD), passed in 2010 in the European Union [20], [21].The EPBD states that by 2020, all new public buildings must be nearly zero energy [21]. To meet this goal, some member states of the European Union created building standards, which include regulations on energy use, such as MoPEC in Switzerland [21], [22]. However, there is an optional higher level of energy regulation, known as MINERGIE in Switzerland [23]. These are similar to programs in the United States. The building standards in the United States from the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) are commonly known as the ANSI/ASHRAE standard. There are different ASHRAE standards, as the parameters are updated every 3 years [24]. The most current version is ANSI/ASHRAE 90.1, released in 2007 [24]. The optional higher efficiency program is known as LEED (Leadership in Energy and Environmental Design) certification, created by the US Green Building Council [24]. In Brazil, the building standards and the energy efficient program are both contained in the same set of standards, Regulation for Energy Efficiency Labeling of Buildings (REELB) [24]. REELB contains 5 levels, ranging from least efficient energy use (E) to nearly zero energy use in a building (A). Melo compared Brazil's REELB to the United States' ASHRAE and LEED standards and found that, taking climate into consideration, levels C through A of REELB are equivalent to the ANSI/ASHRAE 90.1 standard in the United States, while level A of REELB is equivalent to LEED certification.

Once the desired level of efficiency has been established, energy saving measures can be suggested and examined. Several article reviews have looked at which parameters have the most impact on energy consumption, including Pacheco [6] and Zhu and Zhao [25]. Pacheco reviews six categories of building features that are decided in the design stage of a building. Zhu and Zhao review the current green technology, including the what, why, and how of green buildings. Others have taken this idea of including green technology in buildings a step further to include the installation of renewable energy to bring a building closer to zero net energy consumption, including Li, et al. [26] and Visa [27]. Li, et al. reviewed zero energy buildings and discussed the implications for sustainable development. Visa discussed an algorithm for installing additional renewable energy generation to the Solar House in Romania, and expanded his algorithm to include installing renewable energy to buildings which do not have any installed yet. Ramesh [28] examined the reduction of energy consumption from a lifecycle view, where the energy required to construct and demolish the building is included in the overall energy balance. Ramesh reviewed seventy-three case studies of office and residential buildings in thirteen countries and concluded that, in terms of lifecycle energy use, low energy buildings are better than zero energy buildings because the initial energy cost to achieve zero net energy consumption during operation is greater than the energy saved over the lifetime of the building.

One thing common to all of these articles is the effect of occupant actions on a building's energy consumption. The articles focus on improving the building to negate the effect of occupant actions or note that the behavior of the occupants has a significant impact on energy consumption. Several articles highlight the difference between the predicted and actual energy consumption. Brown and Frame [8] studied a school where actual consumption was 2.5 times greater than consumption predicted during the design phase and found that the occupants were not taking any measures to reduce energy consumption. Specifically, occupants left computers and printers on overnight, and these devices consumed more energy than predicted. The authors suggested that an education program for students and staff should be developed, which would benefit both the school and the community as students applied their new knowledge about energy saving strategies to other buildings they occupied. Marchiori, et al. [29] studied the change in energy consumption resulting from different behavior modifications. They asked ten families, motivated to reduce their energy consumption, to do a specific behavior modification each week. When they compared weekly energy consumption, the authors found that the behaviors resulting in greater energy savings mostly agreed with the prior expectations stated and calculated in the article, but also concluded that savings were not as large as expected because people are unreliable. The families in the study were surveyed about how well they implemented each requested behavior and they self-reported that they had difficulty with the changes that required daily effort. Menezes, et al. [9] developed a more accurate modeling procedure to help account for the discrepancy between actual and modeled consumption. They tuned a standard model using data from a basic monitoring system in an office building. The resulting model was accurate to 3% when matched to the area under observation and accurate to 6% when the model was validated against a different part of the same building. Santin [30] proposed that people do not work as hard to conserve energy when they are confident that their building is energy efficient, creating a rebound effect in energy use. He studied the heating habits of the entire Dutch population through a national survey taken in 2005 by the Dutch Ministry of Heating. He found that houses with better envelopes or better heating systems, tended to have higher winter thermostat settings. This did not always result in higher energy consumption than the less efficient houses, though this supports his conclusion of a rebound effect, which could explain some of the difference between actual and predicted consumption. Steinberg [31] states that training is necessary for occupants of green buildings, as the occupants have control over how often they use available green technology. Steinberg helped develop energy awareness training for hospital staff in Pittsburg, Pennsylvania, who were about to expand into a new LEED certified hospital facility. He was asked to develop training to educate the staff on behaviors that would help ensure the success of the new building, as the upper management knew that the staff had to participate for the green policies to succeed. Steinberg accomplished this by translating the LEED checklist into actions the staff could do, and then narrowed the list of actions to include in training by interviewing key members of the staff about what actions were already in common practice, and including only actions that were new and would result in noticeable energy savings.

From these studies, it becomes apparent that occupant actions have a significant impact on energy consumption of a building, especially when the building is designed for low energy consumption. As a result, it is not enough to simply change the technology in the building, to redesign the building envelope, or replace inefficient equipment. As Steinberg [31] stated, the occupants of the building must also change their behaviors and how they are using their building. Bonte, et al. [32] compared the impact of six actions that building occupants could do to potentially reduce total energy consumption. He simulated energy consumption in eight buildings, varying each of the following six actions in each of the buildings: the use of blinds, lights, fans, opening or closing windows, adjusting the thermostat, and clothing adjustments. Bonte found that opening and closing blinds, turning lights on and off, and the thermostat setting had the most significant impact on energy consumption. Lee and Malkawi [33] combined an agent based model with EnergyPlus to predict the effect of occupant actions on the energy consumption of the building. While their model has not been verified, their results suggest that controlling solar radiation through the use of blinds is the most effective occupant action to improve energy performance and increase comfort.

To enact a change in human behaviors, a combination of education and continued incentives must be offered. Education provides initial incentive to make a change, but without additional prompting, occupants revert to their previous behaviors [34]. Jiang, et al. monitored electrical consumption in part of a college computer science lab for four weeks [34]. They noticed a 30% drop in power consumption in the week following their introductory presentation about specific actions that would reduce energy consumption. However, by the 4th week, average power consumption had almost returned to their original levels. The authors noted: "Without drawing any concrete conclusions from this experiment, it appears that a single notice, though initially powerful, may taper off in effect over time without reinforcement" [34]. This observation reinforces the need for continued incentives for occupants to continue their energy saving behaviors. Wong [35] described this effect in more detail, dedicating a chapter of her Master’s thesis to behavioral considerations, specifically methods to work with and around occupants' beliefs about energy consumption to enact building-wide energy savings.

Chapter 3

New Jersey National Guard Armories

The twenty-six operational National Guard Armories in New Jersey have many similarities, despite their differences in size, location, and number of occupants. Twelve armories were constructed between 1955 and 1965. Ten armories were constructed between 1925 and 1940. Three armories were constructed between 1977 and 1982. One armory was constructed prior to 1900 [36]. The exterior walls of most armories are composed of brick and cinderblock. Heat is provided by a central boiler pumping hot water through radiators in each room. Air conditioning is provided by window units, if at all. Size varies from 11,000 ft^2 to 184,000 ft^2. Space is divided between offices, classrooms, restrooms, locker rooms with showers, secured storage, space for vehicle maintenance, and a drill floor. In all but the largest armories, vehicle maintenance is performed on the drill floor. Buildings are typically one or two floors above ground, although there are a few with additional floors or a basement.

Daily use and occupancy of the armories varies over time and between buildings. Some are fully occupied every day, while others are barely occupied, with a maximum of two occupants two days per week. In a typical armory, more than half of the offices are occupied on a daily basis, with the remaining spaces being occupied a few days per week or only during drill events. As reported by the point of contact in multiple armories, the recruiters assigned to those buildings often work in the field. As a result, their offices are empty more days than they are occupied, but not on a predictable schedule. Most armories have regular drill events where the members of the unit stationed at that armory are in the building, including overnight. These events occur one weekend per month and one week per year. These events have a higher daily energy consumption than regular weekdays because of the number of people and specific way the building is used during these events. The daily energy consumption during drill weekends is quantitatively compared to regular daily consumption in Chapter 4. Occasionally, the unit stationed at an armory is deployed for more than a year. While the unit is deployed, occupancy of the building is drastically different. Drill events are not held and typical daily occupancy is reduced. In one armory, occupancy was reduced from multiple officers working every weekday down to a pair of officers from another unit working two days each week. In another armory that normally has ten officers and an armorer working daily, daily occupancy was reduced to the armorer.

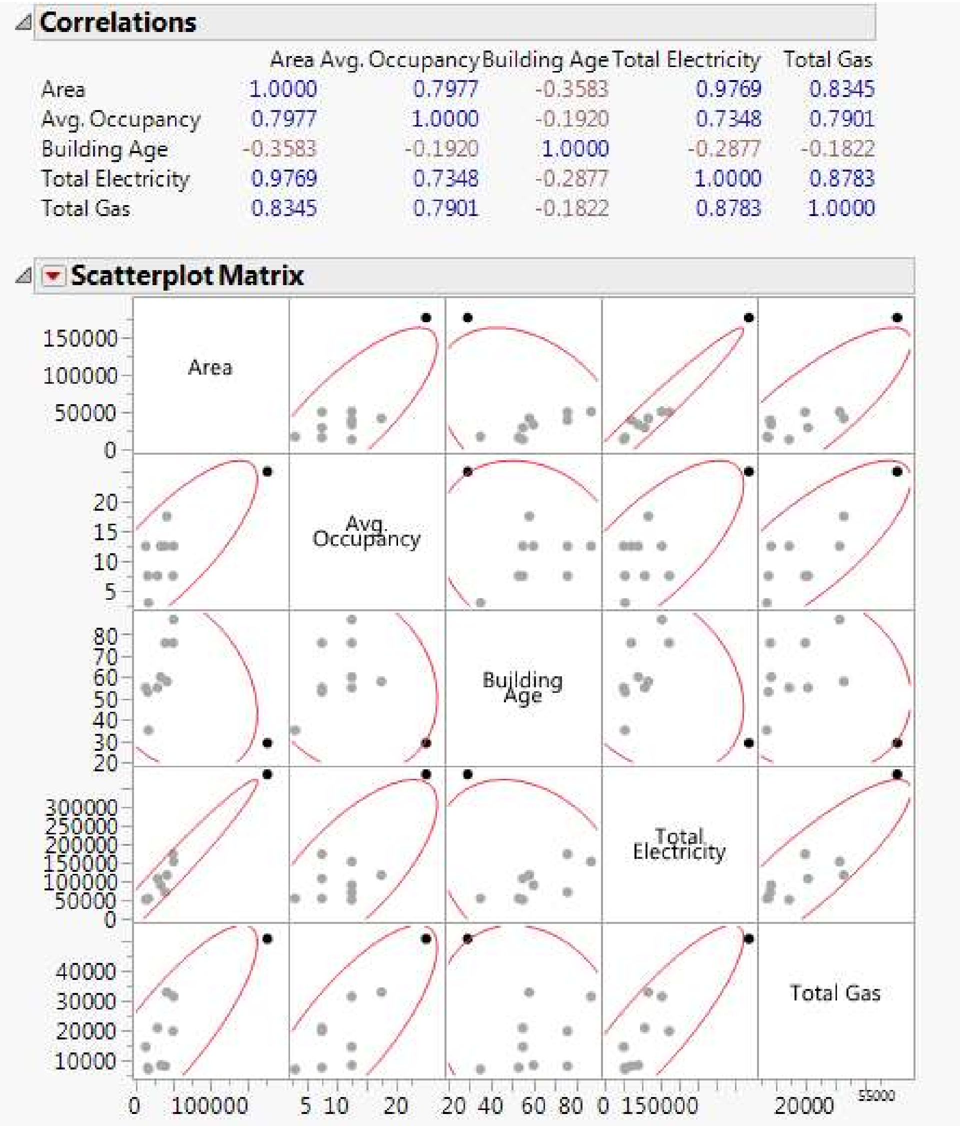
Meta Data Comparison

Information about trends in the whole set of buildings can be obtained by examining energy consumption data for some of the buildings considered in this study. In particular, comparing energy consumption values and numerical building characteristics could show a correlation between one or more of the building characteristics. This correlation, if shown, would provide a prediction of typical consumption based on that numerical building characteristic. Thus, knowing that numerical building characteristic for another armory would allow consumption numbers to be predicted. If the actual consumption is higher or lower than the prediction, the audit of that armory can look for the cause. If consumption is higher than predicted, identifying the cause allows the cause to be addressed, reducing future consumption. If consumption is lower than predicted, identifying the cause could reveal an energy conservation measure to be applied in other armories.

It is expected that building area and gas consumption have a correlation, as the whole building is heated. If occupants are grouped in a part of the building and the rest of the building is heated to a lower temperature, a correlation between average number of occupants and gas consumption could appear. However, the stronger correlation to building area could disguise a correlation between number of occupants and electricity consumption. It is expected that electricity consumption has a weak correlation to both building area and number of occupants, as consumption comes from both area dependent sources and occupant based sources. The division of consumption between area dependency and occupant dependency is proposed but not tested here. It is expected that area-based consumption is from outdoor security lights, indoor emergency lights, and hallway lights not attached to occupancy sensors. It is also expected that occupant-based consumption is from plug loads and lights in occupied offices.

Regression analysis. Ten of the twenty-six New Jersey National Guard Armories were chosen for a statistical analysis of annual energy consumption to specific building characteristics. These armories were chosen because of the availability of complete information about each. The initial information gathered about each building was building area in square feet, average daily weekday occupancy, building age in 2013, annual 2013 electricity consumption, and annual 2013 gas consumption. The data set for these armories can be seen in Appendix A. A multivariate analysis was performed on this data set, looking at the strength of correlations between each building characteristics and each annual energy consumption. The results can be seen in Figure 2. Comparisons between building characteristics are ignored as irrelevant, as all building characteristics are considered driving factors. In the results, it was noted that the Lawrenceville Armory was an outlier in almost every category, which skews the correlations. In the scatterplots, the Lawrenceville Armory is the black dot and the other armories are grey dots, to highlight how it skews most of the linear regressions. The leverage that the Lawrenceville Armory exerts on the regression can be seen especially clearly in the comparisons of area to annual electricity consumption, area to total gas consumption, building age to total electricity, and building age to total gas consumption.

The relationships between building characteristics and consumption at the Lawrenceville Armory are different from the relationships at other armories, so a statistical analysis was performed to determine how significantly the Lawrenceville Armory data was skewing the correlations. These additional analyses concluded that the Lawrenceville Armory was a huge lever on the linear regression analysis shown in Figure 2. The plot of residuals, or size of error, is particularly telling. In the analysis with the Lawrenceville Armory included, there is no pattern to the values of the residuals. Without the Lawrenceville Armory, the residuals are grouped around the same value, indicative of a solid analysis. Another analysis was performed and the results showed that there was a statistically significant probability that the linear regression of the data set including the Lawrenceville Armory was not statistically different from the intercept. This means that the linear regressions with the Lawrenceville Armory in the data set have no statistical relevance.



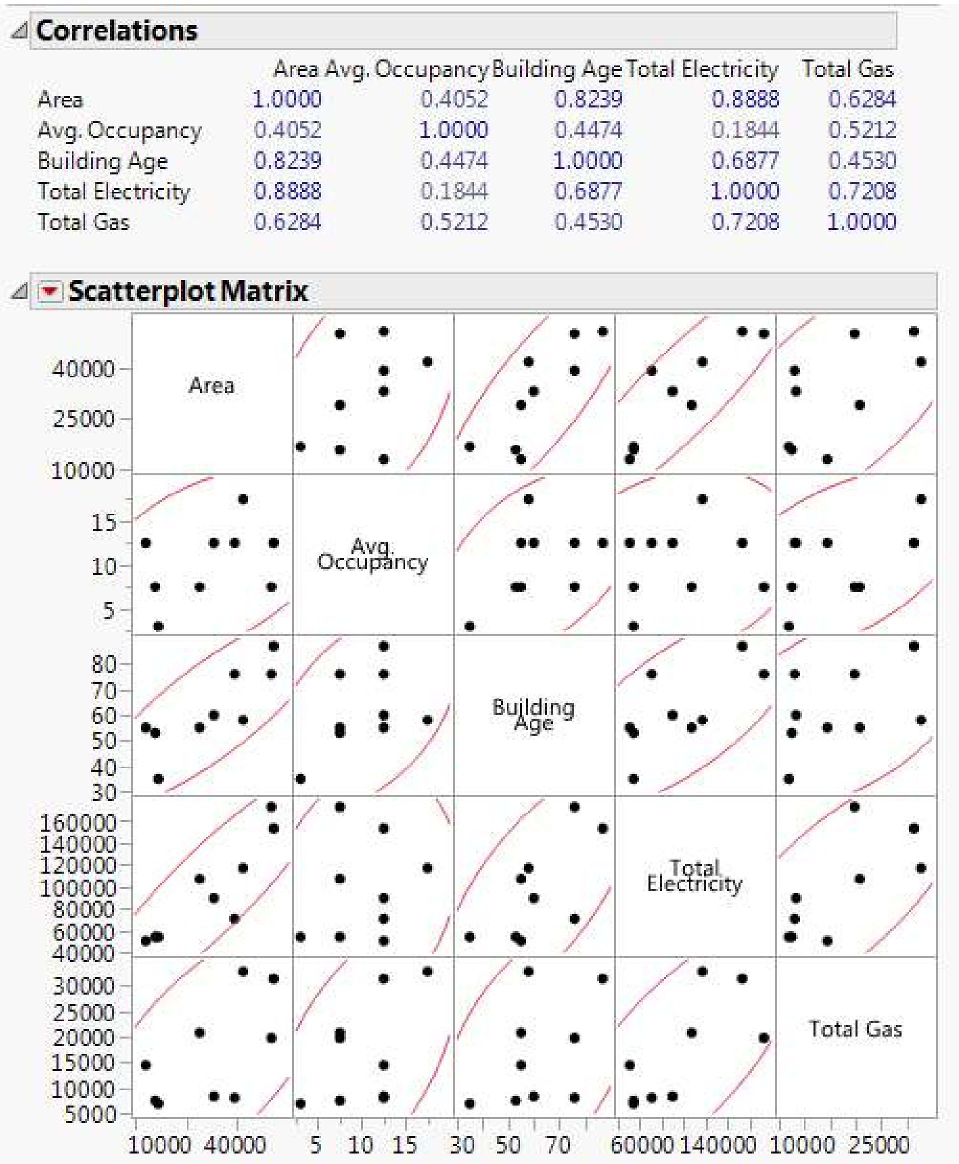
Correlations

	Area	Avg. Occupancy	Building Age	Total Electricity	Total Gas
Area	1.0000	0.7977	-0.3583	0.9769	0.8345
Avg. Occupancy	0.7977	1.0000	-0.1920	0.7348	0.7901
Building Age	-0.3583	-0.1920	1.0000	-0.2877	-0.1822
Total Electricity	0.9769	0.7348	-0.2877	1.0000	0.8783
Total Gas	0.8345	0.7901	-0.1822	0.8783	1.0000

Figure 2. Correlation values and scatterplot matrix results of a multivariate analysis of ten armories, with the Lawrenceville Armory values highlighted in black on the scatterplots.

The Lawrenceville Armory is 3.5 times larger than the next largest armory included in the analysis. It is a sprawling single story building with the usual drill floor and office spaces, as well as a museum and a second large hall, similar to the drill floor. Average daily weekday occupancy in Spring 2014 was twenty to thirty people. This is greater than twice the occupancy of all but one other armory included in the analysis.

Since its inclusion renders statistical analysis of this data set meaningless, it was eliminated and the analysis repeated. The results of the new analysis can be seen in Figure 3. Comparing the correlation values between the two analyses, it is clear that the Lawrenceville Armory was driving the linear regression in all categories, so its elimination from the data set is justified.



Correlations

	Area	Avg. Occupancy	Building Age	Total Electricity	Total Gas
Area	1.0000	0.4052	0.8239	0.8888	0.6284
Avg. Occupancy	0.4052	1.0000	0.4474	0.1844	0.5212
Building Age	0.8239	0.4474	1.0000	0.6877	0.4530
Total Electricity	0.8888	0.1844	0.6877	1.0000	0.7208
Total Gas	0.6284	0.5212	0.4530	0.7208	1.0000

Figure 3. Correlation values and scatterplot matrix results of the multivariate analysis of nine armories.

With the exclusion of the Lawrenceville Armory, there are nine armories in the data set, equal to 36% of New Jersey National Guard Armories. The multivariate analysis seen in Figure 3 shows correlations for each comparison. The strong and weak correlations between a building characteristic and an annual consumption value are discussed below.

There are strong correlations between building area and both types of consumption. Building area and annual electricity consumption have a correlation of 0.889. Building area and annual gas consumption have a correlation of 0.628. Intuitively, it makes sense for a set of similar buildings to have similar energy intensity values. Energy consumption per 1,000 square foot for the nine armories were calculated and then sorted from lowest to highest intensity, with associated relative building size attached. The relative building size was included to facilitate comparison between electricity and gas intensity in each armory. In Table 1, the smallest building is noted as 1 and the largest building is noted as 9. There is some correlation between electricity and gas consumption per thousand square feet in the same building. However, there are likely factors other than building size affecting gas consumption, as the smallest armory has the highest electricity and gas consumption per thousand square feet. This is verified by the correlation between building age and gas consumption values seen in the nine-armory multivariate analysis. The major factor neglected from this analysis, due to lack of data, is the heating season temperature setpoint. It would make sense for a smaller armory to have such a relatively high gas intensity if the temperature setpoint in that building is higher than in other armories.

In addition, the magnitude of the difference between energy intensity in each armory should be noted. The smallest armory has twice the electricity intensity and five times the gas intensity as a medium-sized building with three times the area and the same number of daily occupants.

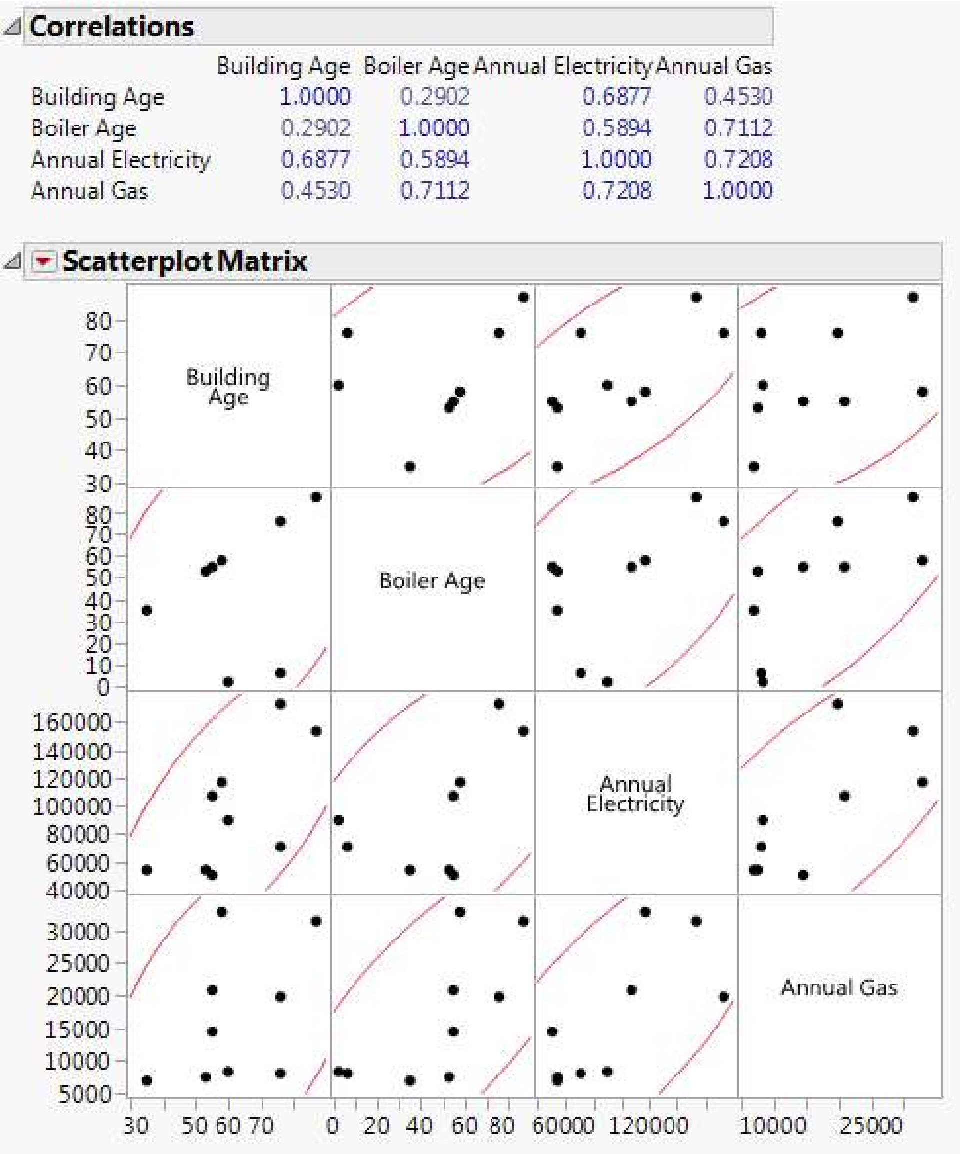
Table 1

Comparison of Annual Energy Intensity to Building Size

Associated Building Size	Electricity Intensity (kWh per year per 1,000 ft^2)	Associated Building Size	Gas Intensity (therms per year per 1,000 ft^2)
6	1,810	6	206
5	2,714	5	252
7	2,808	8	396
9	3,032	3	412
3	3,223	2	473
2	3,419	9	620
8	3,466	4	719
4	3,705	7	786
1	3,865	1	1,103

There are weak correlations between building age and both consumption values. Building age and annual electricity consumption have a correlation of 0.688. Building age and annual gas consumption have a correlation of 0.453. These values can be explained. Buildings, as with equipment, lose efficiency over time due to wear and tear from regular use. For buildings, this includes the introduction of new gaps or widening of old gaps in the building envelope, which result in increased infiltration and higher gas consumption. For equipment, this means looser seals on refrigerators and freezers and lower efficiency in motors from wear and tear. In addition, newer appliances are designed to consume less energy in filling the same purpose as the older appliances. The correlations are not strong enough to predict annual electricity or gas consumption, but it is strong enough to assist in the identification of outliers, indicating higher or lower efficiency than the majority of armories. If an armory is less efficient, more attention should be paid to the building envelope, the walls, doors, and windows of the armory. However, neither is a strong correlation, so it is likely that there are other factors than building age involved in annual energy consumption.

A possible additional factor was examined for gas consumption. Initially, it was assumed that the boiler in each armory was the same age as the building, as is true in most armories. Some research revealed that two of the armories in this data set had their boilers replaced. Thus, building age and boiler age are not identical sets of information. It was possible that boiler age would have a different correlation than building age to annual energy consumption. This analysis was performed and the results are shown in Figure 4. For annual electricity consumption, building age has a slightly better correlation, but the difference is not statistically significant as the drop in correlation is most likely due to the fact of a small data set. For annual gas consumption, boiler age has a stronger correlation than building age. This is sensible, as efficiency of the boiler has a direct effect on gas consumption.



Correlations

	Building Age	Boiler Age	Annual Electricity	Annual Gas
Building Age	1.0000	0.2902	0.6877	0.4530
Boiler Age	0.2902	1.0000	0.5894	0.7112
Annual Electricity	0.6877	0.5894	1.0000	0.7208
Annual Gas	0.4530	0.7112	0.7208	1.0000

Figure 4. Multivariate comparison of building age, boiler age, and annual energy consumption.

Overall, there are strong correlations between building area and annual electricity consumption (0.8888), building area and annual gas consumption (0.6284), building age and annual electricity consumption (0.6877), and boiler age and annual gas consumption (0.7112). From these correlations, it can be concluded that the buildings are similar and can be treated as such in the modeling process.

Chapter 4

Simulation Software and Limitations

The need for energy audits of National Guard Armories is apparent from both federal regulations and the analysis of energy consumption described in the previous chapter. The next step is to perform the audits. The audit process starts with data collection, from which models are created, allowing the identification of significant energy consumers and problem areas. With major consumers and issues identified, mitigation strategies for each can be examined and recommended to the National Guard. The audit process is described in greater detail in the next chapter. This chapter focuses on the modeling process, specifically the choice of modeling program, limiting assumptions built into the chosen program, and the need for a process to work with or around these limitations to model each armory accurately.

Available Software Packages

There are multiple commercially available software packages to assist in the reduction of energy consumption in a building. Many are building simulation programs designed to model energy consumption in a building. Within this category are calculation engines which require another program to allow the user to interface with the engine efficiently, without needing years of training. Other software packages are stand-alone programs, comprised of a user interface and a calculation engine in a single piece of software. Outside this category of building modeling exist other approaches to reducing energy consumption, including utility bill analysis. Each type of software package is discussed below.

DOE-2 and BLAST are simulation engines that interface with the user through text files. The development of each began in the 1970s, through funding from the Department of Energy and the Department of Defense, respectively [37]. Development and improvement continued through the 1990s, until both departments decided to abandon continued development of their engines because they were "too difficult, costly, and time-consuming to add new features" [38]. Instead, the Department of Energy created a new engine, EnergyPlus, with a modular design and including the best attributes of DOE-2 and BLAST [37]. A brief summary of these three calculation engines are shown in Table 2, with information drawn from Crawley, et al.'s 2008 comparison of commercially available building modeling software [39].

Table 2

Comparison of Simulation Engines

Engine	Developers [38]	Basis [38]	Timeframe
BLAST	Army CERL , DOD (USA)	Heat balance for surfaces and interior air	Early 1970s to 1995
DOE-2	DOE (USA)	Series of 4 subprograms calculate hourly energy use	Early 1970s to 1995
Energy Plus	DOE + other US research groups	BLAST & DOE-2: Heat/mass balance	1996 to present

The focus of each engine was their calculation capabilities, so a user-friendly interface was not developed by the design team. As stated previously, the engines accept text file inputs in a very specific format and output text files in a different specific format. The designers of EnergyPlus continued the practice started by the DOE-2 and BLAST designers, relying on the private sector to develop interfaces for their program [40]. Many interface programs were created, though only a few became popular with users. For the DOE 2 engine, J.J. Hirsh and Associates developed eQUEST. This is short for "QUick Energy Simulation Tool" [41]. For EnergyPlus, a group of partners, including NREL and the US Department of Energy, developed OpenStudio. Both OpenStudio and eQUEST are still in use today, with continued updates [41], [42]. These are not the only interfaces developed for these engines, but they are the most commonly used, as shown by BEMBooks's "History of Building Energy Modeling" and Crawley et al. [38] , [39].

These two interfaces are briefly described in Table 3, along with another building simulation program. eQUEST contains three wizard tools: two assist in model creation and the third facilitates comparisons between alternative models. OpenStudio can model a greater range of buildings and contains building options that did not exist when eQUEST was released in 1997. Energy-10 is designed to model single zone residential buildings less than 10,000 ft^2 [43].

Table 3

Comparison of Building Modeling Programs and Alternatives

Program	Description	Creators and Release Date.
eQUEST	Interface for DOE-2, allowing easy model creation and comparison between alternative simulations	J.J. Hirsh and Associates. Originally 1997, latest version 2014 [41]
OpenStudio	Interface for EnergyPlus, with capability to interface with Google SketchUp.	NREL. Originally April 2008, latest Jan 2016 with updates every 3 months [42]
Energy-10	Program that runs hourly heat transfer calculations. Meant for residential buildings smaller than 10,000 ft^2	NREL. Originally June 1996 [43]

Limitations of Software

One of the limitations across all building simulation programs is driven by the trade-off between ease of use and the program's capability for detail. Programs with the capability to accurately model complex systems typically require significant training to use and programs that are easy to learn typically have reduced modeling capabilities. This trade-off is a major limitation, as it puts one of two barriers between a modeler and their ability to create a detailed and accurate model of the building under examination. The first potential barrier is the learning curve of the more complex program - overcoming this requires either self-training from online resources or formal training with an expert. The second potential barrier is reduced model accuracy because of limits imposed by the program. Overcoming this requires either correction factors that increase the accuracy of the general inputs, or using a different simulation program. Overcoming the first potential issue is easier, but requires money and time, both of which are in scarce supply when working with undergraduate students. Formal training with an expert is an ineffective use of limited time with students who work on the project for six to eight hours each week for fourteen weeks. Formal training for eQUEST is either eight hours with a teacher in a single session or ten hours of online training. Either option would consume a week and a half of each student's time and has an associated cost. Online training from energy-models.com would cost $179 per month per student [44]. Overcoming the second potential issue requires knowing the limitations and learning curve associated with the available programs. With this knowledge, a modeler can choose which building simulation software will best fit their modeling needs.

In addition to the limitations present in all modeling programs, each program described here has individual limitations and drawbacks that may discourage new users. The three simulation engines described in Table 3 require the use of interfaces for pre- and post-processing of each model. Two of the three eQUEST Wizards guide the user through model creation and the third Wizard facilitates modification of the base model created in either of the other two Wizards to model alternatives in the building. The complexity and accuracy of the simulations are sacrificed for increased ease of use. OpenStudio has the capability to model complex buildings, including a wider selection of use schedules and HVAC options than eQUEST. OpenStudio lacks any form of wizard tool or guidance on which inputs are required to create an initial model. Energy-10 was designed to model residential buildings smaller than 10,000 ft^2; New Jersey National Guard Armories fit into neither of these categories.

Thus, Rowan University undergraduate students working on the project tested eQUEST and OpenStudio for ease of use and usefulness of the provided outputs by modeling the same building in both programs. For this study, eQUEST was chosen because of its variety of useful outputs, its compromise between a minimal learning curve and ability to handle more complex modeling, and the included Wizard tools.

Details about eQUEST

J.J. Hirsch and Associates developed eQUEST to be able to handle a wide range of buildings and building types. In addition, they developed three Wizards to allow non-experts to use their program. This required introducing assumptions, which limit inputs in favor of an easier-to-use interface. The Schematic Design (SD) Wizard is intended for use when less information is available and the Design Development (DD) Wizard is intended for use when more specific information is known about the building, including HVAC zoning, lighting details and plug load details [45]. The Energy Efficiency Measures (EEM) Wizard allows the creation of a parametric study of design alternatives through non-intrusive modification of the base model. The Schematic Design Wizard is useful when less specific design information is known about the building, especially with users that have not had any formal training about how to use eQUEST. The Design Development Wizard contains a wider variety of inputs and less limiting assumptions, while requiring more information and expertise to use. The assumptions built into eQUEST are based on the team's years of experience working with DOE-2.1 and work for most buildings. However, National Guard Armories are unique buildings that do not fit a number of the assumptions made in eQUEST.

Outputs are both graphical and tabulated, detailing the results of a single model or comparing the results of multiple models. For a single model, monthly energy consumption by end use, annual energy consumption by end use, monthly utility cost, and peak demand by end use are calculated and graphed. Multiple models can be compared by looking at the comparison outputs, including monthly energy consumption, monthly utility cost, annual utility cost, and annual energy by end use. While not of interest to most users, the text input for DOE 2.2 is available. This document details the design of the building being simulated and is useful for reference, especially when looking up heat transfer characteristics for parts of the building. The learning curve is relatively low, such that simple models can be created only a few hours after downloading the program. Once the user is competent and comfortable making a simple model with the program, they can add complexity to the original model. If desired, the user can add more detail to a model created in the SD Wizard by modifying it in the DD Wizard. However, for most of the buildings modeled in this study, the SD Wizard was used due to the minimal learning curve and the limited information available.

The mathematical engine behind eQUEST is DOE-2.2. As described above, the DOE engine was in development for more than 20 years prior to the development of this interface. In addition, this interface was developed by one of the companies involved in the continued development of the DOE-2 engine [41]. Since James J. Hirsch and Associates, the creator of eQUEST, was a major contributor to the DOE 2 engine, their expertise and experience in the development and implementation of modeling software also adds credibility to the newer program's abilities. Thus, it is reasonable to assume that eQUEST has the potential to access and use the full operational capabilities of the DOE 2.2 engine.

Theoretically, a building could be modeled exactly using the detailed inputs in eQUEST, outside the Wizard tools. However, the Introductory Tutorial for eQUEST published by the creators discourages beginning users from working outside the Wizards, with a warning that edits made outside the Wizard tools cannot be translated back into the Wizard tools, including the EEM Wizard [46]. The EEM Wizard will ignore any edits made outside the other two Wizard tools. This means that comparing models with edits made in the detailed interface must be done without the assistance of the EEM Wizard. This is possible, but the comparison process still has limitations. For more details about the detailed interface and comparison of models made in the detailed interface, see the eQUEST tutorial. Use of the detailed interface requires extreme knowledge of the building, such as information from construction documents, which is more than an audit team could obtain from a single walkthrough of an armory. The conclusion from this is that the detailed interface is unsuitable for this study. The DD Wizard, the more detailed of the two input wizards, could be used for this study, but the increase in accuracy would come at the expense of extra time needed to collect and input the required information. The SD Wizard has a reasonable balance between data needed to create a model and accuracy of outputs.

Assumptions in eQUEST

There are three categories of assumptions in the Schematic Design Wizard of eQUEST. The first includes assumptions that are built into the Wizard tool, allowing it to operate. Each of these has a related input which can be altered, but the base assumption cannot be changed. The other two categories are inputs for which eQUEST assumes an initial value. The second category of assumptions includes the typically correct initial values. They should be checked for accuracy at least once, but they rarely required alteration in the author's experience of modeling National Guard buildings. The third category of assumptions includes typically incorrect initial values when modeling armories, in the experience of the author. These inputs require time, attention, and effort to determine the correct values prior to input in eQUEST. These assumptions and inputs are listed and then discussed in the order they are input into eQUEST. Table 4 shows the eQUEST inputs that are discussed here. See Appendix D for a comparison of initial default values and final values for these inputs.

Table 4

eQUEST Inputs with an Associated Assumption

Screen	Screen Title	Inputs
1	General Information	Building type, location, size, HVAC equipment, analysis year, schedule input type
3	Building Footprint	Shape, size, floor height
4	Building Envelope Constructions	Roof construction, wall construction, infiltration
5	Building Interior Constructions	Ceiling material, floor surface
6	Exterior Doors	Type, orientation, number, and construction of exterior doors
7	Exterior Windows	Construction, orientation, and size of windows
13	Activity Areas Allocation	Area types, percent area, and design occupant density and ventilation
14	Occupied Loads by Activity Area	Installed lighting and plug loads in watts per square foot
15	Unoccupied Loads by Activity Area	Lighting and plug loads as a percentage of the loads entered on the previous screen
17	Main Schedule Information	Occupancy schedule, percent occupancy, and percent of installed loads
19	HVAC System Definitions	Cooling and heating sources, system types
20	HVAC Zone Temperatures and Air Flows	Thermostat setpoints, design temperatures, and air flows
23	HVAC Fan Schedules, System 1	Time of fan operation
33	Domestic Water Heating Equipment	Type of heater, daily consumption per person, tank size

Assumptions in the Wizard: base assumptions. National Guard Armories are a unique category of buildings. They do not fall neatly into any of the forty-two building types available in eQUEST. Building type sets the default values for most inputs in the wizard, including building size, HVAC system types, building construction, and electrical consumption per square foot. All of these inputs can be changed as the user goes through the wizard, so it is not imperative that the building type matches the reality of the building. However, a mismatch requires more effort and research by the user to ensure the correct values are entered. For New Jersey National Guard Armories, suggested building type is "School, Middle School" or "Office Bldg, Bank/Financial." The last input on the first screen identifies how the schedule of occupancy will be entered on a later screen.

The details of National Guard Armories are discussed in greater detail in the previous chapter. In summary, the occupancy of each armory can be generalized by room type. Rooms with daily use are offices, classrooms, bathrooms, and hallways. The mechanical room is used daily in the winter and is rarely used the rest of the year. Rooms with use that varies from armory to armory include conditioned storage rooms, unconditioned storage rooms, and vehicle maintenance bays. Rooms with irregular or no use include the kitchen, dining room, and drill floor. The use of these rooms, if at all, occurs during drill events. This varied use is difficult to express in eQUEST, where the schedule is input for a single typical week. The first category of use, the weekday use, can be modeled easily, as it can be entered directly. The irregular use cannot be entered directly; it requires a correction factor to incorporate into the model.

As drill events cannot be entered directly into eQUEST, it is important to determine the contribution of drill events towards total energy consumption. To quantify the exact contribution of a drill weekend, electricity consumption was recorded at the same armory throughout August and September 2014, using the building's electric meter. The meter was read at irregular intervals, covering a calendar month, the September drill weekend, and three weeks of regular occupancy. From these readings, daily consumption was calculated for weekdays, weekends, and drill weekends. Consumption for the month was calculated and compared to the utility data with an error of 3.5%. Daily weekday consumption is the highest, as expected. Daily drill weekend consumption is little more than half the weekday consumption. Regular weekend consumption is one third the weekday consumption. In a temperate month, the drill weekend is responsible for 6% of the baseline consumption. This analysis is a conservative calculation, as the impact of seasonal energy consumption is neglected. While this consumption is relatively low, it contributes to the error between model and reality. As such, it is important to determine the contribution of drill event consumption towards monthly energy consumption and the subsequent effect it will have on model accuracy if not accounted for.

It is possible to directly input some of the regularly occurring non-weekly events into eQUEST, by switching the Usage Details option from Simplified to Hourly Enduse Profiles on Screen 1. However, doing so essentially switches the set of inputs from the SD Wizard to the more complex DD Wizard. Ten more possible inputs screens are added to the original forty screens and the format of many screens are altered [47]. The eQUEST tutorial released by James J. Hirsch and Associates in 2003 [47] describes the hourly enduse schedule inputs screens in the Design Development Wizard tutorial section, with only a brief mention about this capability in the Schematic Design Wizard tutorial section. This added complexity is undesirable for users without formal training, as described previously. Thus, this option was excluded from the list of possible solutions to manage non-weekly events when modeling the building in eQUEST.

Another assumption on the first screen, not related to the building's structure or use, is made about the climate. It is assumed that the weather across a geographical region is similar, allowing weather data from one site to be used for another site. This is an acceptable assumption, as weather and temperature does not typically vary too significantly between neighboring towns.

Once building type, schedule input type, and weather are input, the physical structure of the building is entered. There are several assumptions made about the structure of the building to simplify the user input screens for these attributes. It is assumed that all of the exterior walls share the same materials and the same construction. The only time this is likely to be false for a New Jersey Armory is if an addition is built differently than the original building. For National Guard armories, new additions are rare and the few existing additions were built to match the construction of the existing building. eQUEST is also programed with the assumption that multi-story buildings have the same footprint for each floor. For most armories, this is irrelevant, as they are single story. For the few armories with multiple floors, this is incorrect. For some armories, the height of the drill floor prevents the upper floors from being the same size as the first floor. For others, the upper floors were designed to be smaller than the first floor. Either way, the difference in layout requires a correction factor to address the mismatch in size.

There are several simplifying assumptions about the building envelope. It is assumed that there are only three types of doors and three types of windows. The type includes size and construction. The number of door types is adequate, although if there are single and double doors, a correction factor must be applied to either the infiltration value or the number of doors. The number of windows is typically enough, though sometimes a correction factor is needed to account for the variety of window sizes. Included in this assumption is another window attribute, that occupants cannot open the windows of the building or control the blinds over the windows. The possibility of changing the status of windows or window coverings is not included in eQUEST, as this would over-complicate the model.

After building attributes are entered, eQUEST returns to occupancy and building use. In addition to building type, the building is divided into room types. There are 60 possible room types to choose from, each with its own set of design values for occupancy and ventilation. As with building type, the values set by this choice can be altered. There can only be eight room types identified, so armories with more than this must be simplified by combining multiple room types into a single category. This assumption is not critical, as many room types can be grouped together in the same category, but the user must be aware of this.

There are also assumptions about the HVAC system. These are potentially consequential assumptions, but make it possible for a user with little knowledge about the specifics of the system to model the building. The inputs about the building's HVAC system initially ask for type of heating system and type of cooling system. These are semi-independent from each other, except for limits on which systems can be present in the same building.

Assumptions in the Wizard: assumed to be correct values. The second category of assumptions includes initial values that are typically correct. They rarely need correction or adjustment. The first of these assumptions is the placement of windows and doors on each wall. The user inputs the number and type of doors on each face of the building and eQUEST automatically centers these doors on each face. The user inputs the number and type of windows on each face of the building on the next inputs screen. The windows are placed at the sill height specified by the user and distributed uniformly around the doors. This can be seen in Figure 5, which shows the automatic placement for the specified doors and windows. From left to right, the small windows are the small drill floor windows, the garage doors, the double doors, more drill floor windows, and classroom windows. The location of each door and window can be manually altered using the Custom Window/Door Placement tool, where coordinates for the lower left corner of each door and window can be entered.

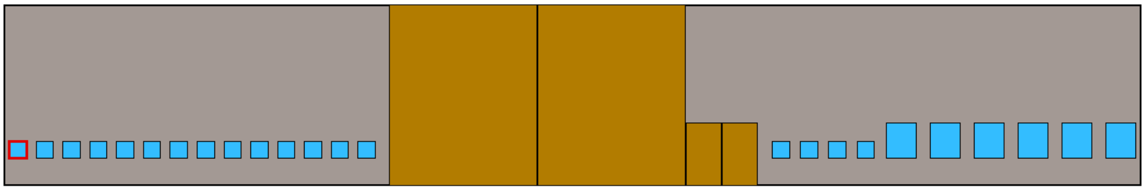


Figure 5. Default door and window placement in eQUEST.

To evaluate the effect of doors and windows placement if each floor of the building is treated as a single HVAC zone, a second model was created. In the second model, the EEM Wizard was used to alter the location of windows and doors on each wall. The number and size of each item on each wall was preserved. Figure 6 shows the adjusted door and window placement for the wall in Figure 5. Only one wall is shown, as a demonstration of what was done.

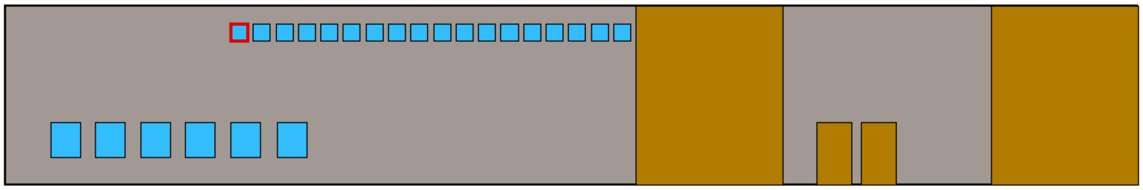


Figure 6. Adjusted door and window placement in eQUEST.

Both models were run and the outputs compared, as seen in Figure 7. The bottom run, denoted in blue, is the model with default placement of doors and windows. The top run, denoted in gray, is the model with accurate placement of doors and windows. There is no difference in energy consumption between the original window placement and the adjusted window placement. Thus, the placement of the doors and windows do not matter if each floor of the building is treated as a single HVAC zone.

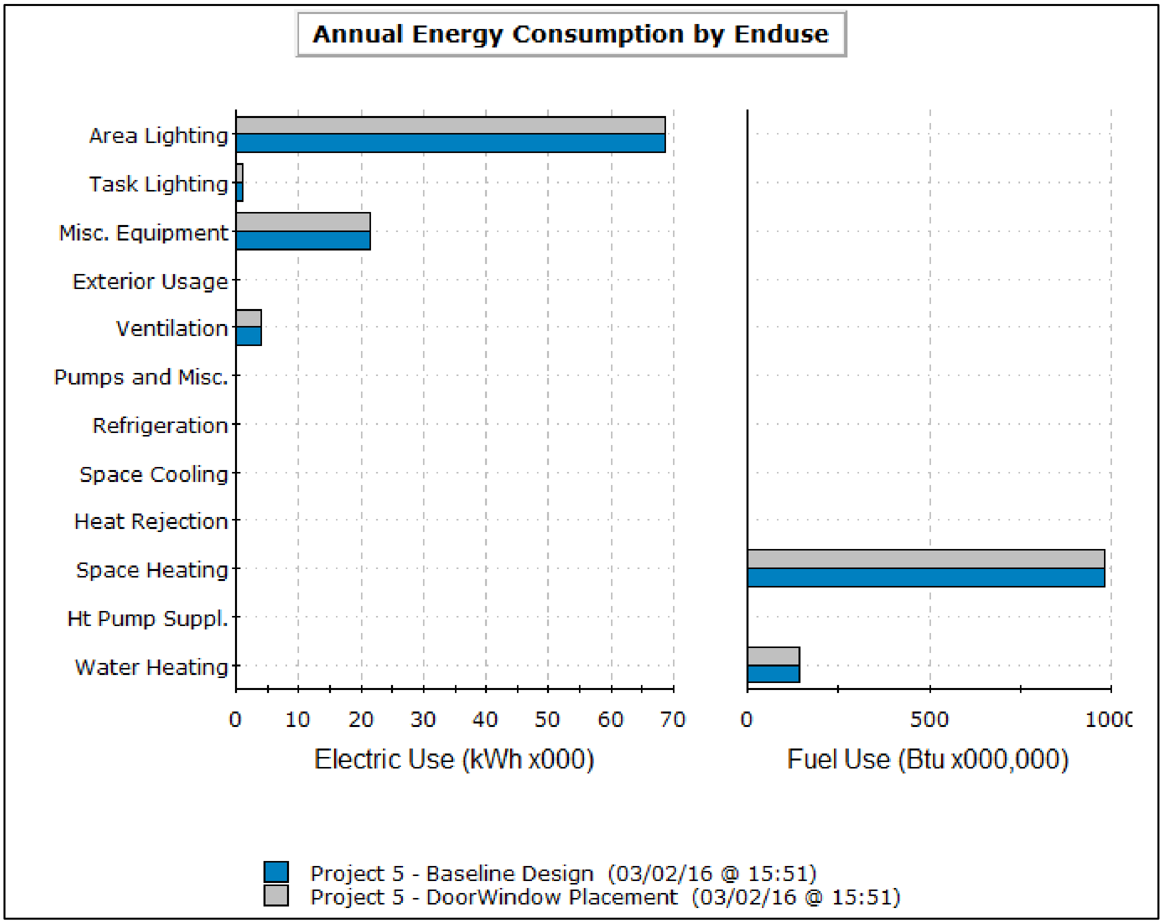


Figure 7. Comparison of eQUEST outputs for two models with different window and door placement, showing identical consumption.

The second and third assumptions in this category both relate to the simplification of the HVAC system. The HVAC design temperatures and size are based on the initial building type and the size of the building. These are difficult to check during a walkthrough of the building, so the default assumptions, based on building type, are used as-is. The use of the default values adds a minimal amount of error to overall model error.

Assumptions in the Wizard: typically incorrect values. For some inputs, eQUEST has default values that poorly match the reality of New Jersey armories. These include infiltration, default room division, temperature setpoints, and water heater details.

Infiltration for a typical new building is assumed to be through an area equivalent to a 1/16th inch gap around every door and window [48]. This is an acceptable assumption for eQUEST's intended audience: members of a building design team [41]. Their design, when constructed, should meet the standard of a well-sealed building. However, this assumption does not hold for older buildings such as New Jersey National Guard Armories. Older buildings have a variety of issues, including broken or cracked windows, aging of window sealant, wear of weather stripping, doors that do not seal properly, and window A/C units that are not well sealed. Each of these contributes to the total area from which conditioned air from inside the building can escape the building envelope. To account for this, the additional area from each of these categories is calculated and summed, then compared to the assumed area if all the doors and windows were well-sealed. The ratio of calculated to assumed area for infiltration to occur is the multiplicative factor applied to the initial infiltration number in eQUEST.

After the building envelope details have been input into eQUEST, the division of room types inside the building must be assigned. eQUEST defines this as area allocation and has the user define the room type for each area definition. This is done by identifying room type for an area and inputting the percentage of building area that will be defined as that room type. The limiting factors are the number of predefined room types and that only eight room types can be entered. The predefined area types set default values for later inputs, but since they can all be changed, this is not really a limiting factor. The limitation of only eight area definitions can be managed by carefully combining room types. In a simple or small armory, there are less than eight room types, making this a non-issue. In a larger armory, there are more opportunities for a variety of room types, so the limited number of area definitions must be addressed through the combination of similar room types.

Once the area types are settled by combining similar room types, the specifics for each area type must be defined. The default values for design occupant density and ventilation are based on ASHRAE 62 and electricity consumption per square foot are based on California's Title24 requirements [49]. These values are typically accurate for an activity area with only one room type, but need adjustment if multiple room types are combined into a single activity area.

Once the details of the building interior are entered, details about the HVAC system are entered. As stated above, most of the HVAC details do not need alteration. However, temperature setpoints need attention as even small changes have an impact on predicted gas consumption. Temperature setpoints can be difficult to input correctly, primarily because of lack of information. Occupants are rarely aware of their building's thermostat settings, even the individuals supposedly responsible for the thermostat. The next step for gathering this data, reading the thermostat, provides some, but not all, of the necessary information. Looking at the thermostat shows the setting at that point in time. It does not provide information about the thermostat setting in other seasons. Even programmable thermostats rarely provide a complete picture, as touching the screen, needed to look at the settings for unoccupied times or other seasons, is discouraged by a locked cover over the thermostat. As such, heuristic assumptions about setpoints must be made. The regulated settings, as per the Army Facilities Management Report, are known by the audit team, but often not known by the armorer or occupant responsible for the thermostat, so this is not helpful information when modeling the current building. It becomes helpful later when modeling alterations to the building to examine potential energy-saving recommendations, specifically the savings resulting from altering temperature setpoints to match the recommended settings. Therefore, assumptions about thermostat settings are made based on conversations with occupants, the temperature in the building during the site visit, and occupant surveys.

In addition, if the model predicts different gas consumption than the bills, the temperature setpoints can be altered to increase or decrease gas consumption. This process is discussed in greater detail in Chapter 6.

One of the last steps in modeling the building in eQUEST is to specify details of the water heating equipment. As per the eQUEST tutorial written by the program's creators, the initial assumptions for this screen are based on rules of thumb, other than amount of water consumption per person per day, which is from the ASHRAE Handbook of Fundamentals based on building type [50]. Details can only be entered about a single water heater. For smaller buildings, this assumption is acceptable, as there is only one water heater in the building. For larger buildings, there are multiple water heaters, so a correction factor must be applied. Typically, this involves combining attributes of each water heater into a single unit that can be entered into eQUEST.

In conclusion, model corrections can help reduce discrepancies between the model and the reality of the armories, especially for high impact assumptions that would otherwise be time-intensive to correct. However, before model adjustment can be pursued, the modeler needs to understand the reality of the building, including building structure, occupancy patterns, typical electricity use, and building systems. This can be accomplished during a walkthrough of the building, when relevant building characteristics and noteworthy issues can be addressed and objective measurements made. In addition to this, data can be collected over time through the use of sensors left in the building. This provides a better view of the building during typical operation, as the walkthrough is done over a few hours on a single day. With these data, discrepancies between the model and the reality of the building can be identified and used to estimate correction factors that can be entered into the models. The process of an audit, including a walkthrough of the building, additional data collection, and modeling, is detailed in the following chapter.

Chapter 5

Methodology and Approach

Purpose of Audits

The end goal of performing an energy audit on a National Guard building is to provide supported quantitative recommendations for energy and cost savings for that building. These recommendations are called Energy Conservation Measures (ECMs). For the National Guard, supported constitutes having an outline of the specific financial and energy numbers, including installation cost, annual costs, annual energy savings, expected lifetime, and associated financial numbers, as shown in Table 5.

Table 5

Example of Financial Summary Provided to National Guard

NAME OF STRATEGY ENERGY SAVINGS SUMMARY	
Installation Cost	$7,000
Incentives	$0
Net Installation Cost	$7,000
Maintenance Savings per Year	$0
Energy Cost Savings per Year	$5,000
Total Yearly Savings	$5,000
Estimated Lifetime (years)	20
Payback (years)	1.4
Savings to Investment Ratio (SIR)	14.3
Lifetime Savings	$93,000
Internal Rate of Return (IRR)	2%
Net Present Value (NPV)	$74,757

Determining the costs associated with each measure is typically straightforward, given the information provided by the National Guard and the volume and depth of information available on the Internet. Calculating exact energy savings is more difficult, as it requires an accurate model of current energy consumption and a reasonable prediction of energy consumption after the adoption of the proposed measure. However, once a model of current energy consumption is developed, the appropriate model parameters can be altered to reflect the implementation of the proposed measure and predict future energy consumption. Thus, the first step is to create a model of current energy consumption.

Models

There are two types of models typically used in auditing New Jersey National Guard Armories. The first is a Light and Plug load Model (LPM), created in a spreadsheet. This model details each electricity-consuming device and its hours of operation to create a summary of electricity consumption in the building. This is accomplished by listing number, wattage, and reported time of use for each appliance and each type of light in each room in the building. The specific inputs for this model are shown in Table 6, separated by light and plug loads. With this information, annual electricity consumption from lights and appliances in kilowatt-hours per year is calculated. To determine the accuracy of the LPM, this model is compared to the baseline electricity consumption calculated from the monthly utility bills. The baseline is calculated by averaging the two lowest months, which typically occur within April, May, September, or October for New Jersey. This minimizes electrical consumption resulting from heating and cooling, which are used minimally during these months. Heating and cooling degree day data for various regions of the United States are available through the EIA, as Tables 1.9 and 1.10 of the Monthly Energy Review [51]. Seasonal devices, such as space heaters and unit air conditioners, are recorded but not included in the LPM. Consumption from these devices can be calculated and compared to seasonal electricity consumption. However, this does not provide useful information, so the LPM only contains baseline consumption.

Table 6

Example Inputs for Light and Plug load Model

<table>
<tr><td rowspan="4">Lights</td><td>Location</td><td>Bulb Type</td><td># of Fixtures</td><td>Bulbs per Fixture</td><td>Total Bulbs</td><td>Time (hr/yr)</td><td>kWh/ year</td><td>Light Intensity (lux)</td></tr>
<tr><td>Office</td><td>T8</td><td>6</td><td>4</td><td>24</td><td>2,080</td><td>1,597</td><td>290</td></tr>
<tr><td>Armorer Office</td><td>T8</td><td>3</td><td>3</td><td>9</td><td>2,000</td><td>576</td><td>407</td></tr>
<tr><td>Exterior</td><td>Halogen</td><td>10</td><td>1</td><td>10</td><td>3,285</td><td>13,140</td><td>-</td></tr>
<tr><td rowspan="4">Plug Loads</td><td>Location</td><td colspan="2">Item/Make/Model</td><td>Wattage</td><td>Quantity</td><td colspan="2">Time (hr/yr)</td><td>kWh/ year</td></tr>
<tr><td>Kitchen</td><td colspan="2">Microwave: Litton, Prestige</td><td>1,200</td><td>2</td><td colspan="2">43</td><td>103</td></tr>
<tr><td>Kitchen</td><td colspan="2">Ice machine: Scottsman</td><td>234</td><td>1</td><td colspan="2">2,920</td><td>683</td></tr>
<tr><td>Office</td><td colspan="2">Laptop: Dell</td><td>25</td><td>3</td><td colspan="2">2,080</td><td>156</td></tr>
</table>

The second model is a computer-based building simulation created in eQUEST. This model covers building footprint, construction, space/area allocation, and water heater size, and contains assumptions about electricity consumption from lights and plug loads, occupancy schedule, and temperature setpoints. These assumptions can be confirmed or altered based on sensor data, but are initially based on conversations with occupants of the building. The inputs for this model are described in greater detail in Chapter 4. In brief, eQUEST takes inputs describing the building structure and outputs energy consumption by fuel type and use. The LPM is only possible with a site visit; the eQUEST model is enhanced by a site visit. The results of both types of models are shown in Appendix B for the nine armories included in the statistical analysis. The typical audit process is described below.

Audit Process

The audit process begins with an examination of monthly utility bills for the two to three years prior to the audit. Electricity consumption in months with moderate temperatures, such as April, May, September, and October, are averaged to create a baseline of electricity use, as these months are likely to see the lowest use of electricity for the purposes of heating or cooling the buildings. Similarly, gas consumption in the warmer months of June, July and August are averaged to determine baseline gas consumption, as these months are likely to have the lowest gas consumption, as the need to heat buildings is presumed to be nonexistent. Baseline gas consumption is from appliances that consume natural gas, such as stoves. In armories without natural gas appliances, the baseline can be zero. A baseline for fuel oil consumption cannot be calculated, as deliveries are not regular and are not billed monthly. The creation of baseline consumption values allows the calculation of seasonal consumption and the identification of trends and outliers at a monthly resolution. This helps to determine heating and cooling patterns across different seasons.

After baseline consumption levels have been calculated using historical billing information, an audit team visits the site and performs a walkthrough of the armory to collect data specific to that building. More than one walkthrough may be necessary to acquire all necessary information, based on the size of the armory and the experience of the audit team. Details about lights and appliances are recorded, including location, quantity, make, model, and time of use as reported by occupants. Light intensity is recorded in each room. This information is collated into the LPM, in the format seen in Table 6. HVAC units are recorded in a manner similar to other appliances, and this information is supplemented with details regarding fuel source and efficiency if available. A member of the building maintenance staff, typically the armorer assigned to the building, is interviewed about the building, including outdoor light controls, temperature setpoints, seasonal timing of HVAC use, outliers and trends in energy consumption as seen in the bills, and whether there are any issues with the building envelope. If present, other occupants are interviewed about their schedules and behaviors that would affect energy consumption. Surveys regarding thermal comfort and energy-saving habits are distributed to the occupants and collected by the audit team for later observation.

Sensors can be placed in the building if more detailed information about energy consumption in an armory is desired. These sensors will be left in the building for an extended period of time to empirically quantify energy consumption patterns in specific rooms. Specifics about the sensor setup procedure and use of the recorded data are described in the Sensor Procedure section.

After data from the site have been collected from utility bills, one or more site visits, and long-term sensors if applicable, the information is combined to form the LPM.

Any unknown information is filled in heuristically using best engineering judgment, typically regarding data points such as appliance wattage and use time for lights and appliances. The estimated values in LPM can be edited after creation to reflect new information. The annual consumption output of the LPM is then compared to the calculated electricity baseline from the utility bills, and an error value calculated. If the error value is too great, the LPM is edited using the correction factors described in the *LPM Initial Model* section of Chapter 6.

The information gathered is then collated and entered into eQUEST. The initial model relies on default values for many inputs, until the audit team collects the relevant information and updates the model. The consumption outputs of the eQUEST model are then compared to the calculated annual electricity baseline and seasonal gas consumption from the utility bills, and two error values calculated. If exact information for an input is unknown and cannot be gathered, correction factors can be applied to reduce error between the model outputs and consumption in the actual building. These correction factors are described in the *eQUEST Initial Model* sections of Chapter 6.

Continued rounds of model modification are pursued based on the error value between each model and the consumption recorded in the utility bills. Modifications can be based on conversations with occupants of the building, records abut the building, observations from additional building walkthroughs, and collected sensor data. When modifying models, the LPM is adjusted first, as its output should be used as an input for the eQUEST model. After the models have been revised to replicate the utility bills with sufficient accuracy, they are considered complete.

These complete models are of the building as it is as of the first walkthrough. The models can be modified to simulate the effect of implementing each potential ECM or recommendation. ECMs are identified after conversations with building occupants, visual inspection during the walkthrough, identification of excessive energy consumers from the LPM, and by specific requests from DMAVA. Once each ECM is modeled and the subsequent alteration in energy consumption quantified, a financial analysis can be created as shown in Table 4. Viable ECMs are recommended to DVAMA.

Sensor procedure. The sensors used in this study are HOBO ZW series wireless sensors and HOBO pendants. The wireless sensors record temperature and/or humidity data at pre-set intervals and transmit the data immediately to a central receiver via an internal network, which then transfers the data to an attached computer. The computer stores data from all sensors on the network. The HOBO pendants record temperature and light intensity at a specified interval and store the data internally. The data records from the pendants are downloaded to the computer after being collected from their locations around the armory.

The data collected by these sensors can be used to reveal occupation patterns in specific rooms and in the building at large. Light data can show occupancy of individual rooms, providing time of use for those rooms. Temperature and humidity data can show variations in these categories across the building, allowing average temperature setpoints to be calculated prior to entry in eQUEST. Below is the typical procedure used for the sensor network.

Pre-visit. Prior to use on-site, the sensors, data nodes, computer, and network connection should be tested. Each component of the wireless sensor network is tested individually prior to arrival on site, including verifying the operation of each component, checking the batteries, and performing a trial setup to ensure that the operator understands the setup procedure.

The floor plan of the building is examined and a preliminary layout for the sensors is proposed. The first step is to propose a preliminary location for the network base station. Since this is the most important component of the network, it requires a secure location in which the occupants are unlikely to disturb it. The next step is to map out proposed locations for the sensors and data nodes. Sensors should be placed in locations relevant to each type of sensor, such as a humidity sensor in a shower room. Data nodes and sensors are placed to cover the entire building with some redundancy, such that data has more than one path to travel to the base station. This is important, as the ability for data to reach the base station is paramount. Communication distance, as well as the tendency of different wall materials to shorten this distance, must be considered when placing sensors and nodes [52]. If communication between sensors is sufficient for this purpose, no data nodes are needed.

1st visit. During the walkthrough, the process of data collection is explained to the occupants, stressing that the sensors should not be disturbed, the occupants should continue with their usual routines, and that the sensors only collect information regarding temperature, humidity, and light intensity, not any audio or video. In addition to being true, this is to influence occupants to continue with their usual activities, as people tend to initially change their behaviors when they believe they are being observed [29], [34]. People tend to return to their usual behaviors over time, as observed by the reduced savings each week by Marchiori, et al. [29] and Jiang, et al. [34].

During a building walkthrough, the proposed sensor locations are examined for feasibility. First, the layout of the building is compared to the floor plan supplied to the auditor. If there are any discrepancies, a corrected version is obtained, either directly from the occupants or, if necessary, by drawing one by hand. While the floor plan does not have to precisely match the actual dimensions of the building, it should be accurate enough to be used as a reference document, to the best judgment of the person placing the sensors. Typical room use is noted by questioning occupants about room purpose, frequency of use, and typical occupancy when in use. If the actual use is different than had initially been assumed, the planned sensor placement should be updated to reflect this. Building occupants should be consulted regarding an appropriate location for the base station, as they are more familiar with the building than the audit team. This information is used to finalize the plan for the sensor placement, including the sensor network and the sensor pendants.

Once the final sensor layout has been chosen, the network can be set up, beginning with the base station. A desk or table near an outlet is chosen for placement of the receiver and laptop, and both are powered through the nearby outlet. The laptop is configured to stay on continuously for the anticipated duration of monitoring. The receiver is connected to the laptop, the appropriate software setup, and network setup started. HOBOware software has built-in network creation capabilities to create a private network for the sensors, independent of any other wireless network. This is a vital capability in National Guard Armories, as the sensor network is not permitted to interact with any internet service or wireless network managed by the National Guard.

Data nodes are placed by working outward from the base station. For each HOBO sensor node, the device is powered on and its network memory reset [53]. The device is powered down and then repowered to connect it to the current network, as per the connection instructions from the manufacturer. If a node is too far from another node already connected to the network, the node will be unable to connect to the network and must be relocated. Jang and Healy [52] detail data loss in a wireless transmission through various building materials at specific distances. To reduce data loss to an acceptable level, the unconnected node must be moved closer to a connected node or another node set up prior to reattempting to connect the aforementioned unconnected node to the network. Once the node is connected, it is plugged into an outlet and its batteries are inserted. The powered node is placed on a flat surface such as a desk, table, or filing cabinet or mounted to a wall using sticky-backed velcro strips. This cycle is completed until all nodes are placed and connected. Then the connection, signal strength, and battery life for each node are checked through the HOBOware interface. Any issues are addressed, and then the automatic network setup process is ended. Sensors are labeled appropriately and any potential issues regarding the network are addressed prior to leaving the site.

Pendant sensors are placed around the building concurrently with the networked nodes. The sensor pendants are launched from the HOBOware software on the base station laptop, programmed with a set interval for data collection. The sensors are placed flat on a surface such as a desk, table, or filing cabinet or mounted with a zip-tie to a vertical pipe.

After this point, the network is left to collect data as occupants go about their normal daily activities.

2nd visit. The next visit to collect the sensors should be approximately two weeks after the sensors started collecting data. Upon arrival to the site, the base station is checked to confirm data collection. A basic visual check of the collected data is performed to identify any missing points or obvious anomalies. Occupants are asked about routine activities and special happenings in the buildings during the period of data recording. Occupants are questioned to discover any significant events which might have created abnormalities in the collected data, such as the power going out, extra people in the building for any period of time, or a major setting change in the main HVAC system.

The network is terminated by disconnecting the sensors and nodes. Nodes are disconnected via a network memory reset, after which they are powered down. Mounted nodes are dismounted and all mounting materials removed from the location. Materials are packed into their appropriate containers.

Sorting and analysis of sensor data. The information collected during the site visit must now be analyzed. If sensor data were recorded, it should be analyzed prior to model creation. If sensor data were not collected, this section can be ignored. Once all the data is in a single file, it is sorted by type. Temperature data are gathered separately from humidity data, and both are kept separate from light intensity data. Each type of data is processed separately. The first step for each type of data is to graph it for the entire time duration.

Past this point, analysis is subjective. Similar processes are used for each deployment, but the exact process depends on what data is recorded, what the analyzer is looking for, and what happened in the building. In addition, an unusual event in the building or a request from NJ DMAVA for special attention to a particular aspect of the building alters the setup and analysis process. If something atypical happens in the building while the sensors are setup, it is usually apparent in the first overview of the collected data or reported by the occupants. In two sensor deployments, there were power outages. In the first, the backup batteries in the wireless sensor network did their job and allowed the network to continue recording until the power came back. The temperature records for this time allowed a view of the efficiency of the building envelope and boiler at that Armory. In the second, the power outage outlasted the batteries in the wireless sensor network, resulting in a loss of information after the computer shut down due to low battery. The sensors were in the building for fourteen days, but only nine days of data were recorded. The pendants continued recording data for the entire period, but their placement did not allow a complete picture of the building, so the data from the pendants after the computer shut down was eliminated from the data set as incomplete.

If a request is made for the audit team to pay special attention to something in the building, the sensor network is set up to record information that would assist in the requested analysis. Typically this means putting extra sensors in a part of the building or decreasing the time interval between samples for greater resolution. One armory was studied closely through multiple periods of data recording. In the second period of recording, special attention was given to the heating of the building. Temperature sensors were placed to have multiple temperature readings in the same room, especially near the overhead metal garage door on the drill floor. This can be seen in Figure 8, a map of sensor location during the January sensor setup. The drill floor is in the center of the building and the kitchen is the small room to the right of the drill floor in Figure 8. There were four temperature sensors in the drill floor and another three in the kitchen, which is open to the drill floor by a 3 foot by 8 foot door and a 10 foot by 4 foot serving counter.

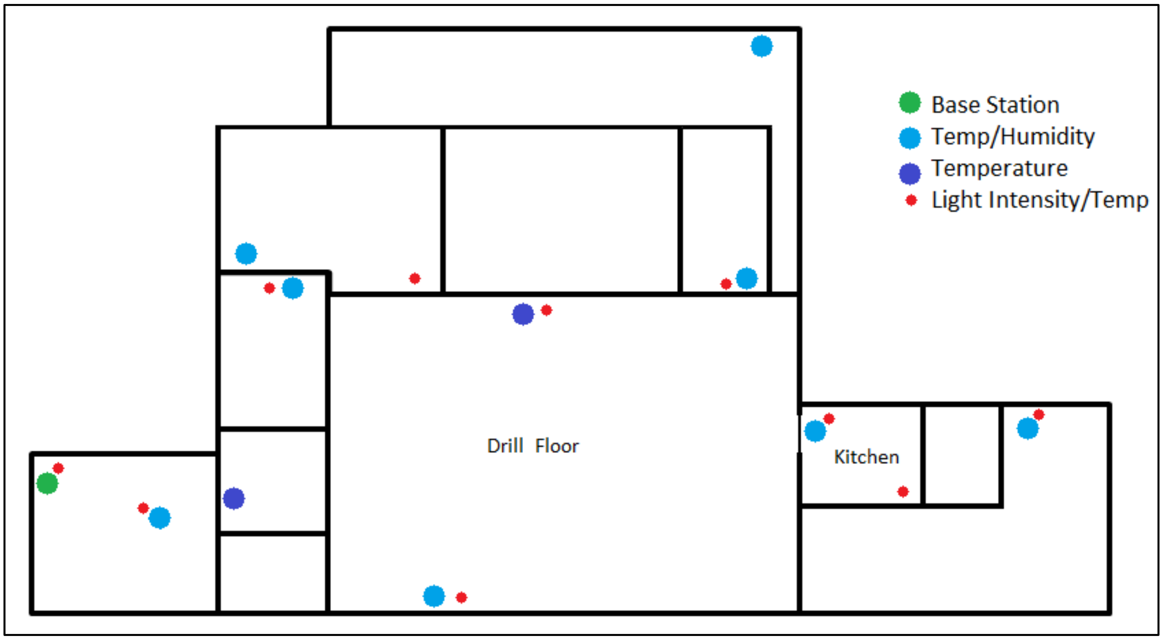


Figure 8. Sensor location during the January 2015 armory sensor setup.

Temperature data. Temperature data were processed first. All temperature data for the building were labeled by location and plotted for the entire time duration. Then additional plots were created for different purposes, each showing parts of the data. The first plots typically separated data records by location in the building, discriminating between occupied and unoccupied rooms. After this, sensor records are grouped by similarity of temperature changes. A common graph comprised of most of the data, minus two or three outlying temperature records. These outliers typically correspond to the boiler room or other unconditioned storage areas.

These divisions help the analyzer see patterns and identify possible causes for them. If most of the building follows the same temperature patterns to within a few degrees, the building is fairly well controlled. The outlying rooms typically have a good reason for not tracking with the rest of the building, such as the room being unconditioned or having an exterior door . The results of additional sensor deployments are described in Appendix C.

Humidity data. Humidity data, if recorded, were analyzed next. Analysis of this closely mirrors the process described above for temperature data. This is partially because of the relationship between temperature and relative humidity. Relative humidity is the ratio of moisture in the air to the maximum moisture that could be in the air at that temperature [54]. Warm air can hold more moisture than cold air, so the same amount of moisture in the air at two different temperatures will result in two different relative humidity readings. As such, the two tend to have similar patterns. Thus, exceptions are significant because something other than temperature had an effect on humidity. The two main causes in a National Guard armory are someone opening a window or using the showers in the locker room. The most prominent example of this is the shower use at the armory shown in Figure 8. Prior to taking a shower after exercising, one of the two officers there said he would turn the hot water in the locker room shower on full and walk away for five to ten minutes. When questioned, he said this was because that was the time it took for the shower to output warm water. His showers are visible in the data as humidity spikes in the locker room and can be seen in Figure 9. The humidity increases in the exercise room corresponding to the spikes in the locker room are the result of an open door between the men's locker room and the exercise room.

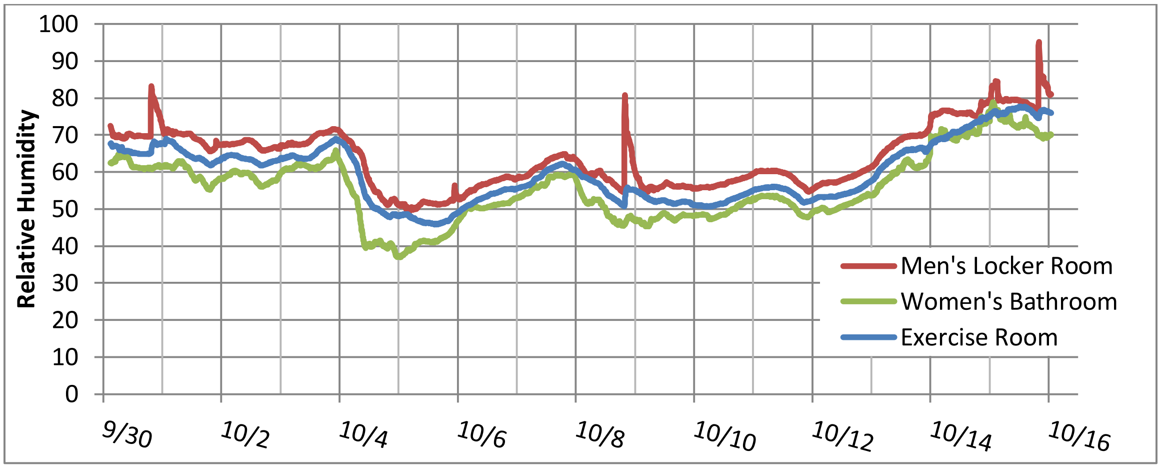


Figure 9. Relative humidity in three rooms during the October armory sensor setup.

Light data. Light data were analyzed last. The first step, as with the other types of data, is graphing all light data. The next step is to separate the high intensity readings from the lower intensity readings. The high intensity readings typically peak at almost an order of magnitude greater than the lower readings. The lower readings peaked at several hundred lumens per square foot. The higher intensity data is examined briefly for events other than the daily spike corresponding to daylight before further examination of the lower intensity data. The lower intensity data is sorted in several ways, but primarily by location in the building. If two pendant sensors were placed in the same room, light intensity levels from both are compared. Rooms with similar occupancy patterns, as reported by the occupants, are grouped and examined for patterns. Offices, regardless of their reported occupancy, are looked at to determine time of occupancy. Other rooms, such as the drill floor or storage, are examined to verify the frequency with which these rooms are used. The amount of time the lights are on during the recorded period is used to approximate the typical time of use for a year, allowing greater accuracy in the LPM.

Additional Data Collection

If there are discrepancies between the model and reality, additional data are required to reduce this discrepancy to an arbitrarily acceptable value. For these audits, the arbitrary error value is 20%. Additional conversations are held after the first walkthrough, either by a phone interview or when the audit team is in the building again. Additional data are collected through an additional walkthrough of the building, additional conversations with people familiar with the building about occupancy patterns, equipment details, and equipment schedules, and the use of sensors to record data over time. These data can be incorporated into the model either directly or through correction factors, as described in Chapter 6. The second walkthrough is similar to the first, except the audit team is looking for answers to specific questions about lights, plug loads, and occupancy in each room. Requests for additional information typically fall into one of the following categories:

1) occupancy patterns, for both specific rooms and the whole building;
2) HVAC system details, mostly about seasonal equipment such as window AC units or space heaters;
3) drill weekend information, including number of people present and additional room use;
4) outliers in utility data, such as months with especially high or low consumption that does not have a clear justification from weather or temperature;

5) general requests for unusual or rare events that occurred within the previous calendar year.

This information helps to improve the initial models, and in combination with the correction factors described in Chapter 6, is usually adequate to decrease model error to below 20%. Appendix D shows several examples of how inputs can be refined after the initial model. Student audits usually do not need the additional information provided by sensor data collection. However, if greater accuracy is desired, sensors are set up in the building to collect data over a period of time, typically two weeks, though the time period of collection in this study ranged from nine to forty days.

Energy Conservation Measures

Once the models are sufficiently accurate, they can be used to evaluate the impact of potential ECMs on energy consumption. Multiple ECMs are proposed and tested by modeling each proposed scenario. This entails the creation of a model for each proposed ECM. For the LPM, this means duplicating the information in Excel and altering the copied version. In eQUEST, this means using the EEM Wizard to modify the base model in a series of parametric runs. Because the base model is acceptably accurate, the results of the altered model are also assumed to be acceptably accurate. The process of model alteration for this purpose is described in more detail in the following chapter. The difference in energy consumption between the altered model and the model of the building as it currently is shows the energy savings associated with implementing that ECM. The ECMs commonly examined for National Guard Armories in New Jersey are briefly described here. They are described in more detail in the *LPM Energy*

Conservation Measures section and *eQUEST Energy Conservation Measures* sections in Chapter 6.

The LPM can be modified to model several potential ECMs. The first is lightbulb replacement, such as replacing T8 and T12 linear fluorescent light bulbs with linear LED bulbs. Another is fixture replacements, such as replacing high pressure sodium bulbs on the drill floor with LED fixtures. Another is appliance replacement, such as replacing old appliances with more efficient appliances. The fourth is the installation of occupancy sensors, which should reduce the time that lights in a room spend on. Specifics of modeling these are described in the *LPM Energy Conservation Measures* section of Chapter 6.

The EEM Wizard in eQUEST model can be used to model several other ECMs. The first is reduced infiltration, achieved by fixing broken windows, sealing visible gaps, closing doors that are often propped open, and applying weather stripping to windows and doors. The second is the installation of programmable thermostats and application of temperature setbacks during unoccupied hours. The third is HVAC repair or replacement, applicable only in select buildings. The process of modeling this is similar to modeling temperature setbacks. Specifics about how to model these are described in the *eQUEST Energy Conservation Measures* section of Chapter 6.

There are a few potential recommendations that cannot be modeled through modification of the existing models, as they do not rely on information from the models. As such, they are not described in Chapter 6. These Renewable Energy Measures (REMs) can be sized from information contained in the utility bills. A solar photovoltaic system can be sized using NREL's online PVWatts Calculator [55]. Typically, the system is sized to match the size of the roof or 90% of the annual electricity consumption of the building, whichever is smaller. The New Jersey National Guard is not allowed to sell excess electricity back to the grid at any point in time, so each armory must consume all the energy produced at that location. A geothermal installation can be roughly sized using engineering judgement based on the heating needs of the building, as determined by the annual natural gas or fuel oil consumption visible in the utility bills. This recommendation is not meant as a formal design, but as an approximation to determine whether it is worth hiring a consultant to properly design a geothermal system.

Results and Reporting

Once the energy savings from each ECM and the energy generation from each REM has been quantified, the results can be recorded and described. Research about installation, maintenance, and lifetime should be done for each proposed measure. The research and energy savings should be described completely in paragraph form and a financial analysis performed. The financial analysis provided to DMAVA and the New Jersey National Guard takes the form of Table 4. Not all examined measures are reasonable to recommend. DMAVA will not implement a recommendation that costs more to install than it will save over its lifetime. This is visible in the financial summary table as a savings to investment ratio less than one and as a payback period longer than the lifetime of the measure. In addition, engineering judgement must be applied before recommending a measure. However, if an ECM was examined and found to be an imprudent investment, this should still be included in the report with the caveat that this measure should not be implemented. This is especially useful for measures that DMAVA typically implements if they are good investments, such as the installation of solar panels.

Chapter 6

Correction Factors

The previous chapter discusses the overall audit process, including model creation and what the results of the models are used for. However, there remain challenges about the modeling process, specifically in reference to the verification and validation of models. Differences between the model and reality can be quantified as the error between the predicted energy consumption obtained from model outputs and the energy consumption reported in the utility bills for the building. This chapter addresses how the accuracy of a model can be improved upon, once the error between the model and reality is known.

Chapter 4 outlines the discrepancies between New Jersey National Guard Armories and the modeling capabilities in eQUEST. Correction factors are introduced and incorporated into the models to minimize the effect of these discrepancies on the accuracy of each model. Some correction factors are applied when modeling the building as it currently is; others are applied when modeling proposed changes to the building or building operation. Correction factors for modeling the present condition of a building are considered separately from correction factors for modeling a proposed Energy Conservation Measure (ECM).

The order of implementation can be important, as model inputs are not isolated. Most inputs can be implemented concurrently, but several inputs with a relatively major impact on the model results should be implemented individually on subsequent model runs. For example, addressing air infiltration problems at windows will reduce the effect of thermostat setbacks. Major inputs in the LPM include significant consumers such as printers, refrigerators, freezers; and groups of metal halide lights, such as those typically found on the drill floor. Major inputs in eQUEST include infiltration and temperature setpoints. Major inputs for both the LPM and eQUEST were identified through engineering judgement gained from modeling multiple buildings. These inputs are implemented one at a time, allowing the impact of that correction factor to be viewed when the model is run. If the correction factor has an undesired effect on the model, it can be removed and that correction factor neglected.

There are several sources of data that are available to provide insight toward the development of correction factors. The two main sources are the utility bills and sensor data, if collected. Differences between model output and the utility bills can give clues about the specific differences between the model and the actual building. The LPM is compared to baseline electricity consumption and eQUEST outputs are compared to baseline electricity consumption and seasonal gas consumption. If the model predicts electricity consumption that is slightly low and gas consumption that is significantly low compared to the bills, the building likely has greater infiltration than previously assumed. If gas is within the acceptable range but electric is not, the model for the building envelope is likely acceptable and the model for internal electricity loads needs to be adjusted. The best indication of the direction and magnitude of necessary model adjustment is the percent error between the model outputs and the actual utility bills. Separate error percentages are calculated for each fuel source and should be used to direct model alterations. Correction factors relating to the fuel source with the greatest error percentage are implemented first. If the percent error for either source is greater than

50%, the model should be recreated after confirming all inputs. Additional data collection may be required to confirm input information.

Some error in the model is unavoidable due to the use of the approximations and assumptions required in the modeling process. Thus, the end goal in modeling is to minimize error between the models and reality to a level that allows reasonable cost benefit analyses of proposed ECMs. For the audits performed by Rowan University Engineering students for the New Jersey National Guard, less than a 20% error has been deemed acceptable. Specifically, 1) the baseline electric consumption predicted by the LPM should have less than a 20% error compared to the baseline electric consumption from the actual bills; 2) the gas consumption predicted by the eQUEST model should have less than a 20% error compared to the seasonal gas use; and 3) the electric consumption predicted by the eQUEST model should have less than a 20% error compared to the baseline electric from the actual bills. It is important to consider baseline electric consumption predicted by both the LPM and the eQUEST models, as they approach the prediction in two different ways. The LPM utilizes an accounting of device-specific consumption while eQUEST calculates building electricity consumption from energy intensity values for each room type, as entered by the user. eQUEST does not

Once the goal of acceptable error is met, the models can be used as bases for calculating cost benefit analyses for proposed ECM's. In addition, once the LPM is sufficiently accurate, it can be used as a source of data for the initial eQUEST model. Thus, correction factors for the Light and Plug load Model (LPM) are discussed first and correction factors for the eQUEST model discussed second. The process of altering a base model for the purpose of evaluating an ECM is described following the description of the process of correcting the initial base model.

Correction Factors for Light and Plug load Model

The LPM must be accurate enough prior to being used as a tool to calculate electricity savings for specific energy conservation measures or as a source of correction for the eQUEST model. The goal is for the LPM to have less than 20% error from the baseline electric consumption. If the LPM is outside the acceptable range of accuracy, correction is necessary. This model is fairly straightforward, so there are few correction factors needed. The accuracy of this model must be calculated prior to the implementation of any corrections. This allows a clear view of the magnitude of correction needed, as well as allows the impact of that correction factor to be viewed clearly.

LPM initial model. If the baseline electric consumption predicted by the LPM is higher than the baseline electric consumption from the utility bills, the time of operation for lights and appliances should be reevaluated for overestimations and these overestimations reduced. If the baseline electric consumption predicted by the LPM is lower than the electric consumption from the actual bills, the model should be evaluated to ensure that no significant users have been omitted, and the time of operation for lights and appliances should be reevaluated for underestimations and increased if necessary. The magnitude of the error provides a guide for how much the time of operation would need to be changed to make the model predictions agree with the actual bills. Engineering judgement should be used throughout this process. If error is larger than 50%, the model should be recreated after additional information is collected. This information can be obtained by contacting someone at the armory with specific questions about time of use or performing a second walkthrough of the building.

In the LPM, the inputs that can be corrected are time of operation and power consumption in Watts. The other inputs, including device type and number of devices in a room, should not be changed unless specific errors are identified. During the creation of the initial LPM, values for operation time and exact consumption were likely chosen from a range of possible values. Because of this, the first correction is to adjust values within these ranges. Consumption should be adjusted and verified before time of use because consumption values are easier to check than time of use for most lights and many appliances. There are several notable exceptions to this, including light bulbs that cannot be clearly identified, refrigerators, printers, and other large appliances with multiple operation states. Computers have multiple operation states, but their use in New Jersey National Guard Armories can be simplified as always in the fully powered state. This is due to the requirement that all computers must be left on overnight, as stated by almost every officer interviewed about computer time of use by an audit team during the last two years.

Once the consumption numbers are checked, time of use is adjusted within the initial range. For example, in an office shared by multiple occupants, lights could be powered from eight to ten hours per weekday, depending on the specific schedule of each occupant in that office. The initial value would be set at nine hours per weekday, based on the assumption that both officers work almost the same schedule and leave the lights on when they leave for lunch. If the model is an underestimation from the bills, the time of operation for the lights in that office should be increased to ten hours per weekday. If the model is an overestimation of the bills, the time of operation should be decreased.

A more accurate method to confirm hours of operation for lights and some plug loads is by recording light intensity with sensors. In the light intensity data, distinct light levels are usually visible over several days. Change from one level to another indicates a change in the number of powered lights. The time at which lights are turned on and off each day can be seen by visually inspecting the light intensity data. Assuming occupancy during the period of data recording is typical for the whole year, operation time shown by the light intensity data can be used to set operation time for the year. An additional assumption, allowing a wider application of this data, is that appliances other than computers in the offices share the same operation hours as the lights. This allows operation times to be set for many of the appliances in the building.

Once the light and most consumers are adjusted, model error should be recalculated. Using this new error percentage, consumers with multiple operating states should be adjusted if necessary. These consumers include printers, refrigerators, freezers, and copiers. These devices can be adjusted by adjusting consumption values for each operating state or hours in each operation state. Newer refrigerators and freezers tend to have a lower duty cycle because of improved design and lack of aging.

LPM energy conservation measures. There are several Energy Conservation Measures that can be examined by altering the LPM. Some entail replacing consumers; others entail reducing hours of operation. For lights, bulbs can be replaced, fixtures can be replaced, bulbs can be removed from fixtures, or operation time reduced through use of occupancy sensors. For plug loads, power strips can be used to eliminate consumption when the building is unoccupied or appliances can be replaced with more efficient equivalents.

Lights. Light bulb replacement is modeled by replacing the wattage of the current bulb with the wattage of the proposed new bulb in the LPM. This preserves the current hours of use in the model, with the assumption that occupant will not change their light use with the installation of new bulbs. Light fixture replacement is modeled similarly, by replacing the consumption from a type of fixture with the consumption of the proposed new fixture. This assumes that fixtures will be replaced on a one-for-one basis. If this is not true, the fixtures being replaced should be removed and the new number of fixtures added to the model, preserving the hours of operation from the current fixtures to the new fixtures.

Delamping is selectively reducing the number of bulbs per fixture. Modeling this requires the use of engineering judgement. Light intensity measurements should be taken in each room, allowing a comparison between the light level in a room and the recommended light level for that type of room. Table 7 summarizes the US General Services Administration's recommended light levels for area types commonly found in New Jersey National Guard Armories [56]. If the light levels in a room are significantly higher than the recommended level, the room is a candidate for delamping. Calculations should be performed to determine the number of bulbs per fixture that should be removed to reduce the light level in the room to the recommended level. After the new number of bulbs per fixture is calculated for each candidate room, the LPM should be updated. Energy savings are equal to the electricity consumption of the removed bulbs, or the difference between the updated LPM and the base LPM.

Table 7

Recommended Average Interior Illumination Levels from GSA.gov [56]

Area Type	Nominal Illumination Level (Lux)
Normal work station (office)	500
Conference room	300
Internal corridors	200
Entrance lobbies, Atrium	150-200
Stairwell	200
Bathrooms (toilets)	200
Locker room	200
Mechanical, electrical room	200
Dining area	150-200
Kitchen	500

The installation of occupancy sensors is another ECM that requires engineering judgement. Candidate rooms include rooms that are used most weekdays but not constantly, such as conference rooms and bathrooms. The use of occupancy sensors is modeled by reducing the hours of use for lights in the candidate rooms. If occupants report that they try to turn off lights when they leave a room, installing occupancy sensors is unlikely to produce significant savings.

Plug loads. Consumption from appliances can be reduced by replacing significant energy consumers with new or Energy Star appliances. Newer appliances are designed to consume less power than their older counterparts. Energy Star appliances are more efficient than newer appliances. Research should be done to determine the best replacement for an appliance and the associated consumption for the replacement. The replacement is modeled by replacing the consumption of the current appliance with the consumption of the potential replacement.

Power strips can be used to reduce unnecessary overnight consumption, commonly called phantom draw. This is modeled by initially including standby consumption and removing it for this model. Devices with standby modes include TVs, computer displays, power adaptors, speakers, music players, microwaves, and coffee makers. Each devices consumes only a few watts in its standby mode [57], but the time spent in this state magnifies this consumption to a significant level. Devices used actively during working hours will spend approximately 6680 hours in standby mode. Devices that consume 2 W in their standby mode will consume 13.4 kWh each year. At $0.12 per kWh, this costs $1.61 per year per device. This is relatively low compared to the total annual electric consumption, but the initial cost is also typically low. If three devices are plugged into the same power strip and the strip is turned off every night and weekend, the savings should pay for the cost of the power strip in about four years.

Correction Factors for eQUEST

Once the base LPM is deemed accurate enough based on error percentage, the base eQUEST model should be corrected. The primary goal is for the eQUEST model to have less than 20% error from the annual gas consumption. A secondary goal is for the eQUEST model to have less than 20% error from electricity consumption. This is secondary because the LPM also models electricity. Modeling electricity consumption twice in this manner does not create redundancy, as each model contains different information. The LPM contains device-specific consumption that eQUEST does not. Instead, the eQUEST model calculates building electricity consumption from energy intensity values for each room type, as entered by the user.

If either gas or electricity consumption is outside the acceptable accuracy range, correction factors are necessary. Because eQUEST simulates the entire building to predict energy consumption, many of the correction factors do not deal directly with either gas or electricity consumption. These inputs should be corrected first. There is one input that directly affects electricity consumption and two inputs that directly affect gas consumption. These three inputs should be corrected after the rest of the model has been examined and building correction factors applied. Correction factors for inputs directly effecting gas and electricity consumption are described after the building correction factors.

For some correction factors, additional data are required. Additional data can be collected in one of three ways. The first provides qualitative information without needing to arrange another trip to the armory. Contacting an occupant of the building, typically the maintenance person, with questions about time of use, light bulb type, HVAC details, and building structure allows greater detail to be entered into the models. The occupant is typically questioned about things the audit team has a tendency to overlook on the first walkthrough. The contact at the building is usually able to provide clarification on most but not all questions the audit team asks them.

Quantifiable data collection can come from two sources, both of which involve another trip to the armory. The first is a second walkthrough, during which the team repeats the initial visit, checking anything they missed the first time and asking occupants more directed questions. The second is data collection over time using sensors. Data collection and basic analysis of data collected by sensors are discussed in the previous chapter. In summary, temperature, light intensity, and humidity data are collected by sensors left in the building for a week or two. Analysis of these data points identifies patterns, which can be used to categorize behavior in several categories. These categories include occupancy time in specific rooms and actual building temperature. From the patterns, one can infer regular energy consumption habits of armory personnel which can then be added to the models.

eQUEST initial model - building details. There are nine correction factors used to adjust the eQUEST model so the results are more accurate to the reality of New Jersey National Guard Armories. Each correction factor corresponds to a specific eQUEST input in the Schematic Design Wizard. The building correction factors are listed here in the order the associated inputs are requested by the Wizard. After the nine building correction factors are described, the three correction factors directly impacting gas and electricity consumption are described. For a particular armory, not all correction factors will be used. The use of each should be evaluated on a case-by-case basis after considering the relevance of each factor to the armory. The developers of eQUEST describe building performance modeling as an art and that their program mitigates the need for a modeler to be experienced in this art [41]. However, there is still an element of art in building energy modeling, which is why engineering judgements must be used in the creation and application of correction factors.

HVAC system type. One of the inputs on the first screen of the SD Wizard is the HVAC system type. This sets default values for the HVAC system definitions on screen 19 [58], where more detail about the system or systems can be entered. All armories are heated by a central furnace that heats water to be pumped through a system of radiators. In eQUEST, the heating source should be entered as “hot water coils”. For armories cooled by unit air conditioners, the cooling source should be entered as “none”. This includes most armories in New Jersey. In the author's experience, trying to model unit air conditionings in eQUEST tends to result in mismatched parameters, which cause fatal errors when the model is compiled prior to simulation. These errors prevent the model from running, even if inputs are returned to their previous values or states, forcing the modeler to completely recreate the model in a new file.

Story height. In eQUEST, it is assumed that the building being modeled has the same layout for all floors. As stated on page 22 of the eQUEST tutorial provided by J.J. Hirch in 2003 [59]: "Currently, the selected footprint shape applies to all floors in the project." In addition, there is a single input for floor height. For armories with a drill floor, these assumptions lead to discrepancies between the model and the actual building, as the drill floor ceiling is a different height than the ceiling for the rest of the building. For single story armories, the drill floor is taller than the rest of the building. For armories with more than one story, the next correction factor is more applicable, as there are other factors on the same screen that must be addressed, such as story height, footprint size, and number of stories.

There are two potential ways to handle this discrepancy in single story armories. The first is to model the entire building at the lower height. This requires reducing the height of the garage doors to fit in the shorter wall space. This makes sense, as most of the armory has the lower ceiling height and changing the volume of the unconditioned drill floor should not change the demand for conditioned air. To keep the same area of door, the garage door can be widened. The second is to model the entire building at the taller height. The garage doors stay the same height. The windows are not affected significantly because they are entered as a percentage of wall area. The first method is more accurate to reality. However, the second method is typically used for New Jersey National Guard Armories to artificially increase modeled gas consumption, which is typically underestimated beyond the acceptable range.

Building layout and size. As stated previously, the footprint of the building entered on Screen 3 is for every floor of the building [59]. This does not match the reality of most armories with multiple stories, because of the height of the drill floor. To model these multi-story armories in eQUEST, a modified building footprint is input. In most cases, this is the average area of each story, calculated as the total building area divided by the number of stories. The overall building shape is retained, though smaller outcroppings that only exist on one story, such as entryways, are often removed.

The impact of averaging the floor sizes was examined. The total exterior area is reduced as the modeled building is made more compact than the actual building. This results in two categories of things that need attention. The first is the window to wall ratio, used to determine the total area of windows on a later screen. Since the team measures the windows, calculates window area, and then calculates the percentage of window area to wall area from the totals, the team only needs to substitute the model wall area in for the actual wall area in this calculation. The second category is the amount of heat transfer through the building envelope. The more compact modeled building has less surface area for solar radiation to impact, resulting in less heat gain throughout the year. The reduced exterior surface area of the modeled building also results in lower winter heat loss. In the winter, assuming the reduction in solar heat gain and the increase in heat retention are equivalent allows their individual effects to be neglected. In the summer, the reduction in solar heat gain decreases the amount of energy needed to cool the building. However, since cooling is typically performed on a per-room basis and thus is not included in the eQUEST model, this is a minor source of error between the real building and the modeled building. Overall, this means that the modeled building should accurately predict heating demand in the winter. If cooling is included in the eQUEST model, the cooling demand predicted by eQUEST will be an underestimation in the summer months.

An example of altering floor layout is described here. The armory shown in Figure 10 has three distinct floor layouts for its four stories. This armory is fairly unique in its age and layout. Its drill floor is smaller than most, sharing the same ceiling height as the rest of the building. The first story, at the top of Figure 10, is the largest. The vehicle garage is partially shown on the left side of the first story floor plan. The second and third stories, each about one fifth the size of the first story, share the same layout and exist above the center section of the first story. The third story floorplan is not shown because it is essentially identical to the second story. The basement, two thirds the size of the second story, exists under the right wing of the first story.

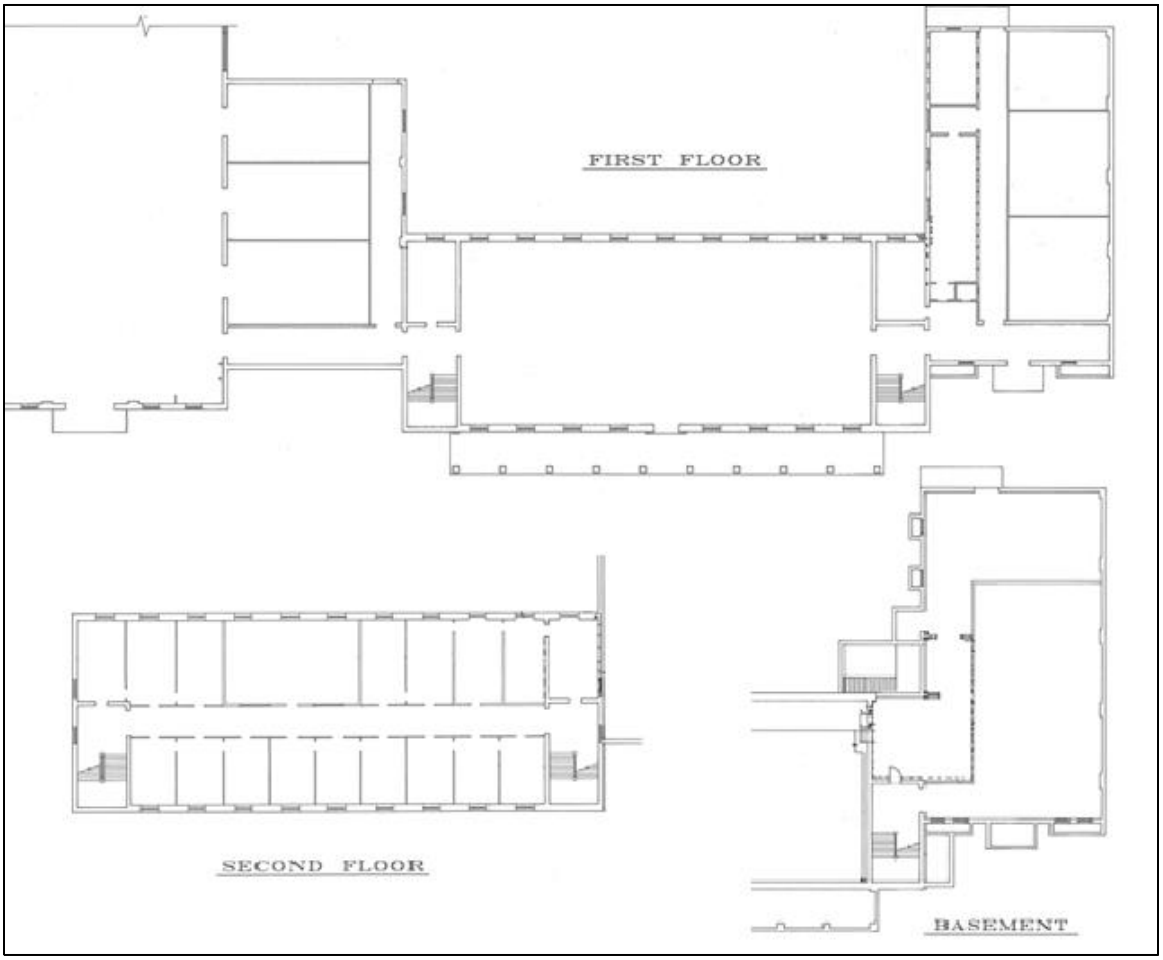
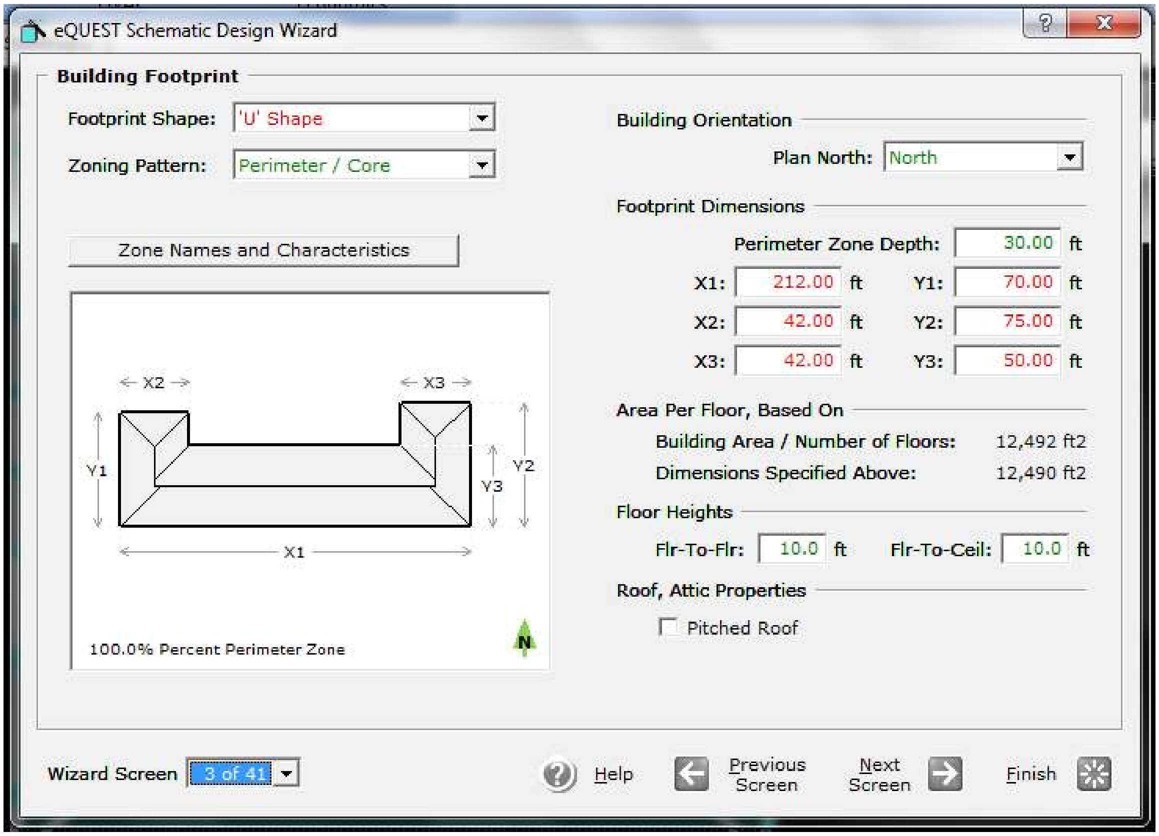


Figure 10. Floor plan of a four story armory.

In eQUEST, this building was entered as a four story U-shaped building with one story underground. This preserves heat transfer occurring through the walls of the wings and the heat transfer characteristics of the basement. The left wing of the first story was reduced by eliminating the area of the garage space at the far left of the building. This garage space is equal to half the area of the first floor. It was retained in the area allocation as unconditioned storage space. In addition, the right wing was shortened to match the left wing and both wings were brought forward to align with the front of the building. This created the overall U-shaped footprint seen in Figure 11.



eQUEST Schematic Design Wizard

Building Footprint

Footprint Shape: 'U' Shape

Zoning Pattern: Perimeter / Core

Building Orientation

Plan North: North

Footprint Dimensions

Perimeter Zone Depth: 30.00 ft

X1: 212.00 ft Y1: 70.00 ft

X2: 42.00 ft Y2: 75.00 ft

X3: 42.00 ft Y3: 50.00 ft

Area Per Floor, Based On

Building Area / Number of Floors:	12,492 ft2
Dimensions Specified Above:	12,490 ft2

Floor Heights

Flr-To-Flr: 10.0 ft Flr-To-Ceil: 10.0 ft

Roof, Attic Properties

☐ Pitched Roof

100.0% Percent Perimeter Zone

Wizard Screen 3 of 41

Figure 11. Screenshot of eQUEST representation of the same four story armory.

Compared to reality, the basement is not well-represented, the area of the second and third stories are approximately doubled, and the first floor is significantly altered. However, it retains the presumed important characteristics of the building: the wings of building, the existence of the basement, and the overall area and volume of the building. This is evidenced by the relatively low error numbers when comparing the model to the utility bills. Electricity consumption in the model is a 2.4% underestimation of the bills and gas consumption is a 10.5% underestimation of the bills. The gas consumption error is assumed to be mainly due to the oversized furnace in the building, based on conversations with the armorer.

Building envelope construction and materials. Building construction details are entered on Screen 4 in eQUEST [60]. For an armory, these are assumed based on visual inspection, as the available design documents do not contain this information. If design or construction documents containing this information exist, the audit team is not authorized to see them. As such, past audit teams have been directed to input building envelope details as they see them, working under the assumption that no additional materials, such as insulation between interior and exterior surfaces, exist. Proof of this would be difficult to obtain, other than destructive testing. This assumption has resulted in what is assumed to be minimal error, as there are other sources of error when large error occurs between the predicted consumption and the actual reported consumption.

Door details. Only three door categories can be entered on Screen 6 in eQUEST [61]. Once the size and material of each door category are entered, the number of door categories on each building face can be entered. This is a straightforward process and rarely needs correction. Correction factors are needed if a door is not aligned with the exterior wall or if there are more than three types of doors. If a door does not share the same orientation as the wall around it, as seen in Figure 12, the orientation of that door in the model should be altered to match the wall around it. Figure 12 shows an exterior door facing west, when the walls around it are facing north. The orientation of this door should be counted as north, allowing the shape of the building to be simplified by aligning the two walls. The rotation of the modeled door's orientation does have an effect on the heat transfer through the door, by changing the amount of solar radiation reaching the door, but this effect is negligible compared to effect of excluding the existence of the door. This method also applies to a door in an alcove. The alcove should be eliminated and the orientation of the door should be altered to match the orientation of the exterior walls around it.

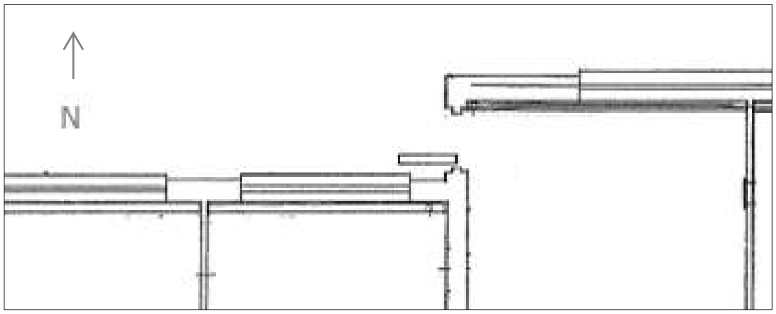


Figure 12. External door misaligned with exterior walls.

If there are more than three types of doors, door types must be combined into a shared category. The combining process can be avoided by a careful application of door counting. Single and double doors sharing the same construction can be combined in the same category, as long as each door is counted. A pair of double doors would count as two single doors. Thus, two individual doors and a pair of double doors would count as four individual doors. Infiltration is already accounted for using this method of combination. If the gap between a pair of double doors is assumed to be twice the size of the gap around a single door, then there is no difference in infiltration between a pair of double doors and two individual doors.

Window details. Windows are entered in the same way as doors, except windows are entered as percentage of total wall area for each orientation. Windows are entered in eQUEST on Screen 7 [61]. Because of the similarities, the door correction factors can be applied to windows. The largest difference is the method of combining windows, as doors come in a few standard sizes and windows have a greater variety in size. Since windows are typically multiple panes, entering the pane size as window size in eQUEST and entering the total number of panes in the real building as the number of windows in eQUEST is a valid option to match total window area between the model and the real building. This works if there are only a few pane sizes across the whole building.

If there are only a few windows that differ from the majority of windows in the building, the area of those few windows can be added into another category of windows, with the understanding that it will introduce some error into the model. Alternatively, if window size for a window category is not specified, eQUEST assumes the glass for that window category stretches the width of the building face. If this method is used, infiltration must be adjusted to account for the lack of perimeter. The process of adjusting infiltration is described as one of the eQUEST correction factors that directly affect gas consumption.

Area types, details about each area type. Details about building occupancy are entered on Screens 13, 14, and 16, starting by dividing the building into area types [62]. Once the area types and the corresponding percentage of building area they occupy are identified on Screen 13, details about each area type are entered on Screen 14. Details about consumption during unoccupied periods is entered on Screen 16. In eQUEST, up to eight area types can be entered. If there are less than eight types of rooms, as is true for many smaller armories, this correction is unnecessary. For larger, more complex armories, multiple types of rooms must be combined in a single area type.

It is good practice to combine similar types of rooms, such as offices and shared meeting spaces, storage rooms and the drill floor, locker rooms and bathrooms, museums and conditioned storage, and computer labs and the server room. Not every building has every type of space, so the modeler must use their discretion and judgement in combining rooms into a single area type. Once the rooms are combined, several values must be set for each are type. These values include design occupancy, light loads per square foot, plug loads per square foot, and design ventilation. There are several methods that can be used to determine these combined values, all of which rely on the modeler's discretion and judgement. The first method is to use the default values for the room type that dominates the area type. The second method is to do a weighted average of the default value for each of the room types in the same area, based on the relative area of each room. The preferred method is generally the second method, except when one of the room types being combined is greater than 75% of the area being combined into that area type. Then the default values for the majority room should be used directly.

Schedule details. The overall schedule for the building is entered on Screen 17 [62]. In the Schematic Design Wizard, two schedules can be entered, a main and an alternate. The alternate schedule can be used for rooms that are used with a different frequency than the rest of the building, such as rooms used only part of the week. For each schedule, up to three day types can be assigned. Each day of the week plus a general holiday category are divided between the day types. Each day type is assigned values for opening time, closing time, occupancy percentage, light load percentage, and plug load percentage. The last three are percentages of the occupied design loads, entered on a previous screen. Typically, two day types are entered: week days and weekend days. This is a valid method if occupants work every weekday. If occupants work a compressed work schedule, where they work nine hour days Monday through Thursday and take every other Friday off, three day types should be used. The first day type reflects Monday through Thursday directly. The second day type reflects average Friday use, so the assigned values for occupancy and loads should be half the values of the first day type. The third day type reflects the weekends directly.

Drill events are not entered directly. In addition to the difficulty of inputting them into the SD Wizard, they are a relatively low contributor to total electricity consumption. As shown in Chapter 4, one drill weekend at an armory with eight regular weekday occupants is responsible for 6% of the monthly electricity consumption. While this calculation neglects the seasonal heating and cooling requirements, it shows that intentional neglect of drill event consumption falls within the range of range of acceptable error set for these models. However, drill events can be accounted for in the model by slight increases in light and plug load percentages. The exact percentage depends on the regular weekday occupancy and use of the armory. Drill events can be entered more directly into the DD Wizard, using multiple alternate seasons. Up to six seasons can be entered into the DD Wizard, so the first season can be for regular weekday use and the others for specific drill events. However, use of the DD Wizard changes the set of input screens and increases the set of required information. This makes the use of the DD Wizard undesirable.

eQUEST initial model - gas. Correction factors for gas consumption should be applied after all the building correction factors have been implemented. Infiltration is technically also a building correction factor as it deals with the building envelope. However, since it is desirable to observe the impact of infiltration separately from other correction factors, it is incorporated into the model subsequently from the other building corrections. Temperature setpoints are modeled subsequently from infiltration, to view the impact of this input separately from the other inputs and correction factors.

Infiltration. Infiltration is a measure of the amount of conditioned air escaping the building envelope. Leckie et al. describe two methods of calculating heat loss due to infiltration: air exchange and crack method [48]. Both methods develop an infiltration rate and then multiply that rate times the temperature difference between the interior and exterior of the building. The air exchange method calculates infiltration in terms of the number of times in an hour the air inside the building is replaced. This is impractical to measure, so an estimate must be made based on the condition of the building. Leckie offers a range of air exchange values for residential buildings. Nonresidential buildings such as armories are outside the scope of his work, so no value or range of values is offered. The crack method calculates infiltration in terms of the rate at which air leaks through cracks in the building envelope. Leckie duplicates a table of ASHRAE-specified values for infiltration through cracks of windows and doors, in units of ft^3/hr-ft. Using values from this table, heat loss due to infiltration can be calculated for the building. However, heat loss calculated using this method cannot be entered directly into eQUEST on Screen 4, as infiltration is entered in CFM/ft^2, volume of air escaping per area of gap over time [60].

A combination of these methods can be used to calculate the infiltration value in the unit eQUEST uses. According to Leckie's *Other Homes and Garbage*, a well-constructed house has an average gap size of 1/16th of an inch around every window and door [48]. An older or poorly constructed house has a larger average gap size, assumed to be 1/8th of an inch. Assuming that the armories have the same construction standards as residential buildings, the area of infiltration can be calculated and converted into the unit eQUEST uses. It is assumed that eQUEST calculates infiltration based on a gap size of 1/16th of an inch, as is reasonable for a new building. The armories, 90% of which were built prior to 1965, are assumed to have an average gap size of 1/8th of an inch. Using the default infiltration value provided in eQUEST, a ratio can be used to determine the infiltration value that corresponds to the building as it currently is. This ratio, seen in Equation 6.1, is the infiltration value in CFM/ft^2 over the calculated area of infiltration. The eQUEST infiltration value is the initial default value. The eQUEST gap area is calculated as the total perimeter of all doors and windows in the modeled building times 1/16th of an inch. These can be calculated from door and window size, entered on Screen 6 and 7 in eQUEST [61]. If the user entered typical window width as "0" on Screen 7, an additional step must be performed to calculate window perimeter. A typical window width of zero is interpreted by eQUEST as one long window across that face of the building, as stated on that screen in eQUEST. The user can observe the dimensions of each modeled door and window using the "Custom Window/Door Placement" option at the bottom of Screen 7 and use this information to calculate the total perimeter of all windows and doors in the model. The actual gap area is calculated as the perimeter of all the doors and windows times 1/8th inch plus the area of any other openings that are observed. These openings include open doors, open windows, and broken windows. The size of each opening or gap should be measured during the site visit.

$$\frac{Infiltration_{eQUEST}}{Gap\ Area_{eQUEST}} = \frac{Infiltration_{actual}}{Gap\ Area_{actual}} \tag{1}$$

The actual infiltration in CFM/ft^2 can be calculated from Equation 1. Rearranging the equation and substituting in the equation for each term, Equation 2 is obtained.

$$Infiltration_{actual} = Infiltration_{eQUEST} * \frac{Area_{actual} + Area_{open}}{Area_{eQUEST}} \tag{2}$$

This equation provides the actual infiltration value in CFM/ft^2, which can then be entered into eQUEST on screen 4. The use of this equation is described further in Appendix E. Once infiltration has been adjusted, the updated model should be simulated and the new error percentage calculated. If further adjustment is desired for gas consumption, the next correction factor should be incorporated into the model.

Temperature setpoints. Temperature setpoints have a significant impact on gas consumption in an armory. For this reason, the Army created a set of temperature guidelines for its buildings, described in the Army Facilities Management Report: Energy and Water Management. The National Guard follows many of the Army's facility guidelines, including these temperature guidelines. Section III, Chapter 22-12 b of the Army Facilities Management Report describes the specific setpoints [2]. For offices spaces, heating set points should be 72 ˚F± 2 ˚F during occupied times and 55 ˚F± 5 ˚F during unoccupied times. Warehouse spaces like the drill floor and storage rooms should be heated to 60 ˚F± 5 ˚F during occupied times and 45 ˚F± 5 ˚F during unoccupied times. If cooling is authorized, cooling set points in office spaces should be 74 ˚F± 2 ˚F during occupied times and 85 ˚F± 5 ˚F during unoccupied times. Cooling is not permitted in non-office areas. These temperature setpoints are summarized in Table 8.

Table 8

Army Regulation Temperature Setpoints [2]

	Occupied Temperature (˚F)	Unoccupied Temperature (˚F)
Office (Heating)	72 ± 2	55 ± 5
Office (Cooling)	74 ± 2	85 ± 5
Warehouse (Heating)	60 ± 5	45 ± 5

In most National Guard Armories visited by audit teams, these temperature setpoints were not in use. Actual thermostat setpoints varied by armory. When questioned, most occupants reported that the thermostat in their building was only set twice a year, when the central heating system was turned on and off. Cooling setpoints varied by room within each armory, as each individual window air conditioning unit could have a different temperature setpoint. As such, cooling is typically neglected from the model.

There are several factors that must be considered in the process of setting the model's temperature setpoints, entered on Screen 20 of eQUEST [63]. Thermostats throughout the building may have multiple settings. The audit team can only observe thermostat setpoints and building temperature for the season they visit the building, leaving building temperature during the other season unknown. If the team visits during the heating season, this is a minor issue as cooling is neglected from the eQUEST model. If the team visits during the cooling season, experimentation in eQUEST may reveal the actual setpoints. Occupants may attempt to conceal the typical setting, thinking they will face repercussions if the audit team observes and reports wasteful thermostat settings to their superiors. The inclination to conceal unfavorable information has been observed during a few armory walkthroughs. There may be issues with the heating system, known or unknown to the armorer. If there is a known issue with the heating system, attempted alterations to the temperature setpoints should be skipped. Instead, the modeling process for HVAC issues, described at the end of this section, should be followed.

With these factors in mind, several measures can be implemented to attempt to minimize the effect of these unknowns. For the current season, thermostat settings throughout the building can be averaged and that value input as the occupied setpoint in eQUEST. To verify temperature setpoints and see if temperature setbacks are used, temperature sensors can be deployed for a multi-day period to record temperature fluctuations. Ideally, sensors should be deployed for several weeks, as per Jiang, et al. [34], to allow occupants to become accustomed to the presence of the sensors and return to their usual habits. Data from these sensors will show daily temperature fluctuations and provide the modeler with information to decide on sensible temperature settings for that season. For both seasons, occupants can be questioned about setpoints and temperature in the building. If their responses match the current state of the building and/or thermostats, their responses about temperature setpoints during the unobserved season can be accepted as stated.

If the predicted gas consumption still has significant error with respect to the bills after reasonable temperature setpoints are entered, there are two alternatives to attempt. The first is to alter the model's temperature setpoints after verifying the infiltration value as described above. If the modeled gas consumption is low, the heating setpoints should be increased a few degrees Fahrenheit and the new model simulated. If the setpoints are forced outside a reasonable range to match modeled and actual gas consumption, the temperature setpoints should be returned to a reasonable value and the next alternative considered.

The second alternative for correcting an under-prediction of gas consumption is to consider the possibility of issues with the HVAC system. This is not uncommon in New Jersey Armories, as most systems are the same age as the building they heat, where 90% of the armories predate 1960. The first step is to review notes from previous site visits and to question the armorer about any previously unidentified issues that might be the cause of the unexplained gas consumption. Temperature sensor data should be examined for areas or rooms that are abnormally hot or cold. Identifying the source of these abnormality will allow inclusion of it in the model.

Once the abnormality or possible cause has been identified, careful modeling in eQUEST can be attempted. Before this process is started, the current post-infiltration model should be saved and set aside. This is to provide a point of comparison to evaluate energy savings resulting from the repair of the HVAC issue. In addition, continued editing in the same eQUEST file can create mismatched parameters which will produce fatal errors when that model is simulated. If this occurs, the model should be recreated in a new file name.

The process of modeling an armory with an HVAC issue is unique to each building. Instead of providing a step-by-step process, an example is described. In one armory audited, several rooms at one end of the building are significantly overheated in the winter. The thermostat in one room showed the actual temperature as 90 ˚F and the heating setpoint as 54 ˚F. This thermostat is shown in Figure 13. The temperature in the rest of the building was 75 ˚F. The issue is thought to be a broken control valve.

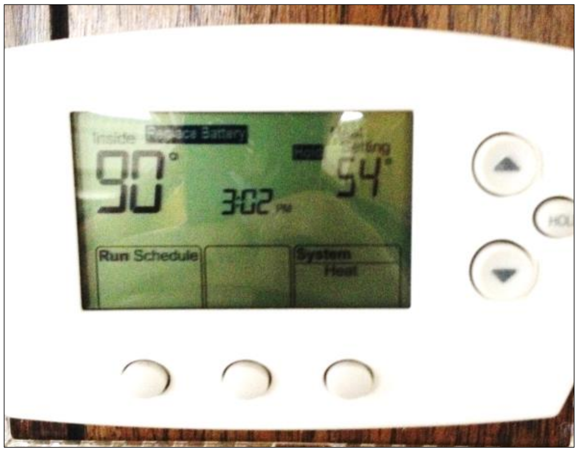


Figure 13. Armory thermostat showing actual temperature of 90 ˚F and heat setpoint of 54 ˚F.

The situation in this armory was modeled using a pair of complementary models. The first model predicted gas consumption for heating the whole building to 75 ˚F. The second model split the building into two HVAC zones on Screen 3: the overheated rooms and the rest of the building. In the second model, the heating setpoint for the zone containing the overheated rooms was set to 90 ˚F and the rest of the building was classified as an unconditioned zone. This was done to work around the limitation that the same temperature setpoints are applied to all conditioned zones. The predicted gas consumption from both models was summed. This pair of models still under-predicted actual gas consumption with 23% error, even after infiltration in the overheated zone was increased to reflect open windows. This was the closest the audit team could get their model without pushing inputs outside reasonable values, so the model was considered acceptably accurate. This is an atypical situation. Most of the time, a heating issue can be modeled directly by increasing infiltration or changing temperature setpoints. Once gas consumption is reasonably accurate, the final initial correction factor should be applied.

eQUEST initial model - electricity. This correction factor should be applied last, as it does not affect any other input. Electricity in eQUEST does not significantly affect gas consumption. In eQUEST, details about electricity loads are entered on Screens 14 and 16 [62]. Screen 14 is electric consumption during occupied periods from lights and plug loads in watts per square foot for each area type. Screen 16 is electric consumption during unoccupied periods as a percentage of occupied loads for each area type. The default values for both of these screens are taken from California Title24 Requirements based on the default building type entered on Screen 1 [62].

Electricity consumption per square foot for each area category can be calculated from the LPM, after the LPM is acceptably accurate. For each area category entered in eQUEST, wattage from the appliances in those rooms should be summed, then divided by the total area of those rooms. If there are appliances with multiple operating states, a weighted average should be calculated of wattage weighted by time. Once this correction factor is implemented, model error should be recalculated. At this point, the model should be within the acceptable error range. If it is not, inputs and correction factors should be rechecked and re-implemented if necessary.

eQUEST energy conservation measures. Once the base model is acceptably accurate, it can be used as the basis for examining the effects of implementing specific energy consumption measures. There are two methods to compare a potential ECM in eQUEST. The first is to create a separate model with a new file name. Most of the inputs will be identical to the base model, except for the inputs relating to the ECM being examined. The second method is to use the Energy Efficiency Measures (EEM) Wizard in eQUEST [64]. This built-in functionality allows quick alterations to the baseline model, without the need to reenter every input. In addition, the results viewer in eQUEST is set up to compare alternatives created using the EEM Wizard. This section is written with the assumption that the EEM Wizard will be used.

There are several ECMs, commonly recommended for New Jersey National Guard Armories, that can be modeled in eQUEST. These include infiltration reduction, installing programmable thermostats to implement the Army Regulated temperature setpoints and replacing single pane windows with double or triple pane windows. Other alterations to the building, either to the building envelope or building operations, can be modeled in eQUEST but are not described here.

Replacing functional single pane windows with thicker or multi-pane windows is typically a poor recommendation. Mahdy and Nikolopoulou examined the long-term cost effectiveness of various types of windows in Egypt [15]. One conclusion from their research is that single pane windows with a reflective coating resulted in lower energy consumption than non-reflective double pane windows. Complete window replacement was considered for an armory with excessive infiltration from broken windows and poorly mounted window air conditioning units. The calculations, including infiltration reduction, showed that the payback period was greater than 30 years. For better sealed armories, the payback period is even longer.

Infiltration reduction. Infiltration is air escaping through the building envelope. Infiltration reduction is achieved by replacing broken windows, closing visible gaps, resealing windows and installing weather stripping on doors. Common sources of gaps are broken windows, propped open doors, and gaps around the edges of window air conditioning mounts. Typically, these are inexpensive solutions. Modeling the effects of reduced infiltration is straightforward, using a slightly modified version of Equation 2. In Equation 3, the numerator is exactly the same as Equation 2. The denominator reflects the predicted change in area where infiltration can occur. The perimeter of actual doors and windows should be multiplied by a smaller average gap size. It is reasonable to assume the new gap size is 1/16th of an inch, reflecting better construction.

$$Infiltration_{actual} = Infiltration_{eQUEST} * \frac{\left(P_{eQUEST\_window} + P_{eQUEST\_door}\right) * \frac{1}{16}}{\left(P_{actual\_window} + P_{actual\_door}\right) * \frac{1}{16} + Area_{open}} \tag{3}$$

In the EEM Wizard, the model of reduced infiltration must be entered as a "Whole Building" measure category. Once the infiltration value on Screen 4 is changed to reflect the new value from Equation 6.3, the pair of models can be run and the results compared. The change in energy consumption is the energy savings resulting from the implementation of this measure.

Temperature setbacks. Temperature setbacks are altering thermostat settings to reduce the demand for conditioned air during unoccupied periods. This is performed by changing the thermostat setting closer to the outside temperature during unoccupied periods. In the heating season, this means lowering the temperature setpoint during nights and weekends. In cooling season, this means raising the temperature setpoint during nights and weekends. This process of decreasing the temperature difference between the building interior and exterior environment reduces the rate of heat transfer through the envelope of the building. The energy saved by this slower heat transfer is partially offset by the increase in energy needed to return the building interior to its daytime setting, but total energy consumption is reduced [65]. For residential buildings, the Department of Energy recommends an occupied heating setpoint of 68 ˚F in the winter, an occupied cooling setpoint of 78 ˚F in the summer, and changing the thermostat towards the outside temperature by 10 ˚F during unoccupied periods. Turning the thermostat down in the winter by 10 or 15 ˚F for eight hours while the occupants are at work can save 5 to 15% of the original annual heating bill [65]. For each degree Fahrenheit setback, there is about a 1% savings on the annual heating bill [65]. This shows the potential for savings if a similar thermostat setback program were implemented in National Guard Armories.

Since most armories do not follow the Army Regulated temperature setpoints shown in Table 8, its implementation may produce savings similar to the Department of Energy's residential recommendations. These setpoints are modeled by directly altering the temperature setpoints. In the EEM Wizard, the setpoints from Table 8 can be entered in the "HVAC System" measure category and the "Thermostat Management" measure type. This brings up a window showing the setpoints entered in the baseline model and input fields for new heating and cooling setpoints. Once the Army Regulated setpoints are entered in these input fields, the pair of models can be simulated and the results compared. The change in energy consumption is the energy savings resulting from the implementation of this measure.

In addition, Section III, Chapter 22-12 b (2) describes the use of portable heating and cooling devices, such as space heaters and window air conditioning units [2]. The use of these devices are typically neglected from the eQUEST model. If they are included, they are modeled as increased plug load. Detailed modeling of the use of space heaters is discussed in the next chapter.

Once these correction factors have been implemented, the results of potential ECMs should be written up in the format described in the *Results and Reporting* section of Chapter 5.

Chapter 7

Supplemental Model to Evaluate Space Heater Use

National Guard Armories present another unique challenge to audits when the unit stationed at that armory is deployed. Occupancy is further reduced from a low number of daily occupants and a larger number of occupants for a few days each month because these occupants are deployed to another location. In their place, a few officers from another unit are stationed at the otherwise-empty armory part time. This extended period of low occupancy presents an opportunity for energy savings that cannot be pursued in a fully occupied armory.

Armory While Under-Occupied

When a particular armory was audited, the unit stationed there had been deployed for several months and would be deployed for most of another year. The building was occupied two days each week by two officers from another unit, with no additional use. The two officers shared the same large office and worked the same days. They occasionally used other rooms in the building, such as the locker room and the exercise equipment in the club room. The rest of the armory, designed for 10 to 15 daily occupants, was used sparsely, if at all. There were no drill events in the armory during deployment. The temporary occupancy of this armory is estimated as less than 10% of the typical occupancy of the armory.

Baseline energy consumption was easy to model because of the low number of contributing devices and the lack of drill weekends. However, seasonal energy consumption was more difficult to model. For the summer, unit air conditioners had been installed and used in rooms with occupants. During the spring and fall, no formal temperature regulation methods were identified. It is assumed that consumption from HVAC is minimal during these seasons, so no attempt was made to identify or mitigate the consumption resulting from these methods. In the winter, the building is heated by a central boiler that pumps steam through radiators in each room. The setpoints for temperature in the building are dictated by the Army Facilities Management Report [2]. This report describes temperature setpoints for occupied and unoccupied spaces by category of use, such as office, maintenance bay, or warehouse. These setpoints can be seen in Table 8. Mechanical cooling is not always authorized, so a study of cooling was not performed.

The relatively large difference in temperature between occupied and unoccupied heating temperatures and the low occupancy indicates the possibility of an energy reduction strategy that would not be practical for a fully occupied armory. The details of this strategy are discussed below.

Energy Reduction Strategy: Space Heaters

The Army Facilities Management Report proposes an alternate heating and cooling option for under-utilized buildings. Section III, Chapter 22-12 b (2) of the Army Facilities Management Report, revised March 28, 2009, discusses the use of supplemental heating and cooling systems [2]. The relevant passage can be seen at the end of this chapter. These systems are allowed when cost effective energy reductions can be achieved through their use, in combination with reduced use of primary conditioning systems. Specifically mentioned is the situation described above: low occupancy concentrated in a small section of the building.

Central air conditioning is not installed in most New Jersey armories, so use of unit air conditioners in occupied rooms in the summer is standard practice. There is not much than can be done to reduce this use beyond alterations to occupant behaviors, which is beyond the scope of this study. However, two commonly suggested strategies for addressing occupant behavior are employee training and signs posted around the building reminding occupants about specific energy saving actions like turning off lights when leaving a room. However, space heaters are different from unit air conditioners in that space heater use can be modeled more easily. It can be difficult to accurately model electricity consumption from air conditioning units, due to the non-uniformity of unit efficiency. Space heaters are more simple to model because each unit can be approximated as having 100% efficiency in converting electric energy to heat.

Modeling approach. Modeling space heaters is not possible in eQUEST, even using correction factors. The program was created to model buildings in the design stage, and it is assumed that a building designer would size heating and cooling systems to handle all the conditioning needs for the building. Thus, the ability to model space heaters or unit air conditioners was not programed into eQUEST. Furthermore, there is no ability to model appliance use that is dependent on temperature or weather.

An alternative approach was needed to model the use of space heaters. One model was not sufficient, so several complementary models were created and used in conjunction. Several cases of energy consumption were examined: in the office room during working hours, in the office room during non-working hours, and in the rest of the building. Since the rest of the building is always unoccupied, working and non-working hours can be combined in the unoccupied category. During non-working hours, the office can be modeled with the rest of the building at the unoccupied temperature setpoint of 55 °F. eQUEST is capable of modeling the building as unoccupied, so the complementary model needs to cover the difference between occupied and unoccupied energy consumption in the office. This can be done through the use of a pen-and-paper heat transfer model to calculate the heat generation necessary to bring the temperature of the room from 55 °F to 72 °F during working hours.

The office area was approximated as a single room. The officers only use one of the rooms in that section of the building but the doors between office rooms are left open. The door between the office area and the rest of the building is typically kept closed, so it is reasonable to model the office room as independent from the rest of the building. The thermal characteristics of the room envelope, including walls, windows, roof and floor, were taken from the thermal characteristics listed in the detailed building description in eQUEST. There are many possible sources for the thermal characteristics, but using the values from eQUEST ensures consistency between models, as much as is possible.

Heat transfer through each of the six surfaces was calculated separately. It is assumed that the ground has a large enough thermal mass that its temperature does not change significantly throughout the day or season [66]. Thus, the HT calculation for the floor is for a fixed temperature delta of 23 °F (72 °F – 50 °F). A similar assumption was made for the rest of the building and the interior walls. It is assumed that the boiler will run as needed to keep the interior of the building at 55 °F, so the HT calculation for each interior walls is across at temperature delta of 17 °F (72 °F – 55 °F).

For the exterior walls and the roof, this assumption of constant temperature difference is not valid. The temperature of the air around the building changes over the course of a day as well as over a longer period of time. One way to account for the changing external temperatures is to look at degree days, a measure of temperature difference over time.

Degree days represents the integral of the difference between a reference temperature and outside temperature over a set period of time. In the United States, degree days are typically reported in degrees Fahrenheit times days. Degree days can be looked up in a reference book for specific reference temperatures, usually 65 ˚F, or looked up online for a variety of reference temperatures. For one example, see Tables 1.9 and 1.10 of the EIA Monthly Energy Review [51] For the purpose of this calculation, degree days for part of the day are desired. Since the smallest resolution for reporting degree days is whole days, degree days for the desired part of the day had to be calculated. Degree days for a partial day were calculated from a reliable weather station in a town near the armory in degrees Fahrenheit times hours. The unit conversion simplified calculation of degree days and the final heat transfer calculation. The weather station was chosen because it has hourly, or more frequent, historical temperature records for several years. Daily records for a year were downloaded into a spreadsheet, where the overnight records were trimmed, leaving only the records between 8 am and 4 pm, with two extra readings: one prior to 8 am and one after 4 pm. A trapezoidal approximation from these readings yielded degree hours from a reference temperature of 72 ˚F during working hours only. The results of this calculation are visible in Appendix F.

Once the degree hours for the working hours were calculated, they were used in the heat transfer calculation for the surfaces interacting with the exterior air. The heat transfer equation for the whole room can be seen in Equation 4 below. The results of this equation can be combined with the results of the unoccupied eQUEST simulation to show total energy consumption for this scenario.

$$Q = UA_{ext.wall} * HDH + UA_{roof} * HDH + UA_{int.wall} * T_{int.} * t + UA_{floor} * T_{ground} * t \tag{4}$$

where $UA_{ext.wall}$ is the thermal characteristic times the areas of the exterior walls in BTU/hour-˚F,

UA_{roof} is the thermal characteristic times the area of the roof in BTU/hour-˚F,

$UA_{int.wall}$ is the thermal characteristic times the areas of the interior walls in BTU/hour-˚F,

UA_{floor} is the thermal characteristic times the area of the floor in BTU/hour-˚F,

HDH is the heating degree hours during working hours in ˚F - hour,

$T_{int.}$ is the fixed temperature of the rest of the building in ˚F,

T_{ground} is the fixed temperature of the ground in ˚F, and

t is the time of work, equal to 8 hours per day.

Several simulations of the armory were run in eQUEST, all using the input parameters developed using the process of correction factors described in the previous chapter. Utility bills were available for the period when the building was fully occupied, so the initial model was created to match the bills. Once this model was developed and simulated, a second model with reduced temperature setpoints was simulated. The output of the first model is energy consumption when the boiler is used to heat the whole building to 72 °F. The output of the second model is energy consumption when the boiler is used to heat the whole building to 55 °F. The results of the heat transfer model are added to the outputs of the second model to determine the total energy consumption when using space heaters for that size room.

To evaluate the impact of the results, three annual metrics were examined: total energy consumption in therms, CO_2 emissions resulting from each type of energy consumption, and cost from the purchase of each type of energy. These metrics were chosen because the National Guard is trying to meet federal requirements to reduce annual totals in these three categories. Implementing space heaters in the one occupied office during working hours and reducing the overall building temperature to 55 °F is projected to reduce annual consumption by 3,600 therms and 105 kWh, saving $5,876. This is approximately 30% of the current annual utility bill. In addition, annual CO_2 emissions associated with electricity production and fuel consumption would be reduced by 19 metric tons, 28% of the current annual CO_2 emissions.

This is a worthwhile energy reduction measure to study further, as implementation was not possible in the timeframe of this study. It was not possible to test these results in the armory modeled because the unit stationed at the armory returned from deployment prior to the start of the heating season after these calculations were performed. In addition, the temporary occupants would have used space heaters in the other rooms they occasionally used, such as the bathroom and the club room. This would have skewed the results, but presents additional situations to study: the effect of using space heaters in additional rooms.

Expansion of these results. The model was expanded to determine the percentage of building it makes sense to heat using space heaters before switching back to heating the whole building with the central boiler. The three metrics from above were used to determine the effective switching point. For a particular scenario to be considered for implementation, all three metrics must be less than the values for the current heating scenario. Total energy consumption, CO_2 emissions, and cost were calculated for specific percentages of building area. These percentages are based on the floor plan, with each larger section including an additional section of the building. The office area originally modeled is 1.8% of the total building area. The next larger area, at 6.8% of the building, includes the adjoining office rooms. The third area, 12.3% of the building, includes the whole office area and the bathrooms. Each larger area includes more of the building, until just over one third of the building is being heated by space heaters. These areas, in the order they were included and the percentage of building heated with the inclusion of that area, are the rest of the office rooms (6.8%), the bathrooms (12.3%), the classroom (21.6%), the club room (30%), and the kitchen (33.8%). The remaining 66.8% of the building contains the drill floor, the mechanical room, storage, and hallways, all areas where space heaters would not be used. This results in nine heating scenarios that can be compared: the current heating method, seven reasonable scenarios of space heater use, and an unreasonable scenario of space heaters heating the whole building from 55 °F to 72 °F. The results of these nine heating scenarios are described below and shown in Figure 14, Figure 15, and Figure 16, with a summary of the results in Table 9.

The first scenario shown is heating the whole building to 72 °F using the central boiler. The second scenario is heating the whole building to 55 °F using the central boiler, with no space heaters in use. The rest of the heating scenarios use this as their base, with the assumption that the central boiler is used to heat the whole building to 55 ˚F. The third situation, labeled as 1.8% in the figures below, is heating the one office from 55 ˚F to 72 ˚F using a space heater. The next situation, labeled as 6.8% below, is the previous situation with the rest of the office area added. This pattern continues, with the respective addition of the bathrooms, the classrooms, the club room, and the kitchen. The final heating scenario is heating the entire building from 55 ˚F to 72 ˚F using space heaters. This iteration of the model is unrealistic, but it was included as a reference for energy consumption. An alternative approach to model each scenario is outlined in Appendix G.

Figure 14 shows the annual energy consumption for each of the heating scenarios, separated by gas and electricity. The black line is equal to the current annual energy consumption, facilitating a comparison to the current heating scenario. While the final heating scenario is unrealistic, it shows that the same amount of heat is necessary to heat the building to 72 ˚F, independent of heat source. This scenario serves as validation that the heat transfer model accurately predicts heat transfer through the exterior walls. This graph shows that any reasonable space heater scenario will consume less energy than heating the whole building with the boiler.

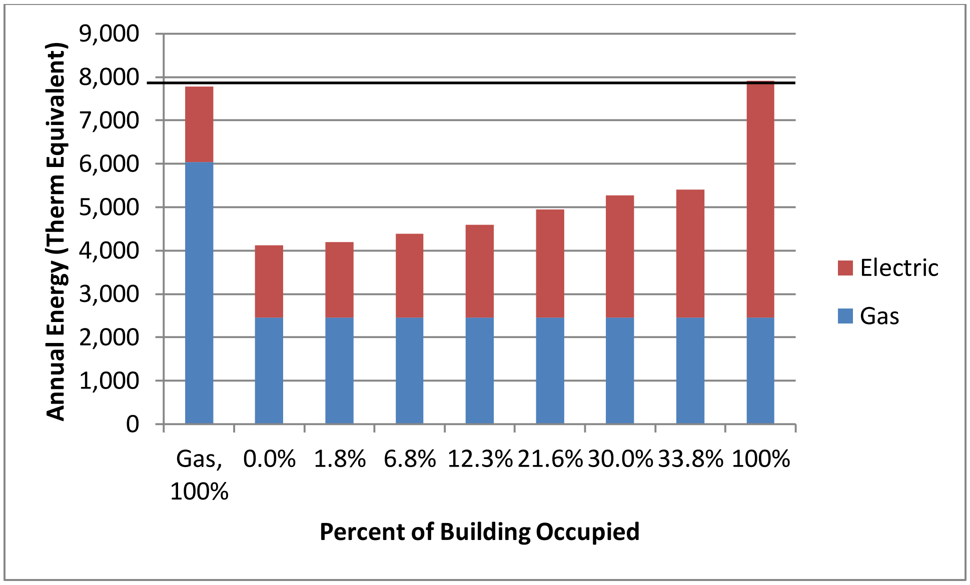


Figure 14. Annual energy consumption in therm and therm equivalent for the nine heating scenarios, with a line to facilitate comparison with the current heating scenario.

Figure 15 shows the annual CO_2 emission for each of the heating scenarios, by fuel source. The black line is equal to the current annual CO_2 emission, facilitating comparison to the current heating scenario. This graph shows that heating a third of the building with space heaters results in fewer emissions compared to heating the whole building with the boiler.

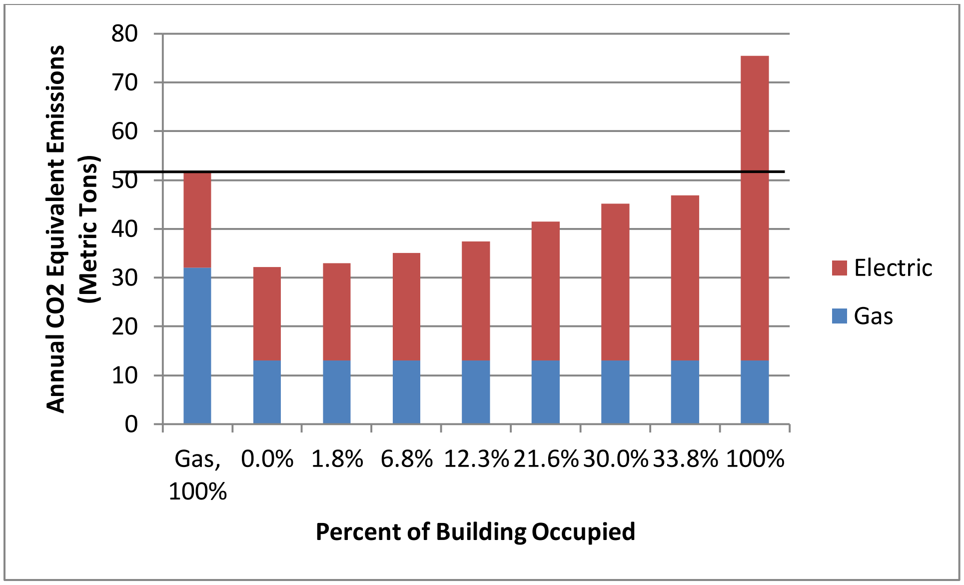


Figure 15. Annual CO_2 equivalent emissions in metric tons, calculated from electricity production and gas consumption, with a line to facilitate comparison with the current heating scenario.

Figure 16 shows the annual utility cost for each of the heating scenarios, separated by gas and electricity. The black line is equal to the current annual cost, facilitating quick comparison to the current heating scenario. This graph shows that annual savings can be obtained by heating 30% or less of the building with space heaters. Heating a third of the building with space heaters results in an additional cost of $269 each year over heating the building with the boiler.

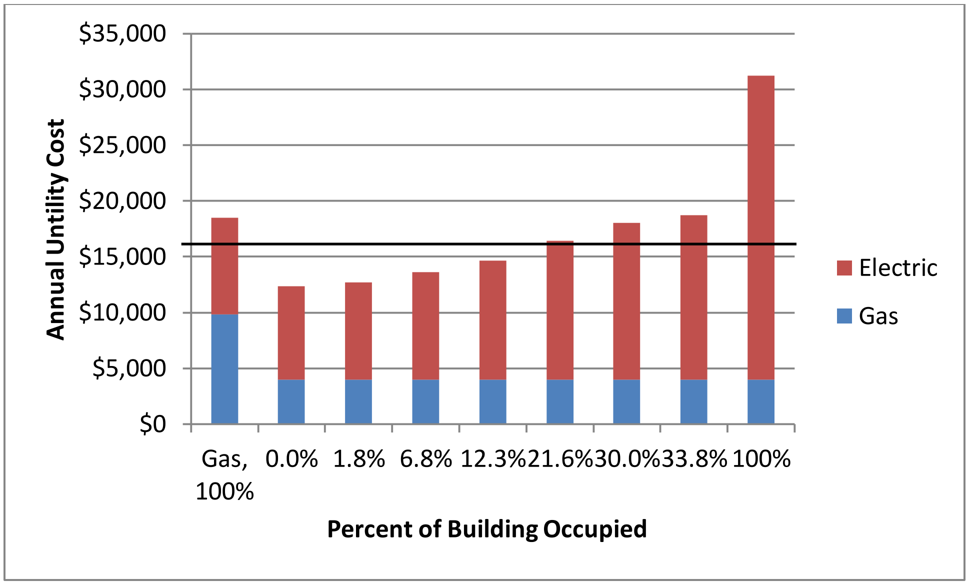


Figure 16. Annual cost for purchasing each type of energy for each of the nine heating scenarios, with a line to facilitate comparison with the current heating scenario.

Table 9 shows the exact annual values for energy consumption, CO_2 emissions, and cost for each of the nine heating scenarios described above.

Table 9

Comparison of Annual Energy Consumption, CO_2 Emissions, and Cost for Nine Heating Scenarios

	% of Bldg. Heated	Energy (Therm Equiv.)			CO_2 Emissions (Metric Tons)			Cost		
		Gas	Electric	Total	Gas	Electric	Total	Gas	Electric	Total
Boiler	Gas, 100%	6,043	1,732	7,774	32.0	19.8	51.8	$9,850	$8,628	$18,477
Unoccupied	0%	2,449	1,679	4,128	13.0	19.2	32.1	$3,992	$8,364	$12,356
1st Office	1.8%	2,449	1,746	4,195	13.0	19.9	32.9	$3,992	$8,698	$12,690
Office	6.8%	2,449	1,937	4,386	13.0	22.1	35.1	$3,992	$9,651	$13,643
Bathrooms	12.3%	2,449	2,143	4,592	13.0	24.5	37.5	$3,992	$10,678	$14,670
Classroom	21.6%	2,449	2,496	4,945	13.0	28.5	41.5	$3,992	$12,437	$16,429
Club Room	30.0%	2,449	2,818	5,267	13.0	32.2	45.2	$3,992	$14,039	$18,031
Kitchen	33.8%	2,449	2,961	5,410	13.0	33.8	46.8	$3,992	$14,754	$18,746
Total	100%	2,449	5,468	7,917	13.0	62.4	75.4	$3,992	$27,243	$31,235

Discussion about Results

There are several assumptions in the model that should be taken into account before applying it to other buildings. The first assumption is that the space heaters used are 100% efficient. This is reasonable if the heaters are electric resistance with no extra features like a fan to move air over the heating element. The second assumption is that the time delay between the space heaters being turned on and the temperature of the room reaching 72 ˚F is unavoidable. Turning on heaters with appliance timers before occupants arrive is a fire hazard. The third assumption is that CO_2 emissions from electricity production are constant. This is reasonable for baseline energy consumption in a single location, but not for peak consumption or locations in different regional electric grids. Peaking plants are power plants used primarily to handle sudden peaks in electricity demand, usually during the summer. These power plants are typically coal-powered and thus produce more CO_2 per kWh than the typical baseline plant, which runs continuously. During the winter, it is reasonable to assume that electricity demand on the regional grid does not spike enough to require the use of peaking plants. As such, CO_2 emissions from peaking plants can be neglected from these calculations. New Jersey is entirely within the RFC East grid region, so the mix of type of power plants for any location within the state can be assumed as constant. Outside of this electrical grid, a different mix of power plants exist, so the CO_2 emissions for that region must be used. For this model, the CO_2 emissions for the RFC East region were used. Compared to the national fuel mix, RFC East has a higher percentage of nuclear and lower percentages of coal and renewable sources, resulting in lower greenhouse gas emissions [67].

There are two major factors that were deliberately neglected in the expansion of this model. The impact of heating adjacent rooms to the occupied temperature was not evaluated. If adjacent rooms are heated to 72 ˚F, less heat will escape each room, resulting in lower energy requirements to keep each room heated. Reduced energy needs means lower electricity consumption, CO_2 emissions, and cost from each room. This means the actual results will be better than predicted when heating adjacent rooms. Including this factor would show the decreased energy needs, but would also limit the application of this method. In the armory under study, the rooms that could be occupied and heated are separated by unoccupied areas like the drill floor, storage areas, and hallways. This setup is similar in other low occupancy armories, so the assumption of isolated occupied rooms works. Another neglected factor is the difference in interior to exterior wall area from room to room. The expansion of the heat transfer model assumes that each additional room has the same ratio of exterior to interior wall area. This is false, but allows each heating scenario to be calculated based on area, without needing the exact ratio of interior to exterior wall. This method is sufficient for this building, as evidenced by the comparison between energy needed to heat the building with the central boiler and the energy needed to heat 100% of the building with space heaters.

In summary, for National Guard Armories in New Jersey where less than one third of the building is occupied, it is more efficient in terms of total energy consumption, CO_2 emissions, and cost to lower the building temperature to the mandated unoccupied temperature of 55 ˚F and heat occupied offices with space heaters to 72 ˚F during working hours. Heating more than a third of the building with space heaters produces slightly less CO_2 emissions but costs more than heating the building completely with the central gas boiler, which is unacceptable for an agency trying to reduce both. The continuation of this work is to expand the model by examining other armories and other building types to see if this conclusion holds. If it holds true, a general recommendation about appropriate space heater use can be issued to NJ DMAVA for all of their buildings.

Chapter 8

Conclusions

Previous chapters detailed the need to audit energy consumption in New Jersey National Guard Armories and then the process for doing so. Armories need to be audited to meet federal requirements and to provide support for specific energy conservation measures (ECMs) so NJ DMAVA can justify the expense of implementing that ECM. The audit process entails analysis of utility bills, data collection during a walkthrough of the building under observation, creation of baseline energy consumption models, application of correction factors to improve the accuracy of the baseline models, and modeling the implementation of potential ECMs. After this, the beneficial ECMs and associated financial analyses are reported to NJ DMAVA so they can decide whether to implement each ECM.

The use of correction factors has been shown to improve model accuracy of a building in its current state. A more accurate model provides more confidence in the results of the baseline model and the models of each ECM implemented in the building, created by altering the baseline model. The correction factors are applied to both types of models used by Rowan University undergraduate engineering students. Their application cannot be strictly regimented as a particular armory may not require all the correction factors described above. Because of this, guidelines are presented for their application.

For the Light and Plug load Model (LPM) created in a spreadsheet, the correction factors address the modification of two inputs: power consumption and time of use. Consumption values are typically easier to check than time of use. When the data sheet or specific consumption information for a particular consumer is unavailable, a range of typical values for that type of device can be found. The correction factor entails adjusting the value for each inexact input within the range of consumption values for that type of device. Time of use for each consumer is based on reports from occupants, assumptions about room use, or data collection from sensors. The first two sources provide a range of possible values that should be adjusted in a similar fashion to consumption values. Modeling ECMs in the LPM is a straightforward process. Replacement of lights or appliances is modeled by changing consumption values to reflect the new reduced consumption. Use of occupancy sensors and power strips are modeled by altering time of use for the consumers controlled by those devices.

For the eQUEST model, correction factors were separated three categories: building details, gas consumption, and electricity consumption. The first category deals with details about the building that do not significantly affect energy consumption individually. These are HVAC system type on Screen 1, story height on Screen 3, building layout and size on Screen 3, building envelope construction on Screen 4, door details on Screen 6, window details on Screen 7, area types and details about each area type on Screens 13, 14, and 16, and schedule details on Screen 17. The second category deals with the two inputs that significantly drive gas consumption in the model: infiltration on Screen 7 and temperature setpoints on Screen 20. The third category is a pair of screens that drive electricity consumption in eQUEST. On Screen 14, the watts per square foot consumed during occupied hours for each area type is entered. On Screen 16, the unoccupied consumption is entered as percentage of occupied consumption. Modeling ECMs in eQUEST is a straightforward process. The new values for infiltration and temperature setpoints can be entered directly. The main complication with modeling these ECMs is creating the baseline model such that the initial values for these inputs reflect the actual state of the building.

In addition, energy reduction for a special case of armory occupancy was examined. When the unit stationed at an armory is deployed, occupancy of that armory is drastically reduced and concentrated in one or two rooms. This presents the opportunity for energy savings by heating most of the building to the unoccupied AFMR setpoint of 55 ˚F with the central heating system and heating the occupied rooms to the occupied setpoint of 72 ˚F using space heaters. Modeling space heater use in a single occupied office, equal to 1.8% of the total building area, resulted in a 46% reduction in energy consumption, a 36% reduction in CO_2 emissions, and a 31% reduction in cost from heating the whole building to the occupied setpoints. The model was expanded to determine the highest percentage of building area at which space heater use resulted in savings for energy, CO_2 emissions, and cost. For that armory, it was determined that heating 30% of the building with space heaters resulted in savings in all three categories, while heating one third of the building with space heaters cost more than heating the whole building with the central heating system. Thus, DMAVA could justify space heater use in 30% of this armory because of the energy, CO_2 emissions, and cost savings.

Future Work

In summary, this work describes why the New Jersey National Guard needs energy audits performed on their buildings, how this need is being met, methods used to audit the armories, and methods used to maximize accuracy of the results returned to DMAVA. However, this process is not perfect. There are several ways that this process could be improved further.

The statistical analysis described in Chapter 3 could be expanded. The data set could be expanded to include all armories, instead of a partial set. The effect of more armory attributes could be examined, such as number of stories, window to wall ratio, building layout, or typical bulb type, to determine if any have a statistically significant impact on energy consumption. If they do, they should be added to the list of important building attributes for the audit team to examine during the site visit. The number of stories alters the ratio of volume to external surface area, impacting how the building is heated. Internal building layout could affect heat transfer inside the building. An open floorplan would result in the whole building being heated equally, where sectioning the building by closing doors allows parts of the building to be heated to different temperatures. The ratio of window to wall area will change the heat transfer characteristic of the building envelope, as more windows will result in increased heat transfer. Light bulbs, as with all electricity consumers, produce heat as a byproduct of their operation, which will slightly alter the demand for heating and cooling.

These factors should be examined in closer detail. The data set is small, so care must be taken when looking for trends or assigning significance to a relationship between variables. As shown in Chapter 3, outliers can skew the analysis because the data set is so small. To minimize the effect of outliers, data for more armories should be included in the analysis.

Current building simulation programs should be tested as an alternative to eQUEST, to circumvent the need for correction factors. OpenStudio has the potential for greater accuracy without the need for correction factors. However, its learning curve is significantly steeper than that of eQUEST, as there was no indication of what inputs were necessary for a basic complete model. In eQUEST, the SD Wizard guides the user through the required inputs.

The correction factors entered in eQUEST have room for improvement. The correction factors described in Chapter 6 can be reexamined, especially the ones without numerical support. This includes default values that are accepted as accurate, usually because of a lack of information about that input. A DMAVA maintenance person, design documents, or construction documents should be consulted for confirmation of these default values. This will increase the confidence that these are accurate values, at the expense of man-hours that could be spent otherwise. Less developed correction factors, such as schedule details, could be given more attention. For example, a formula could be created, detailing how schedule details could be adjusted to better accommodate drill event occupancy based on drill event and weekday occupancy numbers. Additional data about drill events should be collected at multiple armories to support this formula.

The current space heater model has been applied in a single armory. The expansion of this model has two main goals. The first is to model space heater use in other armories with a reasonable certainty of accuracy. The second goal is to test the results of this model. If there are any units being deployed in the near future, this model should be applied to that unit's armory around the time of deployment, so the most economical heating option for the armory can be chosen.

There are many potential improvements for the audits of New Jersey National Guard Armories. They should focus on further development of correction factors and improved data collection by the audit teams. Expansion of the statistical analysis, which would provide additional guidance for new audit teams about potential issues in their assigned armory, is not critical to the success of these audits. Improvements to the audit process will allow more detailed energy audits of armories, resulting in better results: more accurate predictions of energy savings. Knowing the specific savings from an ECM helps the New Jersey National Guard implement the best measures to meet their stated goal of reduced energy consumption.

References

[1] US Government. "Energy Independence and Security Act of 2007. United States Act (H.R. 6)", 2007.

[2] US Army. "Army Regulation 420-1: Army Facilities Management. Chapter 22: Army Energy and Water Management Program. Section III, 22-12: Energy conservation and management guidelines for facilities and buildings", 2012.

[3] U.S. Energy Information Administration. "Monthly Energy Review", 2014.

[4] U.S. Energy Information Administration. "How much of U.S. carbon dioxide emissions are associated with electricity generation?", 2013.

[5] US EPA "Greenhouse Gas Equivalencies Calculator: Calculations and References", 2014.

[6] Pacheco, et al. Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews*, 16 (2012), pp 3559 – 3573.

[7] Bonte, et al. Impact of occupant's actions on energy building performance and thermal sensation. *Energy and Buildings*, 76 (2014), pp. 219 – 227.

[8] Brown and Frame. Green Buildings Need Green Occupants. *Eco-Management and Auditing*, 6 (1995), pp 80 – 85.

[9] Menezes, et al. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy*, 97 (2012), pp 355 – 364.

[10] Hoes, et al. User behavior in whole building simulation. *Energy and Buildings*, 41 (2009), pp 295 – 302.

[11] Li, et al. Zero energy buildings and sustainable development implications - A review. *Energy*, 54 (2013), pp 1-10.

[12] Sozer. Improving energy efficiency through the design of the building envelope. *Building and Environment*, 45 (2010), pp 2581 – 2593.

[13] Dall'o' and Sarto. Potential and limits to improve energy efficiency in space heating in existing school buildings in northern Italy. *Energy and Buildings*, 67 (2013), pp 298 – 308.

[14] Kossecka and Kosny. Influence of insulation configuration on heating and cooling loads in a continuously used building. *Energy and Buildings*, 34 (2002), pp 321 – 331

[15] Mahdy and Nikolopoulou. Evaluation of fenestration specifications in Egypt in terms of energy consumption and long term cost-effectiveness. *Energy and Buildings*, 69 (2014), pp 329 – 343.

[16] Menezes, et al. Estimating the energy consumption and power demand of small power equipment in office buildings. *Energy and Buildings*, 75 (2014), pp 199 – 209.

[17] Korolija, et al. Influence of building parameters and HVAC systems coupling on building energy performance. *Energy and Buildings*, 43 (2011), pp 1247 – 1253.

[18] Perez-Lombard, et al. A review of HVAC systems requirements in building energy regulations. *Energy and Buildings*, 43 (2011), pp 255–268

[19] Menassa, et al. Energy Consumption Evaluation of U.S. Navy LEED-Certified Buildings. *Journal of Performance of Constructed Facilities*, 26 (2012), pp 46 - 53.

[20] Marszal, et al. Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings*, 43 (2011), pp 971 – 979.

[21] Goulouti, et al. Thermal performance evaluation of fiber-reinforced polymer thermal breaks for balcony connections. *Energy and Buildings*, 70 (2014), pp 365–371.

[22] Finger, et al. “Action and influence of the multiple decision levels over the whole energy chain,” in 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, 2009 ©IEEE.

[23] Huber. “The Energy Standard and Label MINERGIE,” presented at Sustainable Development, Prague, Switzerland, 2012.

[24] Melo, et al. Building energy performance assessment: Comparison between ASHRAE standard 90.1 and Brazilian regulation. *Energy and Buildings*, 70 (2014), pp 372–383.

[25] Zhu and Zhao. Green building research–current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, 30 (2014), pp 271 – 281.

[26] Li, et al. Zero energy buildings and sustainable development implications - A review. *Energy*, 54 (2013), pp 1-10.

[27] Visa, et al. Improving the renewable energy mix in a building toward the nearly zero energy status. *Energy and Buildings*, 68 (2010), pp 72 – 78.

[28] Ramesh, et al. Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, 42 (2010), pp 1592 – 1600.

[29] Marchiori, et al. “Building the Case for Automated Building Energy Management,” in the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings, 2012, pp 25-32. ©IEEE. doi: 10.1145/2422531.2422536

[30] Santin. Occupant behaviour in energy efficient dwellings: evidence of a rebound effect. *Journal of Housing and the Built Environment*, 28 (2013), pp 311 – 327.

[31] Steinberg, et al. Developing a Focus for Green Building Occupant Training Materials. *Journal of Green Building*, *4*, No. 2 (2009), pp 175 – 184.

[32] Bonte, et al. Impact of occupant's actions on energy building performance and thermal sensation. *Energy and Buildings*, 76 (2014), pp 219 -227.

[33] Lee and Malkawi. Simulating multiple occupant behaviors in buildings: An agent-based modeling approach. *Energy and Buildings*, 69 (2014), pp 407 - 416.

[34] Jiang, et al. "Experiences with a High-Fidelity Wireless Building Energy Auditing Network," presented at the 7th ACM Conference on Embedded Networked Sensor Systems, Berkeley, CA, 2009.

[35] Wong. "Energy Conservation and Human Behaviors: The Professional Faculties Building in the University of Calgary." Master's Thesis, Dept. of Environmental Design, U Calgary, Calgary, AB, 1997.

[36] C. Moore, private communication with S. Schanck. , Sept. 2015.

[37] CBS. (1998, Summer). *EnergyPlus: The Merger of BLAST and DOE-2* [Newsletter]. Available: http://eetd.lbl.gov/newsletter/cbs_nl/nl18/cbs-nl18-energyplus.html

[38] BemBook. *History of Building Energy Modeling* [Online]. Available: http://www.bembook.ibpsa.us/index.php?title=History_of_Building_Energy_Modeling

[39] Crawley, et al. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43 (2008) 661–673.

[40] Crawley, et al. Contrasting the capabilities of building energy performance simulation programs. Washington, DC: US Department of Energy; 2005.

[41] J. Hirsch. *eQUEST* [Online]. Available: www.doe2.com/equest

[42] NA. *OpenStudio* [Online]. Available: www.openstudio.net

[43] Clyne and Bodzin. (September/October 1997) *Home Energy Magazine Online* [Online]. Available: http://www.homeenergy.org/show/article/nav/column/page/20/id/1336

[44] NA. *eQUEST All Access* [Online]. Available: http://energy-models.com/content/equest-all-access

[45] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, p. 8.

[46] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, p. 80.

[47] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, p. 70.

[48] Leckie, et al., "Solar Thermal Applications," in *More Other Homes and Garbage*, 1975 edition. San Francisco: Sierra Club Books, 1981, Chapter 4, Section “Heat Loss in Dwellings,” pp. 151-152, 160-161.

[49] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, pp. 43-44.

[50] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, p. 60.

[51] US Energy Information Administration. "September 2015 Monthly Energy Review," Report DOE/EIA-0035(2015/09), pp. 20-21.

[52] Jang and Healy. Wireless sensor network performance metrics for building applications. *Energy and Buildings*, 42 (2010), pp 862 – 868.

[53] HOBO® ZW Series Wireless Network Quick Start Guide, Onset Computer Co., Bourne, MA, pp. 1-2. Available: http://www.onsetcomp.com/files/manual_pdfs/13542-D-MAN-ZW-QSG.pdf.

[54] Nave. (January 12, 2007). Relative Humidity [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/relhum.html

[55] NREL. PVWatts Calculator [Online]. Alliance for Sustainable Energy, LLC, Golden, CO. Available: http://pvwatts.nrel.gov.

[56] NA. "6.15 Lighting," General Services Administration, 2003 Facilities Standards (P100), Reviewed July 9, 2015. Available: http://www.gsa.gov/portal/content/101308.

[57] LBNL, (March 3, 2015). *Standby Power Summary Table* [Online]. Available: http://standby.lbl.gov/summary-table.html.

[58] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, p. 45.

[59] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, p. 22.

[60] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, pp. 33-34.

[61] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, pp. 35-36.

[62] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, pp. 41-44.

[63] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, p. 46.

[64] *eQUEST Introductory Tutorial*. J.J. Hirsch, Camarillo, CA, Oct. 2003, pp. 91-96.

[65] US Department of Energy. *Thermostats*, [Online]. Available: http://energy.gov/energysaver/thermostats.

[66] Office of the New Jersey State Climatologist. *NJ Statewide Soil Temperature (10 cm)* [Online]. Available: http://www.njweather.org/maps/nj-statewide-soil-temperatures-10cm

[67] US Environmental Protection Agency. (2015, October 8). *Power Profiler* [Online]. Available: https://www.epa.gov/energy/power-profiler. Enter zip code as 08098 and electric utility as Atlantic City Electric Co.

[68] The Weather Company, LLC. *New Castle, DE* [Online]. Available: https://www.wunderground.com/history/airport/KILG/2013/7/1/DailyHistory.html?req_city=New+Castle&req_state=DE&req_statename=&reqdb.zip=19720&reqdb.magic=5&reqdb.wmo=99999

[69] Martin. (2016, January 28). *R-Value Table: Insulation Values For Selected Materials* [Online]. Available: http://www.coloradoenergy.org/procorner/stuff/r-values.htm.

[70] Arch Media Group. *R-values of Insulation and Other Building Materials* [Online]. Available: https://www.archtoolbox.com/materials-systems/thermal-moisture-protection/rvalues.html

Appendix A

Building Data Used for Statistical Analysis

This appendix contains data used for the statistical analysis in Chapter 3. The data contained in Table 10 falls into two categories: building characteristics and consumption information. The statistical analysis was performed to determine the feasibility of predicting consumption in an armory from numeric building characteristic data. Actual armories names are not included due to security concerns and a request from the New Jersey National Guard.

Table 10

Building Information for Statistical Analysis

Building Characteristic						Consumption				
Building	**Area (ft^2)**	**Stories**	**Average Occupancy (people)**	**Building Age (years)**	**Boiler Age (years)**	**Annual Electricity (kWh)**	**Baseline Electricity (kWh)**	**Annual Gas (therm)**	**Electricity Intensity (kWh/ft^2)**	**Gas Intensity ($therm/ft^2$)**
1	50,638	2	13	87	87	153,520	110,160	31,393	3,032	620
2	41,696	1	18	58	58	117,081	106,146	32,790	2,808	786
3	13,104	1	13	55	55	50,650	33,384	14,452	3,865	1,103
4	15,870	1	8	53	53	54,260	39,480	7,510	3,419	473
5	33,096	1	13	60	2	89,830	40,542	8,327	2,714	252
6	49,966	3	8	76	76	173,186	127,488	19,789	3,466	396
7	28,950	1	8	55	55	107,260	84,936	20,803	3,705	719
8	39,168	1	13	76	6	70,880	48,480	8,068	1,810	206
9	16,806	1	3	35	35	54,160	35,040	6,926	3,223	412
10	176,678	2	25	29	29	387,512	296,136	50,711	2,193	287

Appendix B

Consumption Information about Armories

This appendix contains information about actual and modeled energy consumption in select New Jersey National Guard Armories. These armories are the same armories included in the statistical analysis in Chapter 3 and Table 10 from Appendix A. Billed consumption is from utility bills from January to December 2013. Modeled consumption corresponds to a year prior to the Rowan University energy audit of that armory. The calendar year corresponding to the modeled and reported values for each armory is listed as the Modeled Period. The Report values in Table 11 correspond to the Modeled Period year and these values are the annual total consumption and seasonal consumption values stated in the report submitted to the National Guard.

Table 11

Billed and Modeled Energy Consumption for Select Armories

		Armory Label	1	2	3	4	5	6	7	8	9
		Area (ft^2)	50,638	41,696	13,104	15,870	33,096	49,966	28,950	39,168	16,806
		Modeled Period	2011	2011	2013	2011	2012	2014	2011	2012	2013
Electricity (kWh)	**Bills***	Annual Total	153,520	117,081	50,650	54,260	89,830	173,186	107,260	70,880	54,160
		Baseline	110,160	106,146	33,384	39,480	40,542	127,488	84,936	48,480	35,040
		Seasonal	43,360	10,935	17,266	14,780	49,288	45,698	22,324	22,400	19,120
	Report	Annual Total	142,543	120,300	54,800	51,317	94,250	144,400	94,850	68,000	43,120
		Seasonal	31,360	39,699	10,960	12,316	25,451	29,200	21,815	31,760	9,520
	LPM	Annual Baseline	111,183	80,601	43,840	39,001	68,799	115,200	73,035	36,240	30,274
		Lights	59,868	42,105	33,428	18,987	14,605	69,312	43,631	25,980	17,139
		Plug loads	51,315	38,496	10,412	20,014	54,194	36,100	29,404	10,260	13,135
	eQUEST	Model Total	-	-	-	-	96,550	-	-	-	43,400
		Lights	-	-	-	-	12,200	-	-	-	17,360
		Plug loads	-	-	-	-	55,190	-	-	-	26,040
Gas (therm)	**Bills***	Annual Total	31,393	32,790	14,452	7,510	8,327	19,789	15,020 gal. #2 oil	5,825 gal. #2 oil	5001 gal. #2 oil
		Baseline	102	0	0	0	39	120			
		Seasonal	31,291	32,790	14,452	7,510	8,288	19,669			
	Report	Annual Total	24,375	18,160	8,260	6,046	6,450	21,800	7500 gal #2 oil	5500 gal #2 oil	6910 gal #2 oil
	eQUEST	Total	-	-	-	-	4,006	-	-	-	7.811
		Baseline	-	-	-	-	2,467	-	-	-	238
		Seasonal	-	-	-	-	1,539	-	-	-	7,572

* Note: Bill consumption and modeled consumption may not be for the same time period. Billed consumption for all armories is for calendar year 2013. Report and model consumption values are for the year noted in the Modeled Period row.

Appendix C

Additional Sensor Results

This appendix details data collected by a sensor setup and the analysis drawn from that data. Data sets from several armories are included and described.

December 2015 Sensor Setup - Unoccupied Armory

In December 2015, sensors were placed in an armory. The National Guard contact for this building at the time was the regional armorer supervisor. He stated that the armory was unoccupied, a statement supported by visual inspection of the building. Figure 17 shows the location of each pendant sensor in this armory. Figure 18 shows all the temperature records for this setup.

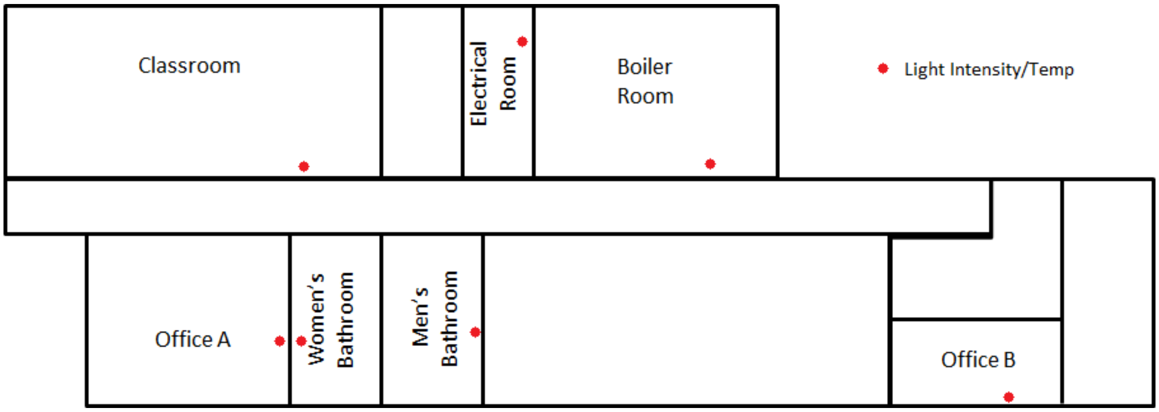


Figure 17. Floor plan of armory from December 2015 sensor setup.

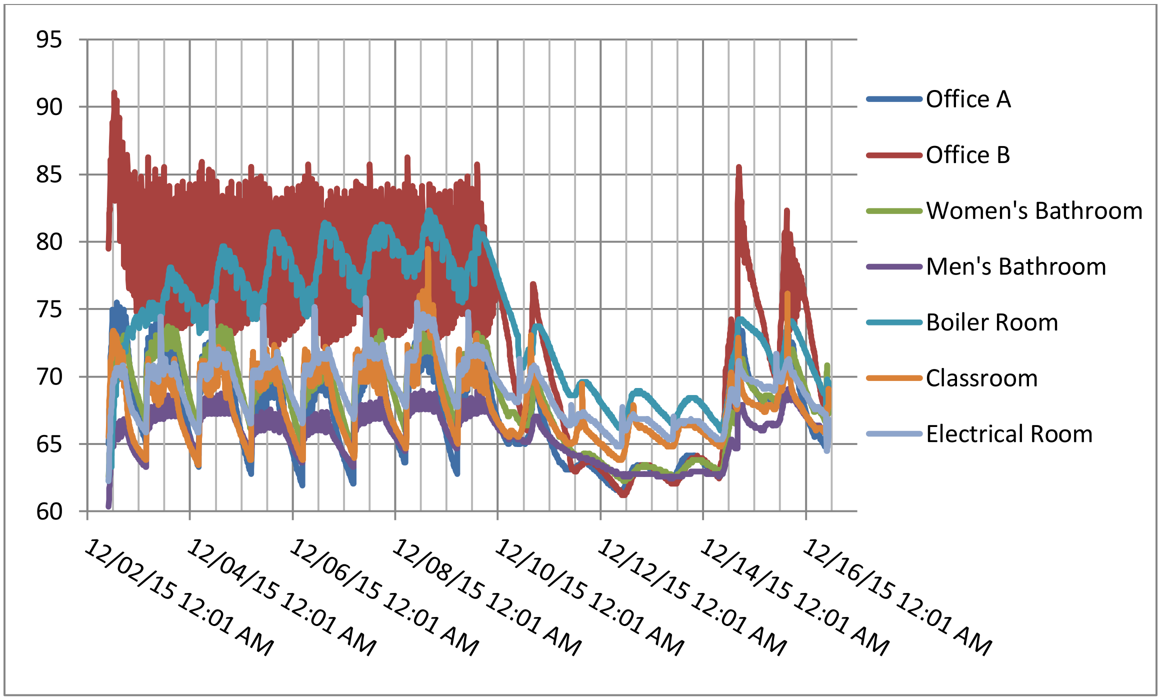


Figure 18. All temperature records from December 2015 armory setup.

The temperature records were split into two graphs to better analyze the details of each record. The temperature in the building is fairly well controlled, as evidenced by the grouping of temperature in the five temperature records seen in Figure 19.

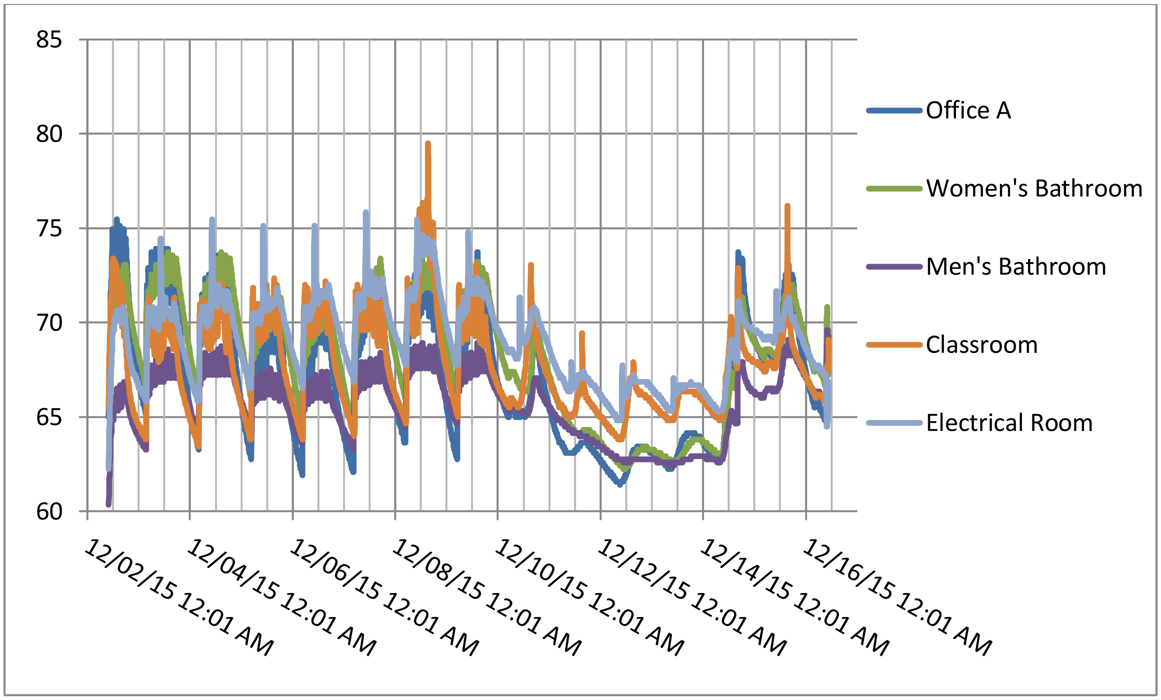


Figure 19. Select temperature records from December 2015 armory setup.

The two outlying data records, visible in Figure 20, reveal the times of operation for the boiler. During the first week, December 2 to December 9, the boiler was running, as evidenced by the warmer temperatures and the wild variations of the temperature records from the sensor in Office B, which was placed against an exterior wall. The temperature variations, unique to this sensor, are assumed to be the result of the sensor measuring the temperature of the surface of the cinderblock wall it was placed against rather than the temperature of the air in that room. This is supported by the temperature record realigning with other temperature records from December 11 to December 14, as seen in Figure 18.

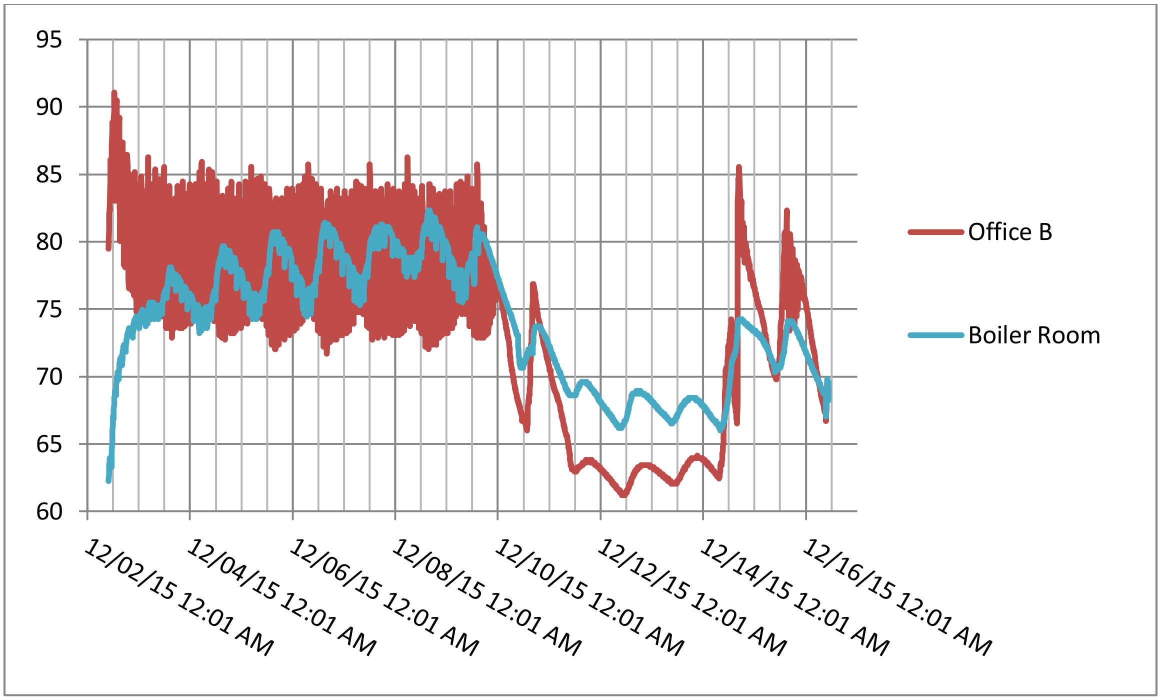


Figure 20. Other select temperature records from December 2015 armory setup.

In summary, the boiler was turned on December 2, turned off on December 9, and turned on again on December 16, as stated by the armorer and confirmed by temperature records taken in this unoccupied armory.

October 2015 Sensor Setup - Fully Occupied Armory

In October 2015, sensors were setup in a fully occupied building. The temperature records are visible in Figure 21. No floor plan is provided for this building due to security concerns. The most notable occurrence during the period of study was the change in operating state of the boiler. When the sensors were placed, the boiler was off. When the sensors were collected, the boiler was running. Visual inspection of the temperature records shows that the boiler was turned on just before 8 am on October 27 and it took several hours to bring the building to an average temperature of 72 ˚F. The relative uniformity of temperature after the boiler was turned on shows that the thermostat in the building is not altered for the unoccupied periods, such as nights and weekends.

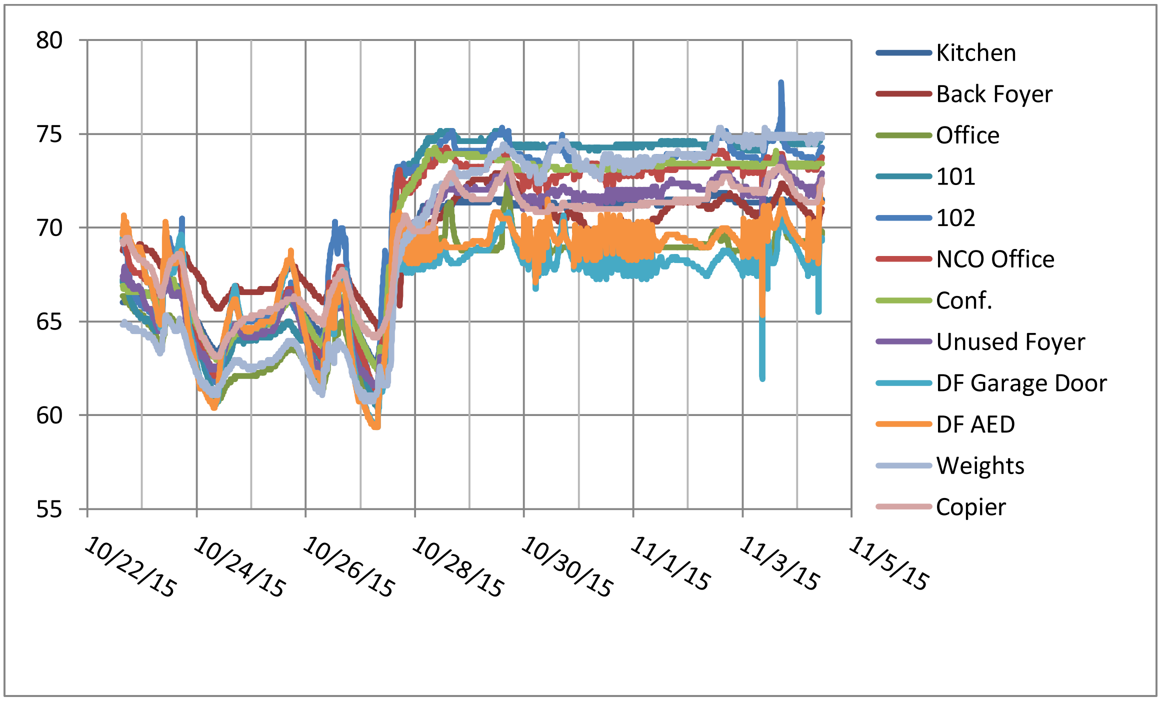


Figure 21. All temperature records from October 2015 sensor setup.

It is notable that the temperature in office spaces across the building varies by roughly 5 degrees at a single point in time, indicating an issue with temperature regulation across the building. This temperature variation is visible both before and during boiler operation, indicating that this is most likely an issue with the building envelope instead of the HVAC system. This is best seen in Figure 22, which shows temperature records for the office spaces in the building. The four temperature records removed from Figure 21 to create Figure 22 are from sensors in the two foyers and in two locations on the drill floor.

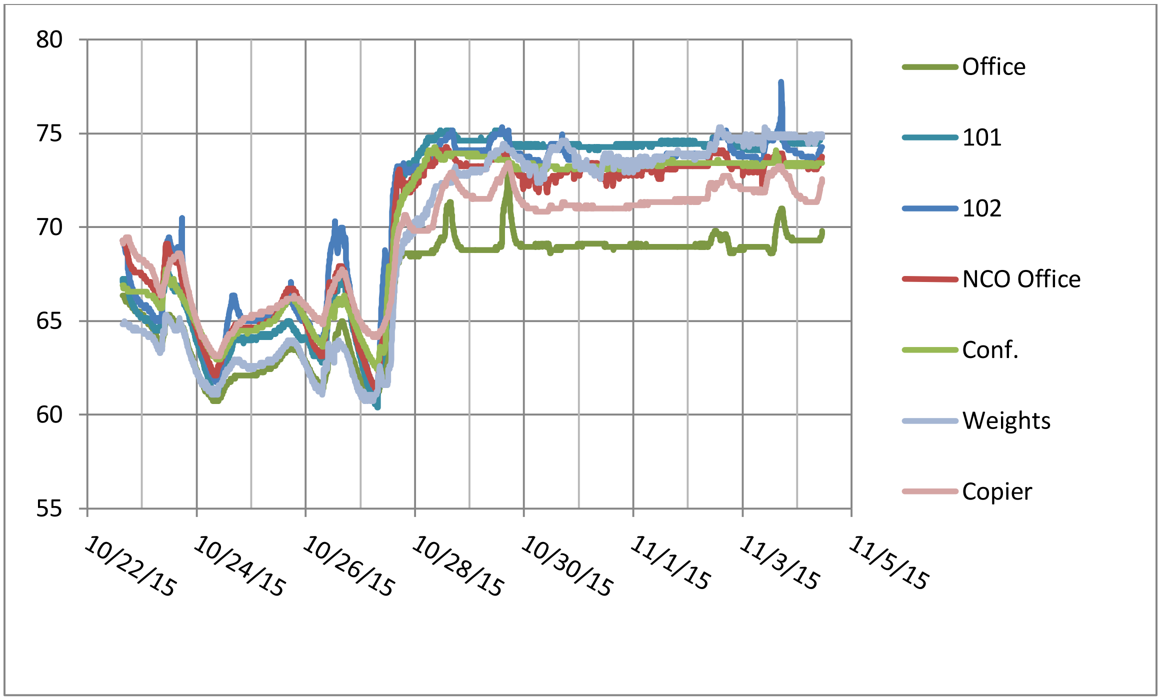


Figure 22. Office temperature records from October 2015 sensor setup.

Appendix D

Initial and Final Input Values for eQUEST Model

This appendix details the initial and final values for the inputs that are altered in an eQUEST model of a New Jersey National Guard Armory. Table 12 shows default eQUEST values for a two story office building and final input values for the important inputs for two armories. Table 13 shows the default values for energy intensity for each room type. Table 14 shows the final values used for energy intensity in models of two eQUEST armories.

Table 12

Initial Default and Select Final eQUEST Input Values

Input	Screen	Default Value	Final Values for Two Armories	
			5	9
Building Type	1	Office Bldg, Two Story	Office Bldg, Two Story	Retail, Large Single Story
HVAC Equipment	1	DX Coils, Furnace	Chilled Water Coils, Hot Water Coils	Furnace, No Cooling
Floor height (ft)	3	12 ft	12 ft	20 ft
Roof Construction	4	Metal Frame, built-up finish, 3 inch R-18 insulation	Metal Frame, aluminum finish, 3 inch R-18 insulation	Metal Frame, built-up finish, no insulation
Wall Construction	4	Metal Frame, wood finish, R-2 & R-19 insulation	6 in. HW concrete, concrete finish, no insulation	Metal Frame, stucco finish, no insulation
Floor Surface	4	Earth contact, 6 in concrete, no insulation, vinyl tile	Earth contact, 6 in concrete, no insulation, ceramic tile	Earth contact, 6 in concrete, no insulation, vinyl tile
Infiltration (CFM/ft^2)	4	P: 0.038, C: 0.001	P: 0.038, C: 0.001	P: 1.190, C: 0.001
Ceiling Material	5	Lay-in Acoustic Tile, no insulation	Lay-in Acoustic Tile	None
Door Type	6	Glass (7 x 6 ft)	Opaque (3 x 6 ft), Glass (7 x 6 ft), Opaque (7 x 6 ft)	Overhead (20 x 16.4 ft) Opaque (7 x 4 ft)
Window Construction	7	Double Clr/Tint (5.22 ft tall, width unspecified)	Single Clr/Tint (4 x 2 ft)	Single Pilkington glass (2 x 2 ft) Single Pilkington glass (3.4 x 4 ft)
Schedule Information	17	8 am-5 pm, M-F, else unoccupied	7 am-4 pm, M-F, else unoccupied	7 am-3 pm, M-F, else unoccupied
HVAC System Definitions	19	C: DX Coils in single zone, H: Furnace	C: Cold water coils, H: Hot water coils	C: No cooling H: Furnace, no zone ventilation
Temp Setpoints	20	C: 76 ˚F, 82 ˚F, H: 70 ˚F, 64 ˚F	C: 72 ˚F H: 70 ˚F	C: 76 ˚F H: 64 ˚F
Water Heater Details	36	148 gal, 197.7 kBtuh	502 gal, 753.1 kBtuh	70 gal, 120 kBtuh

Table 13

Default Area Type Details in eQUEST for Two Story Office Building

Area Type	Design Max Occup. (ft^2/ person)	Design Ventilation (CFM/ person)	Lighting (W/ft^2)	Plug Loads (W/ft^2)
Office (Executive)	100.0	15.00	1.10	1.50
Corridor	100.0	15.00	0.50	0.20
Lobby (office reception)	100.0	15.00	1.30	0.50
Restrooms	100.0	15.00	0.90	0.20
Conference Room	14.9	7.46	1.30	1.00
Mechanical/Electrical	333.3	50.0	1.50	0.20
Copy Room	333.3	50.0	1.50	0.20

Table 14

Final Area Type Details in eQUEST, Screens 13, 14 and 16

Area Type	Design Max Occup. (ft^2/ person)	Design Ventilation (CFM/ person)	Lighting (W/ft^2)	Plug Loads (W/ft^2)
Storage (conditioned)	226.3	337.50	0.60	0.02
Office (general)	22.6	337.50	0.63	1.50
Restrooms	19.8	337.50	0.50	0.20
Mechanical/Electrical	14.1	337.50	0.61	0.20
Auditorium	10.5*	15.0*	0.10	1.00*
Storage (conditioned)	450.0*	67.5*	0.10	1.00*
Lobby (office reception)	150.0*	15.0*	1.10	1.00
Restrooms	52.5*	50.0*	0.50	0.20*
Kitchen	300.0*	15.0*	0.10	9.75
Mechanical/Electrical	450.0*	22.5*	0.10	5.00

*Note: these values are defaults for building type "Office Bldg, 2 Story".

Appendix E

Sample Infiltration Calculations

This appendix shows how to use the infiltration formula provided in Chapter 6. An example of calculating infiltration in a building is provided below. The equation is:

$$Infiltration_{actual} = Infiltration_{eQUEST} * \frac{Area_{actual} + Area_{open}}{Area_{eQUEST}} \tag{5}$$

Where:

$Infiltration_{eQUEST}$ = 0.038 CFM/ft^2

$Area_{open}$ is the area in ft^2 of any open holes in the building envelope and should be calculated from measurements taken during the site visit. *

$Area_{actual}$ is the gap area in ft^2 around of all doors and windows in the armory, calculated as the total perimeter of all doors and windows times the assumed average gap width of 1/8 in. *

$Area_{eQUEST}$ is the gap area in ft^2 around all doors and windows in the eQUEST model, calculated as the total perimeter of all modeled doors and windows times the assumed average gap width of 1/16 in. The perimeter of doors can be calculated from the door inputs entered on Screen 6 in eQUEST. The perimeter of windows can be calculated using the Custom Door and Window Placement option on Screen 7 in eQUEST. *

* Note: The unit for this term is stated as ft^2 but it can be in in^2, as long as all three area terms share the same units.

Table 15 calculates the area of each gap and hole in the building envelope. Table 16 calculates the area of infiltration in the actual armory under study as the perimeter of each door and window times a gap width of one-eighth inch. Table 17 calculates the area of infiltration in the eQUEST model of the armory as the perimeter of each modeled door and window times a gap width of one-sixteenth inch.

Table 15

Calculation of Area of Infiltration Through Gaps in the Building Envelope of an Actual Armory

Type	**Length (in)**	**Width (in)**	**Dia. (in)**	**Gap (in)**	**Qty.**	**Total Area (in^2)**	**Total Area (ft^2)**	**Calculation Basis**
Open windows	45	2	-	-	8	720	5.00	Area of opening
	54	6	-	-	3	972	6.75	Area of opening
	54	2	-	-	9	972	6.75	Area of opening
	30	6	-	-	1	180	1.25	Area of opening
Missing windows	46	9	-	-	1	414	2.88	Area of opening
	18	16	-	-	3	864	6.00	Area of opening
Gaps around AC unit	18.5	14	-	1/8	2	16	0.11	Perimeter gap
	18.5	12	-	1/8	3	23	0.16	Perimeter gap
	21	12	-	1/8	1	8	0.06	Perimeter gap
	16	11.5	-	1/8	1	7	0.05	Perimeter gap
	26	18	-	1/8	1	11	0.08	Perimeter gap
	26	18	-	1/4	1	22	0.15	Perimeter gap
	46	15	-	1/16	2	15	0.11	Perimeter gap
Holes in windows	-	-	12	-	1	113	0.79	Area of hole
	-	-	5.5	-	1	24	0.16	Area of hole
	-	-	2	-	1	3	0.02	Area of hole
						Total:	**30.31 ft^2**	

Table 16

Calculation of Area of Infiltration Around Doors and Windows in an Actual Armory

Type	**Length (ft)**	**Height (ft)**	**Perimeter (ft)**	**Gap (in)**	**Qty.**	**Total Area (ft^2)**	**Calculation Basis**
Door	6	7	26	1/8	3	0.81	Perimeter gap
	3	7	20	1/8	2	0.42	Perimeter gap
	16.4	20	73	1/8	1	0.76	Perimeter gap
Window	8	4	24	1/8	49	12.25	Perimeter gap
	1.5	1.5	6	1/8	72	4.50	Perimeter gap
	46.25	2	97	1/8	2	2.01	Perimeter gap
	77.5	2	159	1/8	1	1.66	Perimeter gap
	10.5	2	25	1/8	1	0.26	Perimeter gap
	30	2	64	1/8	1	0.67	Perimeter gap
	24.5	2	53	1/8	1	0.55	Perimeter gap
	47.5	2	99	1/8	1	1.03	Perimeter gap
	13	2	30	1/8	1	0.31	Perimeter gap
	3.5	2	11	1/8	1	0.11	Perimeter gap
			686		**Total**	**25.34 ft^2**	

Table 17

Calculation of Area of Infiltration Around Doors and Windows in an Armory eQUEST Model

Type	Length (ft)	Height (ft)	Perimeter (ft)	Gap (in)	Qty	Total Area (ft^2)	Calculation Basis
Door	6	7	26	1/16	3	0.41	Perimeter gap
	3	7	20	1/16	2	0.21	Perimeter gap
	16.4	20	73	1/16	1	0.38	Perimeter gap
Window	8	4	24	1/16	49	6.13	Perimeter gap
	1.5	1.5	6	1/16	72	2.25	Perimeter gap
	46.25	2	97	1/16	2	1.01	Perimeter gap
	77.5	2	159	1/16	1	0.83	Perimeter gap
	10.5	2	25	1/16	1	0.13	Perimeter gap
	30	2	64	1/16	1	0.33	Perimeter gap
	24.5	2	53	1/16	1	0.28	Perimeter gap
	47.5	2	99	1/16	1	0.52	Perimeter gap
	13	2	30	1/16	1	0.16	Perimeter gap
	3.5	2	11	1/16	1	0.06	Perimeter gap
			686		**Total:**	**12.67 ft^2**	

The totals from Table 15, 16, and 17 are used in Equation 5 to calculate a value for actual infiltration, in the units used by eQUEST. The calculated value, seen for this example in Equation 6, is entered on Screen 4 of eQUEST.

$$Infiltration_{actual} = 0.038\ {}^{CFM}/_{ft^2} * \frac{25.34\ ft^2 + 30.31 ft^2}{12.67 ft^2} = \mathbf{0.167}\ {}^{\mathbf{CFM}}/_{\mathbf{ft^2}} \tag{6}$$

Appendix F

Heating Degree Day Data

This appendix details historical heating degree days for the purpose of the heat transfer model of the alternative heating scenario described in Chapter 7. Table 18 details the heating degree days, in hours, for daily working hours from a reference temperature of 72 ˚F. All days, including weekend days, are included in the monthly total at the bottom of the table. This leads to an overestimation of required energy consumption for space heater use when used in the heat transfer equation stated in Chapter 7, leading to a conservative estimate of energy savings.

Table 19 details heating degree days for the whole day from a reference temperature of 65 ˚F. This is provided to allow comparison between partial and whole day degree days. Table 18 is presented in units of heating degree hours while Table 19 is presented in units of heating degree days. The values in Table 18 should be divided by 24 hours per day to put them in the same units as Table 19. Both sets of data are calculated from Weather Underground [68] data.

Table 18

Daily Heating Degree Hours from 72 ˚F for 8 am to 4 pm, July 2013 to June 2014, from the KILG Weather Station in Wilmington, Delaware

	July	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**
1	0	4	0	21	50	232	276	245	312	169	24	22
2	0	0	0	8	77	210	310	213	262	176	57	10
3	0	0	0	5	153	179	452	303	423	93	69	3
4	0	2	6	8	226	182	398	325	393	179	96	0
5	0	5	3	2	136	152	305	300	280	144	91	27
6	0	9	32	12	100	181	244	347	342	178	49	10
7	0	1	20	12	105	259	501	300	279	200	82	3
8	0	0	1	85	190	348	413	358	157	86	70	1
9	0	0	18	96	192	290	319	355	234	101	65	2
10	0	0	0	126	116	313	297	376	198	119	10	0
11	0	1	0	75	167	325	155	384	125	21	7	29
12	0	0	0	34	272	370	221	392	137	50	4	12
13	0	4	13	60	263	298	202	291	362	34	4	0
14	0	22	74	73	176	305	207	252	258	9	86	4
15	0	12	44	50	179	258	258	294	112	57	21	8
16	0	7	50	61	173	337	285	361	253	247	68	0
17	0	6	93	29	93	317	262	366	373	188	77	0
18	0	9	68	73	57	288	314	272	275	209	73	0
19	0	6	34	96	185	243	299	266	233	93	38	0
20	0	2	21	110	239	181	218	216	156	144	11	5
21	0	0	13	94	192	79	388	169	186	110	65	21
22	0	0	30	96	155	59	499	170	135	54	24	1
23	0	0	83	142	226	122	433	160	227	137	23	1
24	0	4	77	186	339	270	456	270	326	138	28	1
25	24	8	50	181	330	353	390	325	289	118	7	0
26	1	6	39	175	279	290	393	337	317	69	2	0
27	0	0	44	138	254	252	274	317	289	109	1	0
28	1	0	31	137	288	187	467	413	132	115	18	0
29	1	0	32	129	268	224	447	-	172	187	131	0
30	2	1	36	146	290	240	395	-	210	172	57	0
31	0	0	-	77	-	297	300	-	165	-	6	-
	29	**109**	**913**	**2,536**	**5,769**	**7,638**	**10,374**	**8,376**	**7,610**	**3,703**	**1,362**	**160**

Table 19

Daily Heating Degree Days from 65 ˚F, July 2013 to June 2014, from the KILG Weather Station in Wilmington, Delaware

	July	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**
1	0	0	0	0	3	26	33	28	38	18	0	2
2	0	0	0	0	7	21	36	25	28	15	3	0
3	0	0	0	0	19	19	49	28	44	9	5	0
4	0	0	0	0	26	21	48	36	46	16	10	0
5	0	0	0	0	17	12	34	29	35	17	8	0
6	0	0	1	0	12	15	30	37	37	19	4	0
7	0	0	1	0	11	29	57	34	30	19	8	0
8	0	0	0	7	21	36	47	39	19	9	0	0
9	0	0	0	7	24	30	36	40	24	15	0	0
10	0	0	0	7	13	34	31	42	19	15	0	0
11	0	0	0	3	19	38	15	46	14	1	0	0
12	0	0	0	0	25	42	24	46	17	4	0	0
13	0	0	0	2	31	38	23	34	38	0	0	0
14	0	0	7	6	22	33	20	28	27	0	3	0
15	0	0	6	4	22	28	25	32	12	11	0	0
16	0	0	0	2	18	35	31	39	28	24	3	0
17	0	0	7	0	7	33	31	40	37	21	7	0
18	0	0	9	7	6	34	35	28	27	18	7	0
19	0	0	3	10	23	29	33	27	25	10	6	0
20	0	0	0	11	29	22	22	27	17	14	2	0
21	0	0	0	12	24	10	40	17	21	14	0	0
22	0	0	4	10	14	2	56	21	12	4	0	0
23	0	0	7	14	22	14	50	18	26	14	0	0
24	0	0	7	19	38	32	51	31	35	14	1	0
25	0	0	4	20	38	40	42	36	34	14	0	0
26	0	0	3	20	20	33	42	39	33	5	0	0
27	0	0	0	16	19	30	32	40	32	12	0	0
28	0	0	2	16	32	24	49	47	14	14	0	0
29	0	0	3	14	31	21	49	-	14	17	9	0
30	0	0	5	14	32	29	50	-	21	11	0	0
31	0	0	-	6	-	33	36	-	16	-	0	-
	0	**0**	**69**	**227**	**625**	**843**	**1157**	**934**	**820**	**374**	**76**	**2**

Appendix G

Comparison of U Values

This appendix compares U values for several common armory construction materials from different sources, including the values used in the heat transfer model described in Chapter 7, eQUEST, and reference tables [69, 70] based on values in the ASHRAE Handbook of Fundamentals. The reference tables were used as they are free to access, instead of the ASHRAE Handbook which must be purchased. The U value for each wall surface was calculated as the reciprocal of the sum of the reciprocal of each U value for the component materials. Table 20 shows that values from a reference document are similar to the values eQUEST uses. This indicates that heat transfer models that use U values from reference tables will produce similar but not identical results to simulation the armory in eQUEST.

Table 20

U Values for Materials Commonly Used in New Jersey National Guard Armories

Material	Values used for Space Heater Model (BTU/hr-ft^2-°F)	eQUEST Model of Armory 9 (BTU/hr-ft^2-°F)	Reference Text (BTU/hr-ft^2-°F)
Concrete Block 8"	-	-	0.90
Brick 4"	-	-	1.25
Single Pane Glass	-	1.097	1.10
Metal Door	-	-	2.17
Poured Concrete 6"	-	-	2.08
Tile	-	-	20.0
Carpet (fibrous pad)	-	-	0.48
Metal framing + insulation	-	-	8.55
Asphalt Shingles	-	-	2.27
Air film (interior)	-	-	0.68
Exterior Wall (4" brick + 8" concrete block)	0.243	0.435	0.30
Interior Wall (8" concrete block + 8" concrete block)	0.302	2.700*	0.27
Floor (poured concrete + carpet)	0.045	0.066	0.25
Roof (metal framing + insulation + asphalt shingles)	0.198	0.215	0.29
Whole Building	-	0.186	-

*Note: this value in eQUEST appears to be independent of interior wall construction entered in eQUEST.

Appendix H

Simplified Estimation Approach for Alternative Heating Scenario

This appendix describes an alternative approach to model space heater use in low occupancy armories as described in Chapter 7. It was noted that the use of a building simulation program limits the application of this approach. Thus, an approach was developed to eliminate the need for modeling the building in eQUEST. This approach described here is less accurate than the original, but can be done without knowledge of building simulation software. The original approach models energy consumption with temperature setbacks during unoccupied periods, while this method assumes a constant temperature setting during the heating season.

There are three significant heating scenarios for which energy consumption needs to be calculated. For these simplified estimates, electricity consumption is ignored in the two scenarios where space heaters are not used. The energy consumption in each of these two scenarios is the gas consumption of the central boiler, in heating the whole building to 72 ˚F and 55 ˚F, the occupied and unoccupied temperature setpoints. The energy consumption in the third scenario is the electricity consumption of the space heater combined with the gas consumption from the unoccupied heating scenario. Gas consumption for the first two scenarios can be calculated by comparing gas utility bills to heating degree day records. Electricity consumption from space heater use can be calculated as described in Chapter 7, using Equation 4 and U values from Appendix G.

Approach

Gather monthly gas consumption bills and monthly heating degree days for the same period, covering at least a year. The reference temperature for the heating degree days should be the occupied heating setpoint in the building. See Appendix F for a discussion about heating degree days, heating degree days for a partial day, and reference temperature.

Plot gas consumption against heating degree days as seen in Figure 23. Add a linear trend line for all data, including the equation and R^2 value. The slope of the trend line describes the heat transfer characteristics of the building envelope combined with efficiency losses in the boiler. This value is called the UA infiltration value of the building envelope and includes conduction of heat through the surfaces of the building envelope and infiltration through cracks in the building envelope.

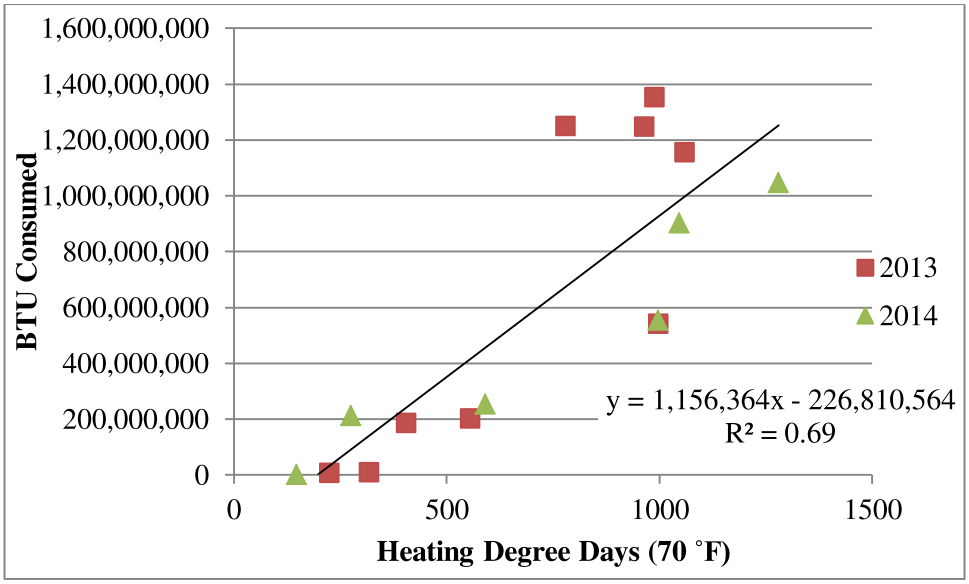


Figure 23. Plot of monthly gas consumption versus heating degree days from 70 ˚F.

As a side note, the separation of data points by year in Figure 23 allows a comparison to be made between the UA infiltration value for each calendar year. This comparison is useful in identifying the relative combined efficiency of the building envelope and HVAC system. If there is a significant difference between the slope of any linear trend-lines, the cause should be sought. Likely candidates include a change in the state of the HVAC system, such as part of the system breaking or being repaired, or a change in the state of the building envelope, such as a newly-broken window or the fixing of a hole in the envelope. Typically, the change is for the worse and this comparison facilitates identification of issues.

The UA infiltration value is used in combination with heating degree days to calculate gas consumption. For the two heating scenarios using only the central boiler, annual gas consumption is calculated as annual heating degree days times the UA infiltration value. For the occupied heating scenario, the reference temperature for the heating degree days should be 72 ˚F, the occupied setpoint. The calculated consumption for the occupied heating scenario should be close to the billed consumption for the same time period. If desired, the error inherent in this method can be approximated as the percent error between the billed consumption and the calculated gas consumption for the occupied temperature setpoint. For the unoccupied heating scenario, the reference temperature for the heating degree days should be 55 ˚F, the unoccupied setpoint.

At this point, energy consumption values for the two heating scenarios reliant on the central boiler are calculated. The next step is to calculate electricity consumption from the space heater. A more detailed explanation is contained here to facilitate better understanding of the process briefly described in Chapter 7.

Equation 4 calculates heat transfer through the building envelope, based on the thermal characteristics of each surface in a room and heating degree hours that occur during working hours. Calculating heating degree hours that occur during working hours is straightforward but time consuming, so an approximation of this value is made by taking forty percent of the total heating degree days in the heating season, from a reference temperature of 72 ˚F. In addition, an approximation for the thermal characteristics of each surface is made. Construction of each armory is close to identical, so the U values from Table 21 for materials in an armory can be used here.

Equation 7 is formed by rearranging Equation 4 and substituting in fixed values for some of the variables, such as time of work (8 hours), temperature in the occupied spaces of the armory (55 ˚F), and temperature of the ground under the armory (50 ˚F). The area terms in Equation 7 should reflect the actual area of the occupied rooms. When modeling multiple rooms, the area of interior walls between adjacent occupied rooms should be neglected from the total internal wall area, because the internal wall term calculates heat loss from an occupied room into an unoccupied room.

$$Q = \left(U_{ex\_wall}A_{ex\_wall} + U_{roof}A_{room}\right) * 0.4 * HDD_{72^\circ\mathrm{F}} + U_{in_{wall}}A_{in\_wall} * 55\ ^\circ\mathrm{F} * 8\ hours + U_{floor}A_{room} * 50^\circ\mathrm{F} * 8\ hours$$

(7)

where U_{ex_wall} is the thermal characteristic of exterior walls in BTU/hr-˚F-ft^2,

A_{ex_wall} is the area of the exterior walls in the rooms under study in ft^2,

U_{roof} is the thermal characteristic of the roof in BTU/hr-˚F-ft^2,

A_{room} is the area of the rooms under study in ft^2,

$HDD_{72^\circ\mathrm{F}}$ is heating degree days from a reference temperature of 72 ˚F for the heating season in hr-˚F,

U_{in_wall} is the thermal characteristic of interior walls,

A_{in_wall} is the area of the interior walls in the rooms under stud y in ft^2,

U_{floor} is the thermal characteristic of the floor in BTU/hr-˚F-ft^2,

This heat transfer equation calculates heat loss through the surfaces of an occupied room. The calculated heat loss is equal to the amount of heat that must be generated to keep the room at 72 ˚F. Most electric space heaters are electric resistance heaters, with negligible efficiency losses. Thus, electricity consumption from an electric resistance space heater keeping a room at 72 ˚F is equal to the heat loss through the surfaces of that room. To simplify the next step, electricity consumption as calculated in Equation 5 is kept in units of BTU.

The next step is to combine the output of Equation 5 with the gas consumption from the unoccupied heating scenario. This is energy consumption for the third heating scenario. Once combined, energy consumption between the three heating scenarios can be compared. Energy consumption from space heaters should be calculated for several different areas to determine the area at which cost and CO_2 emissions break even between use of the central boiler and use of space heaters. The specific areas should be chosen based on the floorplan and a knowledge of occupancy patterns in the armory under study.