ABSTRACT

VIOLA, ALEXANDER LUKE. Examination of the Interaction Between Lighting and HVAC and the Effect of Lighting Upgrades on HVAC Loads and Costs. (Under the direction of Dr. Stephen D. Terry.)

Conventionally, lighting and HVAC are treated as separate entities and their interaction is often overlooked. While some groups in the past have explored this relationship, none have focused on manufacturing buildings but rather commercial buildings such as offices. This paper does just that using computer modeling to attempt to quantify how these systems interplay. Additionally, the effect of upgrading lighting systems on HVAC loads is also analyzed in an attempt to discover trends between variables such as heating and cooling practices, internal heat generation, and lighting density.

Using the building modeling software eQuest, four buildings representing three different climate control methods (cooled only, cooled and heated, and heated only) were examined by simulating different lighting power densities which represented the upgrading of light fixtures to more efficient types. A second established method was employed to compare and contrast the results of this method. From this process, two major results were observed. The first major conclusion is the relationship between internal heat generation and changes in HVAC costs. As the heating rate per square foot increased, it was shown that the magnitude of change in HVAC costs as a percentage of total utility cost increased nearly linearly. This indicates that buildings which have processes which produce greater amounts of heat per square foot of building area have a greater potential for both HVAC savings and penalties depending on the heating and cooling practices of the facility. The second major result is the discovery of trends in the relationship between lighting power savings from a lighting

upgrade and the resulting HVAC energy savings. From the models, ratios were calculated which allow for estimation of potential changes in HVAC energy usage based on the lighting upgrade power reduction and the heating and cooling practices of the building. This allows for conservative estimation of additional savings or penalties to be calculated when proposing a lighting upgrade project and more accurate overall energy savings and payback time lengths to be determined.

Examination of the Interaction Between Lighting and HVAC and the Effect of Lighting Upgrades on HVAC Loads and Costs

by
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DEDICATION

Dedicated to my awesome wife who always supported me no matter what, my dad, Nonna and Papa, my siblings, my pups, and sidewalks – for keeping me off the streets.

BIOGRAPHY

Alexander (Alex) Luke Viola was born to Alexander James Viola and Diane Lyn Viola in the late 20th century in Staten Island, NY. His family moved to New Jersey shortly afterwards and had four children after Alex, making him the oldest child in a family of four boys and one girl. Alex was always interested in science, technology, and how things worked. He attended Belvidere High School where he graduated in 2009. He then went on to study at Ithaca College until 2013 for his Bachelor in Science in Physics with a minor in Mathematics. Immediately following his B.S. degree, Alex enrolled at North Carolina State University in 2013 for his Masters of Science in Mechanical Engineering degree. He was married on September 20, 2014, in his second year of graduate school. He will complete his MSME degree in July 2015.

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1 INTRODUCTION

1.1 Lighting in the United States

In the United States in 2010, 52 billion kWh of electricity were used to illuminate manufacturing facilities, adding up to 1.3% of the total country's electrical consumption [1]. With such a large amount of energy being used, there are significant opportunities to reduce energy usage and therefore reduce costs. Some examples of such opportunities are making sure lights are turned off when employees leave rooms unattended, installing occupancy sensors to automatically turn lights off or photocells to turn lights off when ambient lighting is present, and upgrading fixtures to newer, energy efficient types. Each of these strategies have both pros and cons.

If all employees turned off lights when not in use, an enormous amount of energy could be saved. This can be a great option because there is almost no cost to implement besides taking time to increase awareness. However, this is not always possible to do because many areas in a manufacturing facility must be constantly lit for safety purposes. Additionally, it can be difficult to make people understand how much energy can be saved by turning lights off consistently. Occupancy sensors and photocells can help alleviate some of these problems because they automatically will turn lights on and off depending on the conditions present. As they are not too expensive, implementing these is often relatively easy. Once again though, these cannot help save energy in parts of the building which must remain lit at all times. Another problem is that many times, occupancy sensors are not set correctly which results in lights being turned off even when people are present. This leads to many people not wanting to use them at all to avoid the annoyance altogether. Upgrading lighting fixtures tends to have much higher savings than any other options as well as having other benefits. The issue with this solution is the sheer cost generally involved. This leads a long period of time before the project pays itself off. The implementation cost is generally difficult to change with the exception of things such as rebates offered by some utilities for replacing older fixtures with energy efficient types. The only other way to reduce the time required for the project to payback is to find additional savings beyond the typical ones associated with upgrading light fixtures.

1.2 Project Objective

Anyone that has ever owned a car for a long period of time knows that eventually there comes a time when the decision has to be made of whether or not to buy something new or continue the old. The repercussions of not upgrading often include high maintenance costs, limited repair support, low efficiency, and poor performance. Buying something new can often remedy all of these problems but it can be difficult to justify the often high initial price. Fuel savings, reduced maintenance costs, and better performance all help but sometimes even that is not enough to convince one to make the jump. Sometimes, however, there are advantages that are neglected which can make a big enough difference to warrant the upgrade. Often forgotten, a new car can help to reduce insurance rates because of advanced safety features that make the car less likely to be in an accident. On the flip side, sometimes a new car can increase insurance rates because the car is worth more and therefore more expensive to insure.

There is a direct parallel with this scenario and lighting upgrades in industrial facilities. Upgrading lighting has many advantages such as increased energy efficiency, reduced maintenance, and better light quality. Even so, the large implementation cost can sometimes take too long to payback based on estimated savings that project never gets approved. Just like with the car example, there is an advantage to upgrading lighting that is often neglected and can make a large enough difference to push the payback low enough to justify the investment. This savings is the reduced heat load on the HVAC system from decreased lighting power consumption.

The main objective of this study is to see if and how significantly lighting upgrades can either help or hurt payback lengths. This is done by examining four facilities which were the subject of energy assessments by the Industrial Assessment Center (IAC) at North Carolina State University, funded by the Department of Energy (DOE). In each facility, the building is modeled using the QUick Energy Simulation Tool: eQuest [2]. The heating and cooling loads are calculated which are verified by comparing the utility bills produced by the software and those obtained during the assessment.

Two simulations are run through the model. The first is using the lighting currently present in the facility. The second uses either a proposed facility-wide lighting upgrade or an estimated "historical" lighting configuration. This is used because some facilities have either already upgraded to newer fixtures or were built recently. Creating a hypothetical lighting configuration allows for a comparison to be made between what is currently installed and what would be typically upgraded from. Comparing these, the energy usage changes and cost differences based on utility rates are added to the expected savings calculated from upgrading the lighting. Ultimately, the goal is to determine how lighting power reductions affect HVAC power consumption and how these results can be applied to other buildings.

1.3 Literature Review

Published in April 1998, the study done by Osman Sezgen and Jonathan G. Koomey examined the effect of lighting density changes on various commercial buildings throughout the United States [3]. The approach was not to use individual real world buildings to represent all types of commercials buildings but rather create prototypes that were generic and could be representative of many individual buildings in a given sector. In total, 75% of commercial building area were represented by these prototypes. Five different climates were used to include buildings from all over the country. Simulations were run using a user-defined DOE-2 function.

The two major results derived from the simulations are the building loads and lighting/HVAC coincidence factors and the effects of HVAC distribution system on building loads. The authors varied the lighting levels in simulations and observed the interaction between the lighting and HVAC loads. Across all simulations, the lighting energy consumption was reduced by 1 kWh and the changes in HVAC energy use were observed. When decreasing the lighting density in the buildings, the cooling load saw a reduction while the heating load increased. Coincidence factors were used to include when lighting was on and when heating or cooling was being called for. The study found less coincidence for heating than cooling due to the fact that lighting is more often used during the day when more cooling is being used and heating is more often used at night when buildings are generally vacant [3].

The results of their study were that, in general, across all building types and geographic locations, there is no significant HVAC related savings or additional costs when the lighting density is decreased [3]. However, the authors did find that when looking at individual climate zones, warmer climates tend to see measurable savings from cooling while cooler climates tend to see increased costs from heating.

R. Zmeureanu and C. Peragine used slightly different approach in their approach to this topic [4]. Focusing on commercial office buildings, their method was to create a model which would be evaluated using the program DOE-2.1D. Its accuracy would be determined by comparing the utility bills generated by the simulation to the actual utility bills from the building. It was located in Montreal, Canada. The model itself was an existing office building with 28 above ground floors and approximately 100,000 ft^2 of floor area. The also inputted various information such as energy consumption and HVAC system specifications.

Good agreement was found between the actual and simulated bills with overall energy consumption within 3.8% of the measured and monthly bills with 8.6% and 9.2% for electricity consumption and electricity cost, respectively. Lighting power densities simulated included 10, 15, 20, and 25 W/m^2. These were based on three different types of light fixtures: suspended, recessed unvented, and recessed vented. The equation used to determine the overall results is shown below:

$$\text{Net Energy Savings (NES)} \quad = \quad (1 + H_C - H_H) \times GES$$

where NES is the Net Energy Savings after the gross electricity savings are combined with the gross change in HVAC costs, H_C is the ratio between the reduction of electricity use for space cooling and the gross reduction of electricity use for lighting, H_H is the ratio between the increase of electricity use for space heating and the gross reduction of electricity for lighting, and GES is the gross energy savings from the lighting system upgrade. Ultimately, if the savings when cooling were greater than the penalties when heating, NES would be greater than GES and the system would be more cost effective than initially expected. If the heating penalties were greater than the cooling savings, NES would be less than GES and the system would be less cost effective than initially expected [4].

The results of this study showed that for their model, NES was smaller than GES due to the heating penalties being greater than the cooling savings. After including this additional cost, the net energy savings was shown to be only 70% of the gross electrical savings from the lighting upgrade. This translates to a net loss of 30% of lighting savings. This is due in part to two major points. The first is that the building in question is located in a cold environment, Montreal, which has higher heating usage than cooling by default. The second is the type of building itself. As an office building, the internal heat generation is much lower than those seen in manufacturing facilities. The hours of operation are generally much different with manufacturing being either much longer or simply around the clock. Additionally, the light fixtures are different in manufacturing buildings, and they often use higher power fixtures rather than the lower power fixtures in office buildings [4].

Another study, this time from China, saw the opposite results of the studies so far discussed. Joseph C. Lam, C.L. Tsang, and Liu Yang examined how lighting density impacted heating and cooling loads in different climates in China [5]. They conducted energy simulations for five different cities with lighting densities ranging from 10 to 30 W/m^2 using the program DOE 2.1E. Five different climates were included and simulated through all parts of the year. Two separate analyses of the results were conducted. The first was how lighting affected heating and cooling loads and the second is the relationship between changing light density and the cooling savings and heating penalties. The model used for this study was a generic office building which served as a baseline reference for comparative energy studies.

The results of this study showed that “the cooling influence coefficient was several times larger than the heating influence coefficient, and the north zone tended to have the largest influence coefficient and vice versa”. In respect to how lighting impacted heating and cooling loads, it was determined that lighting made up a small part of the total heating load but a large part of the cooling loads. Comparing heating and cooling loads, the total cooling loads was determined to always be bigger than the total heating load when both were measured in terms of MWh. While that actual cost differences would depend on the fuel types used for heating, lighting had greater positive effect on cooling energy consumption than the negative effect on heating. The major difference between this and the previously examined studies is the climates in which the simulations were conducted. According to the Lam et al., 98% of China’s land area is between subtropical zones and temperate zones. Compared to the continental United States from the first study and Montreal, Canada from the second, this is a significant difference in climates [5].

Robert A. Rundquist, P.E., Karl F. Johnson, and Donald J. Aumann, P.E. wrote a paper which presented a method for calculating the interactions between lighting and HVAC. It presented a method for estimating the effects on HVAC loads when reducing the lighting power consumption. This method started with the anticipated lighting power reduction and combined this with the hours per year the lights were on including a diversity factor which accounted for some lights being turned off during the course of the day [6].

From here the calculations used a fractional coefficient which accounts for the amount of cooling and the amount of heating done in a building based on its geographic location and therefore climate. Building area to perimeter ratio is included for building heating. System seasonal marginal coefficient of performance for cooling equipment and seasonal efficiencies for heating equipment are also included. The results of this method allow for a monetary cooling savings and heating penalty to be calculated [6].

The limitation of this method is that was designed for use in commercial buildings such as offices. There are significant differences between manufacturing facilities and offices with the largest being internal heat generation. The paper notes that large commercial buildings often do not need heating during the day but manufacturing buildings may not require any heating at any point throughout the year depending on what they produce [6]. This method will be explored later in this paper to see how well it compares to the methods proposed here.

As seen by the sample of studies discussed here, there have been numerous attempts to determine the effect on heating and cooling costs when changing lighting densities. While the methods used are similar, the results are shown to be quite different depending on what type of building is being modeled and where the building is located. The takeaway from all of these previous studies and more comes down to two things. First is that modeling of different building types using a generic model to represent multiple, individual buildings is an acceptable way to examine the trends seen in the relationship between lighting and heating/cooling. This is the same approach that is take in our study. Second is that model location and therefore climate is perhaps the single biggest independent variable in determining lighting effects. Our study limits this to geographic variable substantially to include only North Carolina and potentially buildings located in Virginia and South Carolina as they are geographically very close and are all part of the humid subtropical climate zone [7].

2 FACILITY MODELING

2.1 Overview

The goal in modeling the following buildings is to develop simple models to observe the trends in the changes in HVAC energy consumption, both heating and cooling. Rather than model one building with a high degree of accuracy, a generic model is used for all of the facilities. Major differences such as square footage, heating and cooling systems and set points, location, hours of operation, lighting power density, and process heating density are changed for each simulation. Determining process heating is accomplished by using December as the baseline for average power consumption as that is typically the month with one of the least cooling loads. From this value, compressor and lighting power usage are removed to increase the accuracy of the process heating value.

Variables such as building construction materials are kept the same for each facility to attempt to remove independent variables which may cause discrepancies between the different buildings not related to the lighting upgrade effect. In some cases, the building is a good candidate for a lighting upgrade because of the fixtures currently installed. For these buildings, a proposed lighting list is created with fixtures that would be ideal replacements for those currently installed. In others, the building already has most if not all of the recommended fixture types installed. In these cases, a "historical" list is created which is a list of hypothetic fixtures which would normally be replaced with the lights currently installed. All of this is in an effort to observe the effect of reducing the lighting power on cooling and heating loads throughout the year.

In some cases, these lighting upgrades have a net cost saving effect which will be reported in percentage of savings obtained directly from the lighting upgrade which servers to reduce the expected payback period. In other cases, there may be a net cost increase effect which serves to increase the payback length. By using these simplified models, the end result is to determine which buildings (heated only, cooled only, or heated and cooled) typically see either cost increases or decreases and the typically magnitude of these changes.

2.2 Lighting Upgrade

Before tackling the HVAC side of this project, the lighting specific savings from a facility wide upgrade must be calculated. Created by a previous IAC student, Andrew Murphy, "New Lighting" was an excel spreadsheet which organizes the many properties of various fixtures types and allows for prefilled cells to perform fast calculations for lighting upgrades. The cost data was based of the 2011 RSMeans Electrical book which compiles cost data for industry wide equipment as well as labor costs and individual state and city variations [8].

Part of this project included taking this spreadsheet program and making significant improvements and optimizations. In addition to upgrading the price data to the current year [9], work was done in order to automate the vast majority of program's operation in an effort to reduce user error and streamline calculations. Once the current and proposed fixtures have been added as well as facility specific information, new Visual Basic for Applications (VBA) coding automatically creates the tables and imports the cost data from the RSMeans tables.

For this project, the ability to accurately calculate the implementation costs, savings, and expected payback is vital in determining the effect of changing HVAC loads and costs.

2.3 Paperboard Packing

2.3.1 Facility Information

The first manufacturing building study for this project is a paperboard packaging facility. Located in Central North Carolina, this facility had a total area of 173,000 ft^2. The facility did not space heat as the process produced enough heat such that the building was cooled nearly year round with no heating. For utilities, the facility paid \$0.040/kWh, \$10.42/kW, and \$8.52/MMBTU of natural gas. Manufacturing occurring around the clock, 24/7 for a total of 8,400 hrs/yr.

At the time of the assessment, the building was lit using a combination of metal halide and fluorescent T12 fixtures making it an ideal candidate to study for potential additional savings when upgrading lighting. The facility also employed the use of two rotary screen air compressors which were data logged during the assessment.

Using Newer Lighting, the current lighting list, energy use, and electrical and maintenance costs were calculated and shown below in Table 1.

Table 1: Current Fixtures Installed in Paperboard Packaging Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Sheeting	400W-MH	55	8,400	25.19	211,596	$12,882
Roll Storage	400W-MH	20	8,400	9.16	76,944	$4,684
Corrugated Cardboard	400W-MH	8	8,400	3.66	30,778	$1,874
Shipping	400W-MH	8	8,400	3.66	30,778	$1,874
Garage	400W-MH	12	8,400	5.50	46,166	$2,811
Compressor Room	4xF34-T12	6	8,400	0.98	8,266	$522
Sheeting	1xF96-T12	60	8,400	5.64	47,376	$3,147
Sheeting	2xF34-T12	52	8,400	4.26	35,818	$2,263
Corrugated Cardboard	1xF96-T12	12	8,400	1.13	9,475	$629
Shipping	1xF96-T12	8	8,400	0.75	6,317	$420
Maintenance	1xF96-T12	14	8,400	1.32	11,054	$735
Main Floor	1xF96-T12	526	8,400	49.44	415,330	$27,594
Storage	1xF96-T12	120	8,400	11.28	94,752	$6,296
Folding/ Gluing	1xF96-T12	98	8,400	9.21	77,381	$5,141
Folding/ Gluing	2xF96-T12	108	8,400	18.68	156,946	$10,584
Waste Extraction	1xF96-T12	100	8,400	9.40	78,960	$5,246
Flexo	4xF34-T12	44	8,400	7.22	60,614	$3,829
Garage	2xF96-T12	8	8,400	1.38	11,626	$784
Offices	4xF34-T12	270	2,500	44.28	110,700	$10,882
U bends	2xF34-T12	33	2,500	2.71	6,765	$665
U bends	4xF40-T12	4	4,250	0.77	3,264	$244
Total		1,566		215.63	1,530,904	$103,105

With a yearly energy consumption of 1,530,904 kWh and 8,400 hrs/yr. of production time, the average lighting power is calculated to be 182.25 kW. In order to determine how much heat is created by the process, the utility bills must be examined.

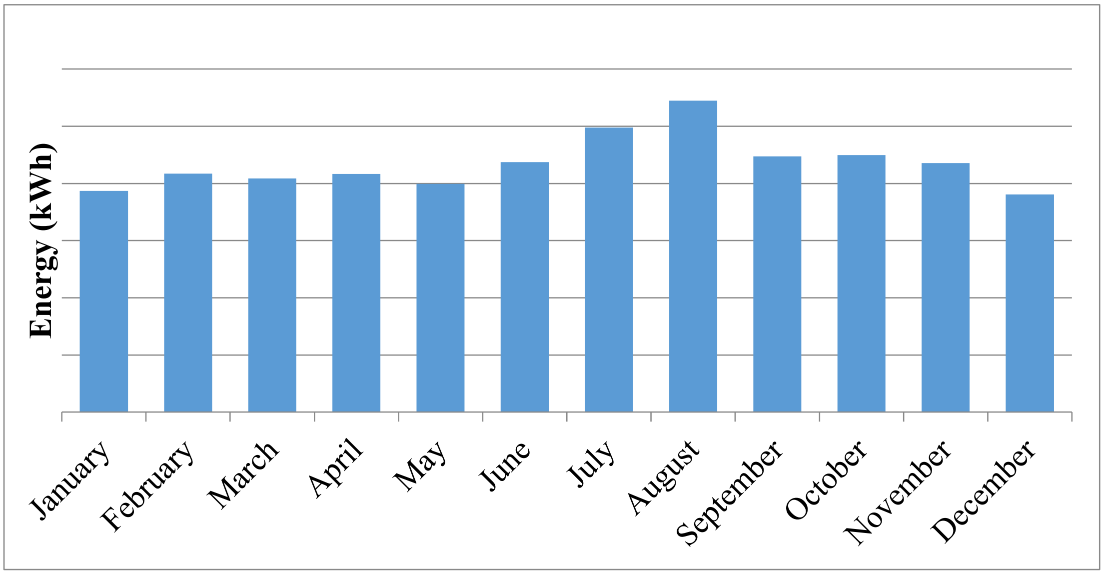


Figure 1: Electric Utility Bills for Paperboard Processing Facility

Looking at the bills, a normal trend is seen in that the electrical consumption is lower in the winter and higher in the summer when HVAC use is the greatest. In order to determine how much heating is done by the process, we need to determine the energy consumption after the HVAC energy use is removed as the energy consumed by this equipment is forced out of the building rather than warming it. To do this, a simple assumption must be made. During the assessment visit, the plant manager stated that no space heating is done and the facility is cooled nearly year round. From this, it can be gathered that during the coldest parts of the year, the HVAC system is turned off as the process heat is just enough to maintain comfortable temperatures inside the facility while not requiring any additional cooling beyond natural means such as shell losses and infiltration.

Based on this idea, we see that the month with the lowest energy use is January with 761,633 kWh. As the facility is operating 24/7, can determine what the average power consumption is to use as a baseline for process heat generation:

Average Power (kW)	=	kWh/month / (days/month x hours/day)
	=	761,633 kWh/month / (30 days/week x 24 hours/day)
	=	1,057.8 kWh/hour
Average Power	=	1,057.8 kW (average)

On average, 1,057.8 kW of electricity are being consumed in the facility. However, not all of this electricity is contributing to the heating of the building. The facility used air compressors which are vented outdoors. During the assessment visit, the air compressors were logged to see what their typical usage was. Figure 2 below shows the data that were collected.

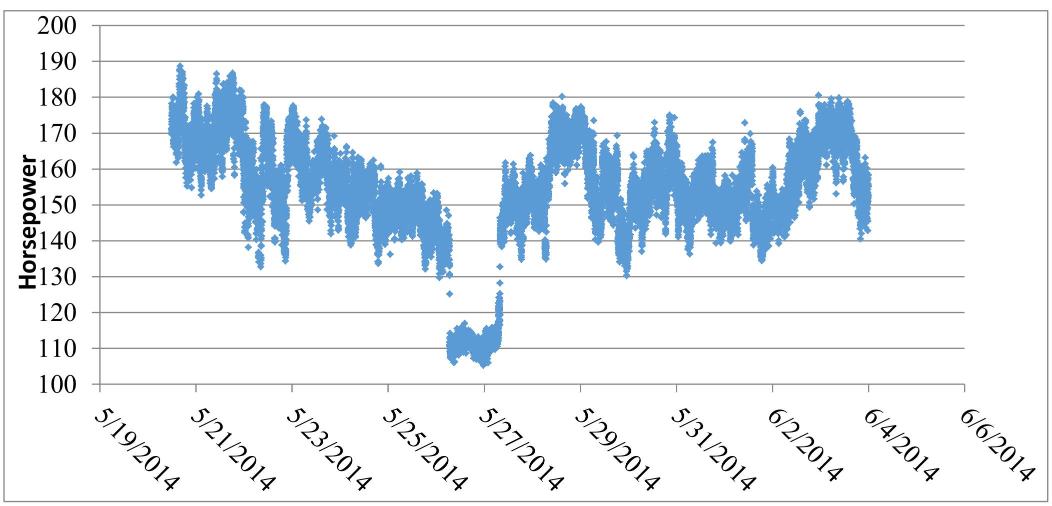


Figure 2: Sum of Compressors' Power at Paperboard Packaging Facility

From the data, it was determined that the average combined horsepower of the compressors was 153.2 HP. This value was then converted to kilowatts below:

$$\text{Compressor Power} = 153.2 \text{ HP} \times 0.75 \text{ kW/hp}$$
$$= 114.9 \text{ kW}$$

This means that of the original 1,057.8 kW consumed by the facility, 114.9 kW is being vented outdoors. Finally, all that is needed is to subtract the 182.25 kW used to light the facility as to not double count it, giving us the power used by the process equipment and the HVAC units:

$$\text{Process Heating (kW)} = 1{,}057.8 \text{ kW} - 114.9 \text{ kW} - 182.25 \text{ kW}$$
$$= 760.65 \text{ kW}$$

Converting this to BTUh:

$$\text{Process Heating (BTUh)} = 760.65 \text{ kW} \times 3{,}412 \text{ BTUh/kW}$$
$$= 2{,}595{,}337.8 \text{ BTUh}$$

On average, 2,595,337.8 BTUh of heating is done by the process inside the building. With this information, the model was built using eQuest.

2.3.2 eQuest Model

The first step in creating the model for the building is to input its construction information. Instead of using exactly the type of building construction used, more generic values are to make it easier to use the same modeling parameters across multiple buildings being studied for this project and reduce the number of independent variables. The construction parameters are shown below as seen in the program for ease in understanding.

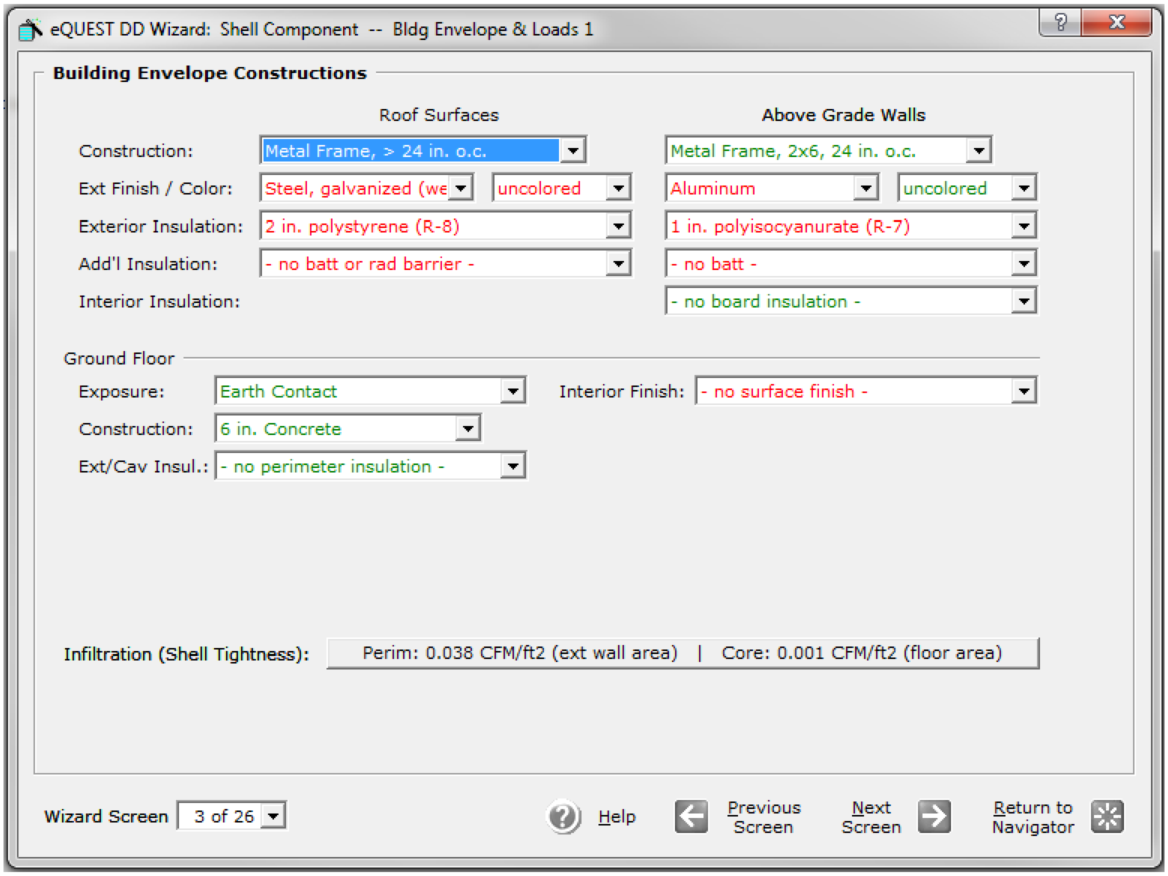


Figure 3: Construction information for the Paperboard Packaging facility

In general, the model was kept as simple as possible to keep lighting changes the central focus of the report. This means that the following items were excluded or removed during the modeling process: Interior ceilings, interior walls, interior and exterior door, and exterior windows. While adding these objects would make the model behave more closely to the building it is based off of, that was not the goal.

The building operation schedule was set to be open 24 hours per day and 7 days per week but closed on holidays. The entire model was simplified to consist of only one area which took up 100% of the square footage. While the building could have been split up into multiple where offices were separate, the manufacturing area was the vast majority of the space and this allowed for further simplification and standardization between modeling different buildings. In this area, the design occupation is input as 7 people per 1,000 ft^2 or 143 ft^2 per person based on ASHRAE Standard 62.1-2010. The design ventilation is 10 CFM/person from the same source.

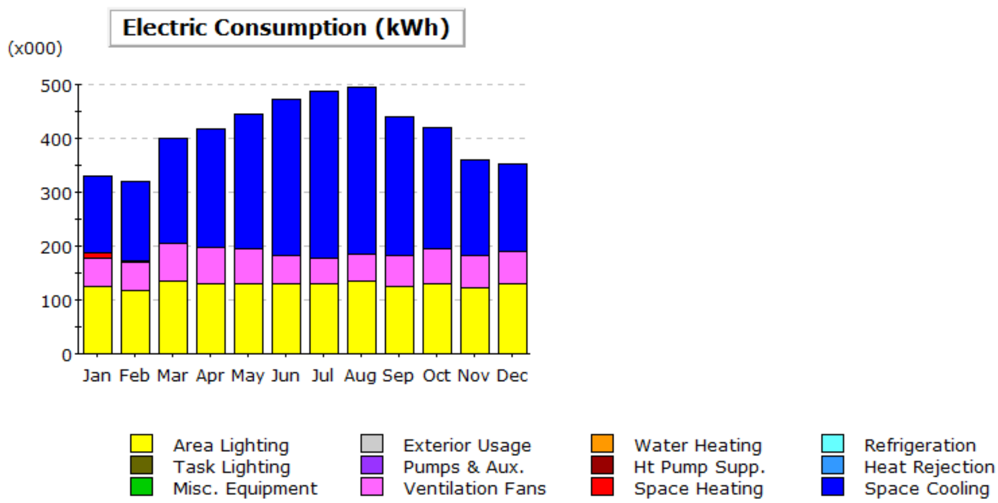
The lighting density unit is Watts per square foot which is found by dividing the average lighting power consumption by the square footage of the building:

$$\text{Lighting Density (W/ft}^2\text{)} = 182.25 \text{ kW x } 1{,}000 \text{ W/kW / } 173{,}200 \text{ ft}^2$$
$$= 1.05 \text{ W/ft}^2$$

For the process load, that average value determined previously needs to be converted to BTUh/ft^2. This was done by dividing by the square footage of the building:

$$\text{Process Density (BTUh/ft}^2\text{)} = 2{,}595{,}337.8 \text{ BTUh / } 173{,}200 \text{ ft}^2$$
$$= 14.98 \text{ BTUh/ft}^2$$

With the characteristics of the building entered, the heating and cooling systems can be input. The facility uses a combination of a chiller and package units to cool the facility but to simplify and standardize, the cooling source will be direct expansion refrigerant coils with electric resistance heating if the simulation called for it. The set points were chosen to be cooling at 75°F and heating at 65° to maintain comfort. Finally, the humidity set point was chosen to be a maximum of 50% to protect the product with reheat being done via electric strip. All sizing of equipment was automatically done by eQuest. With all of these variables set, the simulation could be run. As the bills that were obtained were from 2014, the simulation was set to use that year's weather data for Greensboro. Shown below in Figure 4 are the energy consumption plots and tables generated by eQuest for the heating and cooling of the building.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	143.0	147.9	195.4	219.4	249.2	289.8	309.9	311.1	258.6	224.3	176.2	162.1	2,687.0
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	9.2	0.3	-	-	0.9	-	0.4	-	0.3	0.4	0.5	0.2	12.2
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	51.8	54.4	71.5	68.4	64.1	53.7	48.3	50.3	56.2	65.8	61.5	61.2	707.1
Pumps & Aux.	0.0	-	-	-	-	-	-	-	-	-	-	0.0	0.0
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	125.6	116.8	133.9	129.6	129.8	129.6	129.8	133.8	125.6	129.8	121.3	129.8	1,535.5
Total	329.6	319.4	400.9	417.4	444.0	473.2	488.3	495.1	440.7	420.3	359.5	353.3	4,941.8

Figure 4: Heating and Cooling Energy Consumption at Paperboard Packaging Facility with Current Lighting

It can be seen that unlike the early assumption, cooling is taking place year round though much more is occurring during the summer than the winter. Additionally, it can be seen that there is a very small amount of heating being done by the electric strip heaters during the winter. A small amount of heating is done during the summer months by the electric strip in the form of reheat.

While this model does not fit the facility in question exactly, it does show the important trends that were being searched for. As such, this model is a good candidate to observe the difference in energy consumption of the heating and cooling systems after a facility wide lighting upgrade.

2.3.3 Lighting Upgrade

The facility currently employed metal halide and fluorescent T12 fixtures to illuminate the building. A typical recommendation seen in the IAC would be to upgrade all of the fixtures to fluorescent T8s. In Table 2 below, the recommended fixtures are listed with their power and energy consumptions and electrical and maintenance costs.

Table 2: Upgraded Lighting for Paperboard Packaging Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Sheeting	6xF32-T8	55	8,400	12.10	101,640	$7,034
Roll Storage	6xF32-T8	20	8,400	4.40	36,960	$2,558
Corrugated Cardboard	6xF32-T8	8	8,400	1.76	14,784	$1,023
Shipping	6xF32-T8	8	8,400	1.76	14,784	$1,023
Garage	6xF32-T8	12	8,400	2.64	22,176	$1,534
Compressor Room	4xF32-T8	6	8,400	0.64	5,393	$333
Sheeting	2xF32-T8	60	8,400	3.30	27,720	$1,706
Sheeting	2xF32-T8	52	8,400	2.86	24,024	$1,479
Corrugated Cardboard	2xF32-T8	12	8,400	0.66	5,544	$341
Shipping	2xF32-T8	8	8,400	0.44	3,696	$228
Maintenance	2xF32-T8	14	8,400	0.77	6,468	$398
Main Floor	2xF32-T8	526	8,400	28.93	243,012	$14,959
Storage	2xF32-T8	120	8,400	6.60	55,440	$3,413
Folding/ Gluing	2xF32-T8	98	8,400	5.39	45,276	$2,787
Folding/ Gluing	4xF32-T8	108	8,400	11.56	97,070	$5,993
Waste Extraction	2xF32-T8	100	8,400	5.50	46,200	$2,844
Flexo	4xF32-T8	44	8,400	4.71	39,547	$2,442
Garage	4xF32-T8	8	8,400	0.86	7,190	$444
Offices	4xF32-T8	270	2,500	28.89	72,225	$6,996
U bends	2xF32-T8	33	2,500	1.82	4,538	$438
U bends	4xF32-T8	4	4,250	0.43	1,819	$138
Total		1,566		126.01	875,506	$58,111

The T12 fixtures have all been upgraded to matching T8 fixtures:

- 2 lamp, 4 ft. T12s to 2 lamp, 4 ft. T8s
- 4 lamp, 4 ft. T12s to 4 lamp, 4 ft. T8s
- 1 lamp, 8 ft. T12s to 2 lamp, 4 ft. T8s
- 2 lamp, 8 ft. T12s to 4 lamp, 4 ft. T8s

The 400 Watt metal halides have all been upgraded to 6 lamp, 4 ft. T8s. When deciding which fixtures to choose for replacements, an important consideration is to try and consolidate all lamps to one type to make maintenance as easy as possible rather than having to keep multiple types of lamps in stock.

With the all of the changes implemented, the total demand of the lighting drops from 215.63 kW to 126.01 kW and the yearly energy consumption decreases from 1,530,904 kWh to 875,506 kWh. The annual total savings from this upgrade are shown below in Table 3.

Table 3: Savings from Upgrading Lighting at Paperboard Packaging Facility

Area	Demand Savings (kW)	Energy Savings (kWh)	Electrical Savings	Maintenance Savings	Total Savings
Sheeting	13.09	109,956	$6,035	-$186	$5,849
Roll Storage	4.76	39,984	$2,195	-$68	$2,127
Corrugated Cardboard	1.90	15,994	$878	-$27	$851
Shipping	1.90	15,994	$878	-$27	$851
Garage	2.86	23,990	$1,317	-$41	$1,276
Compressor Room	0.34	2,873	$158	$32	$189
Sheeting	2.34	19,656	$1,079	$362	$1,441
Sheeting	1.40	11,794	$647	$137	$784
Corrugated Cardboard	0.47	3,931	$216	$72	$288
Shipping	0.31	2,621	$144	$48	$192
Maintenance	0.55	4,586	$252	$85	$336
Main Floor	20.51	172,318	$9,458	$3,178	$12,635
Storage	4.68	39,312	$2,158	$725	$2,883
Folding/Gluing	3.82	32,105	$1,762	$592	$2,354
Folding/Gluing	7.13	59,875	$3,286	$1,305	$4,591
Waste Extraction	3.90	32,760	$1,798	$604	$2,402
Flexo	2.51	21,067	$1,156	$231	$1,387
Garage	0.53	4,435	$243	$97	$340
Offices	15.39	38,475	$3,463	$422	$3,886
U bends	0.89	2,228	$201	$26	$226
U bends	0.34	1,445	$100	$4	$105
Total	89.62	655,398	$37,423	$7,571	$44,994

In total, annual savings, excluding heating and cooling, from upgrading the lighting are $44,994/yr. The total costs for implementing these upgrades are shown below in Table 4.

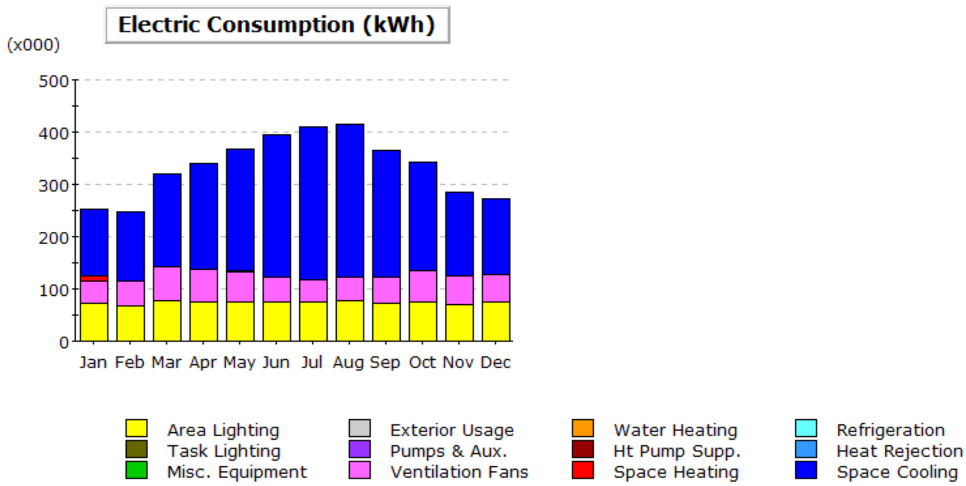
Table 4: Implementation Costs and Expected Payback for Paperboard Packaging Facility

Area	Total Annual Savings	Implementation Costs	Payback (Months)
Sheeting	$5,849	$12,023	25
Roll Storage	$2,127	$4,372	25
Corrugated Cardboard	$851	$1,749	25
Shipping	$851	$1,749	25
Garage	$1,276	$2,623	25
Compressor Room	$189	$623	40
Sheeting	$1,441	$5,757	48
Sheeting	$784	$4,989	76
Corrugated Cardboard	$288	$1,151	48
Shipping	$192	$768	48
Maintenance	$336	$1,343	48
Main Floor	$12,635	$50,470	48
Storage	$2,883	$11,514	48
Folding/Gluing	$2,354	$9,403	48
Folding/Gluing	$4,591	$11,216	29
Waste Extraction	$2,402	$9,595	48
Flexo	$1,387	$4,570	40
Garage	$340	$831	29
Offices	$3,886	$28,040	87
U bends	$226	$3,166	168
U bends	$105	$415	48
Total	$44,994	$166,369	44

The total implementation cost for this lighting upgrade is $166,369 which is expected to payback in 44 months based on the annual savings.

For the simulation, the reduction in annual kWh consumption reduces the average power consumption from 182.25 kW to 104.23 kW. This results in a decreased lighting density of

0.60 W/ft^2. As this is the only change that needed to be changed, the simulation can be run again immediately to observe the effects. Figure 5 below shows the new energy consumption plots and tables.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	127.8	133.7	179.1	203.6	232.8	272.7	292.3	293.2	242.3	208.2	161.1	146.0	2,492.7
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	9.5	0.3	-	-	1.0	-	0.3	-	0.3	0.4	0.5	0.0	12.3
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	43.8	47.7	65.0	63.5	59.1	49.1	44.1	45.9	51.5	60.5	55.2	53.1	638.7
Pumps & Aux.	0.0	0.0	-	-	-	-	-	-	-	-	-	0.0	0.0
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	71.8	66.8	76.5	74.1	74.2	74.1	74.2	76.4	71.8	74.2	69.3	74.2	877.4
Total	252.9	248.4	320.6	341.1	367.0	395.9	411.0	415.6	365.9	343.3	286.1	273.2	4,021.1

Figure 5: Heating and Cooling Energy Consumption at Paperboard Packaging Facility with Proposed Lighting

While the general trend seen in the plot appears to be the same, there is a significant decrease in the electrical consumption of both Space Cooling and Ventilation and only a very small increase in the space heating when the lighting density is decreased. With both simulations run for this facility, the model and simulations of the second facility are next.

2.3.4 Analysis

The analysis of the simulation before and after the lighting upgrade will examine three major pieces: change in cooling energy consumption, change in heating energy consumption, and change in ventilation fans energy consumption. The cost will be based on each facility's utility rates and compared to the savings calculated from upgrading the lighting.

According to the simulation, the total annual HVAC energy consumption before the lighting upgrades is as follows:

- Space Cooling: 2,687.0 MWh
- Space Heating: 12.2 MWh
- Ventilation: 707.1 MWh

After upgrading the lighting, these values become:

- Space Cooling: 2,492.7 MWh
- Space Heating: 12.3 MWh
- Ventilation: 638.7 MWh

The net energy savings is shown below:

$$
\begin{aligned}
\text{HVAC Savings (MWh)} &= \text{Net Cooling} + \text{Net Heating} + \text{Net Ventilation} \\
&= (2{,}687.0\text{ MWh} - 2{,}492.7\text{ MWh}) \\
&\quad + (12.2\text{ MWh} - 12.3\text{ MWh}) \\
&\quad + (707.1\text{ MWh} - 638.7\text{ MWh}) \\
&= 194.3\text{ MWh} + (-0.1)\text{ MWH} + 68.4\text{ MWh} \\
&= 262.6\text{ MWh}
\end{aligned}
$$

Throughout the course of the year, the HVAC system will see a net savings of 262.6 MWh. To determine the costs savings, this value must be converted to kWh and multiplied by the facility's energy rate.

$$\text{Cost Savings (\$/yr.)} = 262.6 \text{ MWh} \times 1{,}000 \text{ kWh/MWh} \times \$0.04/\text{kWh}$$

$$= \$10{,}504/\text{yr.}$$

In total, there is a net decrease in HVAC costs of $10,504/yr. According to the calculations done using Newer Lighting, the savings directly from the lighting upgrade are $44,944/yr. Therefore, the HVAC savings are an additional 23.4% of lighting savings. Originally, the expected payback was calculated to be 44 months. Including the additional HVAC savings, this payback is reduced to 36 months.

2.4 Assembly Manufacturing

2.4.1 Facility Information

The second building studied for this project was a facility which performs hand assembly of heavy components. Located in central North Carolina, the building had a total square footage of 33,000 ft^2 which were both heated and cooled year round. Cooling was done using package units and heating was done using natural gas packs. Utilities cost $0.0676/kWh, $4.20/kW, and $9.14/MMBTU of natural gas.

Production was scheduled for 2 shifts per day Monday through Friday for a total of 4,000 hours per year. At the time of the assessment, the building was lit with a combination of T5, T8, and T12 fluorescent fixtures. The main part of the facility used a 50 hp compressor which was logged during the assessment.

The average power consumption of the lighting is 44.77 kW. Unlike the previous facility, this building had already undergone lighting upgrades. As almost all of the fixtures in place are what would have been recommended, what was done is to create a possible historical lighting list which would have been present before the upgrade. To do this, a lighting list was created which essentially rolled back all of the lights to what the current lights would typically replace.

Additionally, as there are a few outdated lights still in use in the building, a second lighting list was created which would be considered the ideal lighting configuration. In the end, there will be a lighting upgrade from one typical older lighting configuration, or 'historical', to another typical modern lighting configuration, both of which are hypothetical but built using the current configuration as a base. The typical older list is shown below in Table 5.

Table 5: Historical Fixtures Installed in Assembly Manufacturing Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Conference Room	4xF34-T12	4	4,000	0.66	2,624	$233
Main Production Area	250W-MH	72	4,000	21.10	84,384	$7,906
Main Production Area	2xF96-T12	4	4,000	0.69	2,768	$259
Assembly	400W-MH	14	4,000	6.41	25,648	$2,220
Ovens	400W-MH	10	4,000	4.58	18,320	$1,585
Cleaning	400W-MH	12	4,000	5.50	21,984	$1,903
Washing	250W-MH	10	4,000	2.93	11,720	$1,098
Assembly	250W-MH	16	4,000	4.69	18,752	$1,757
Paint Booth	4xF34-T12	9	4,000	1.48	5,904	$526
Testing	2xF96-T12	10	4,000	1.73	6,920	$647
Hallways/Lobby	4xF34-T12	18	4,000	2.95	11,808	$1,051
Breakroom	4xF34-T12	7	4,000	1.15	4,592	$408
Bathrooms	4xF34-T12	12	4,000	1.97	7,872	$700
Total		198		55.82	223,296	$20,293

This lighting list is typically of what is seen in such a facility. It is comprised of a mixture of fluorescent T12s and metal halides, just as what was seen in the Paperboard Packaging facility. With an annual energy consumption of 223,296 kWh and annual operating hours of 4,000 hours per year, the average lighting power is 55.82 kW. Dividing this by the 33,000 ft^2 of the main building, the lighting density is 1.69 ft^2.

For the Proposed lighting upgrade, the list will be similar to the fixtures currently installed in the facility with the only change being the upgrading the remaining T12 fixtures to T8s. This lighting arrangement is shown below in Table 6.

Table 6: Proposed Fixtures Installed in the Assembly Manufacturing Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Conference Room	4xF32-T8	4	4,000	0.43	1,712	$149
Main Production Area	4xF54-T5	72	4,000	17.28	69,120	$5,965
Main Production Area	2xF96-T8	4	4,000	0.44	1,760	$149
Assembly	6xF54-T5	14	4,000	5.04	20,160	$1,740
Ovens	6xF54-T5	10	4,000	3.60	14,400	$1,243
Cleaning	6xF54-T5	12	4,000	4.32	17,280	$1,491
Washing	4xF54-T5	10	4,000	2.40	9,600	$829
Assembly	4xF54-T5	16	4,000	3.84	15,360	$1,326
Paint Booth	4xF32-T8	9	4,000	0.96	3,852	$336
Testing	2xF96-T8	10	4,000	1.10	4,400	$373
Hallways/Lobby	4xF32-T8	18	4,000	1.93	7,704	$672
Breakroom	4xF32-T8	7	4,000	0.75	2,996	$261
Bathrooms	4xF32-T8	12	4,000	1.28	5,136	$448
Total		198		43.37	173,480	$14,982

With all of the lighting upgraded, the annual energy consumption is reduced to 173,480 kWh which results in an average lighting power of 43.37 kW. Dividing once again by the area of the building, the lighting density is calculated to be 1.31 W/ft^2.

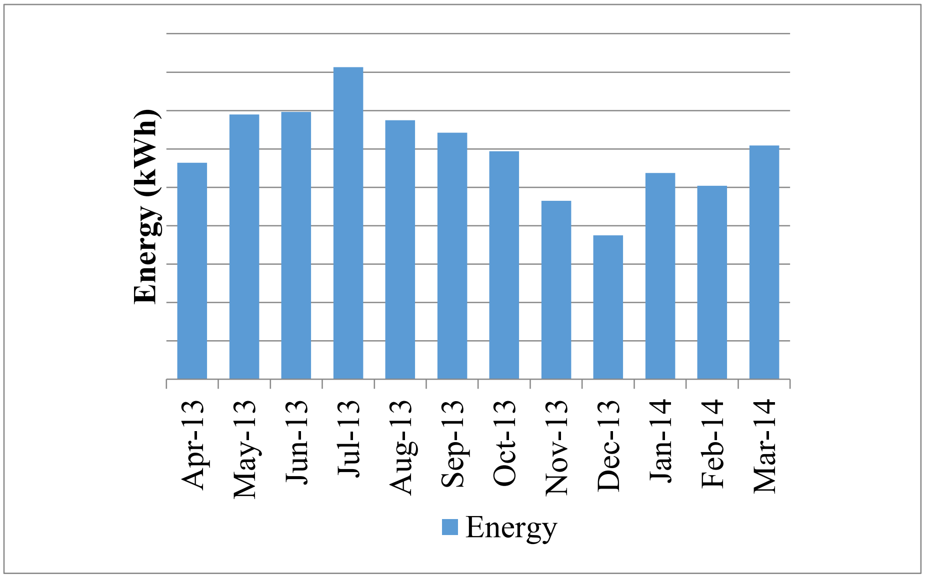


Figure 6: Electric Utility Bills for Assembly Manufacturing Facility

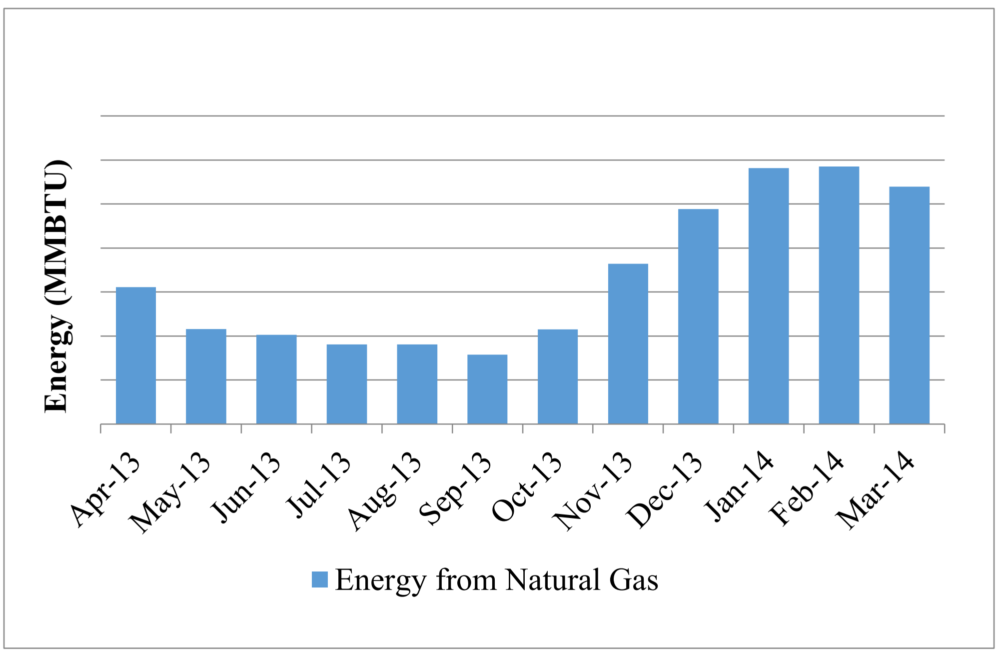


Figure 7: Natural Gas Utility Bills for Assembly Manufacturing Facility

The facility sees a relatively consistent demand throughout the year with electric bills being the highest during the summer due to higher cooling needs. Natural gas usage sees an increase during the winter as heating demand goes up. The facility uses a natural gas fired boiler to make steam and hot water for cleaning parts but this is done outside in an exterior building and does not contribute to heating the main building. As this cleaning occurs year round, there is still significant natural gas usage even during the summer months.

As it is known that the facility is heated during the winter, it will be assumed that during December, no cooling is taking place. Therefore, all electricity being consumed is in the form of process load. This allows for the most conservative estimate possible. December had a total of 37,500 kWh consumed. The average power calculation for the month is shown below keeping in mind that December only had working days:

$$\text{Average Power (kW)} = 37{,}500 \text{ kWh/month} / (20 \text{ days/month} \times 16 \text{ hours/day})$$

$$= 117.19 \text{ kW}$$

On average, 117.19 kW of electricity are being consumed in the facility. The next step is to account for the power use of the compressor and subtract it from this. Figure 8 below shows the logged data from the compressor located in the main building.

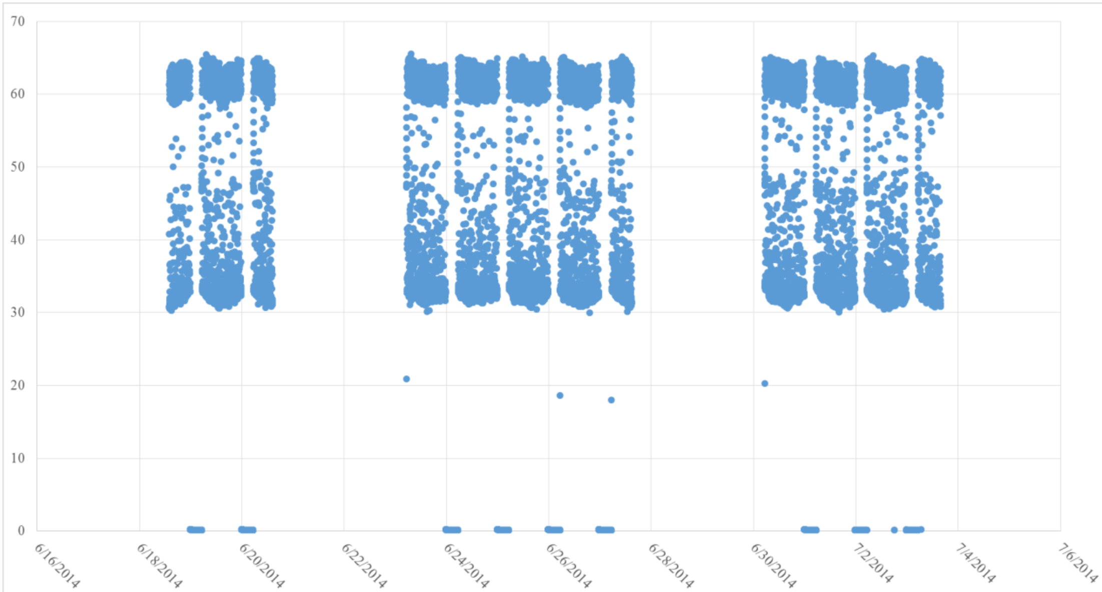


Figure 8: Compressor Power at Assembly Manufacturing Facility

From the data, it was determined that the average horsepower of the compressor was 32.1 hp. Converting to kW:

$$\text{Compressor Power} = 32.1 \text{ hp} \times 0.75 \text{ kW/hp}$$

$$= 24.1 \text{ kW}$$

Subtracting the power consumption of both the lighting and the compressor, the average power remaining is the heating of the process in the building. As the utility bill is based on the true current lighting, that is the value which must be subtracted.

$$\text{Process Heating (kW)} = 117.19 \text{ kW} - 24.1 \text{ kW} - 44.77 \text{ kW}$$

$$= 48.32 \text{ kW}$$

Converting to BTUh:

$$\text{Process Heating (BTUh)} = 48.32 \text{ kW} \times 3{,}412 \text{ BTUh/kW}$$

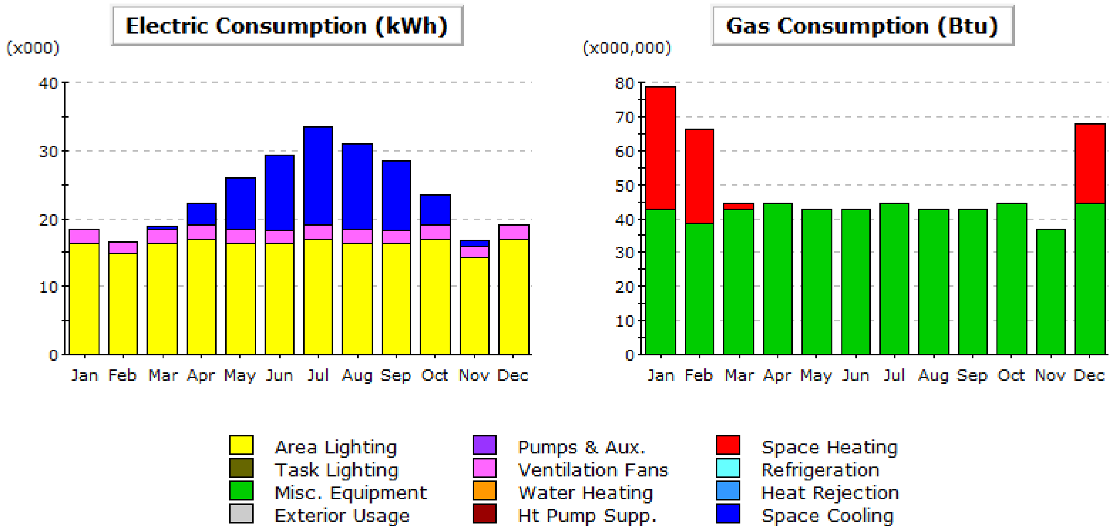
$$= 164{,}867.8 \text{ BTUh}$$

On average, 164,867.8 BTUh of heating is done by the process. With this information, the model is built using eQuest.

2.4.2 eQuest Model

The model used for this building is the same as used in the first facility in terms of construction; the only difference being the square footage. For the building operation schedule, the hours were set to be between 5 AM and 9 PM on weekdays and closed on weekends and holidays. The square footage per person and CFM per person was kept the same according to ASHRAE standards, 143 ft^2/person and 10 CFM/person respectively. The light density is set to 1.69 W/ft^2 which is based on the historical lighting list. The process heat needs to be divided by the square footage of the building to get the power density. This value is calculated to be 5.0 BTUh/ft^2.

For the HVAC side, the cooling source is set to be DX coils and the heating to be natural gas furnaces. Set points are the same for the first building at 75°F for cooling and 65°F for heating. Finally, there were no economizers and no humidity control. With all of these variables set, the simulation can be run and the results are shown below in Figure 9.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	0.02	0.52	3.13	7.68	11.02	14.42	12.61	10.24	4.26	0.74	-	64.64
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	2.02	1.83	2.02	2.12	2.02	2.02	2.12	2.02	2.02	2.12	1.73	2.12	24.18
Pumps & Aux.	0.03	0.02	0.02	0.01	0.00	-	-	-	-	0.01	0.02	0.03	0.13
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	16.33	14.77	16.33	16.94	16.33	16.26	17.01	16.33	16.26	17.01	14.23	17.01	194.81
Total	18.38	16.65	18.89	22.20	26.03	29.31	33.55	30.97	28.52	23.39	16.72	19.16	283.76

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	36.16	27.45	1.80	-	-	-	-	-	-	-	0.24	23.41	89.05
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	42.64	38.58	42.64	44.54	42.64	42.59	44.59	42.64	42.59	44.59	36.72	44.59	509.36
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	78.80	66.03	44.44	44.54	42.64	42.59	44.59	42.64	42.59	44.59	36.96	68.00	598.42

Figure 9: Heating and Cooling Energy Consumption at the Assembly Manufacturing Facility with Historical Lighting

It can be seen that this model fits the description of the building extremely well. Cooling occurs for most of the year except the three coolest months and heating only occurs for four months during the winter. Compared to the actual utilities, the overall magnitudes of energy use are lower in the simulation but this will only result in more conservative HVAC savings which is desirable.

2.4.3 Lighting Upgrade

The estimated savings of upgraded all of the lighting in the building from historical to the proposed fixtures is shown in Table 7.

Table 7: Savings from Upgrading Lighting at Assembly Manufacturing Facility

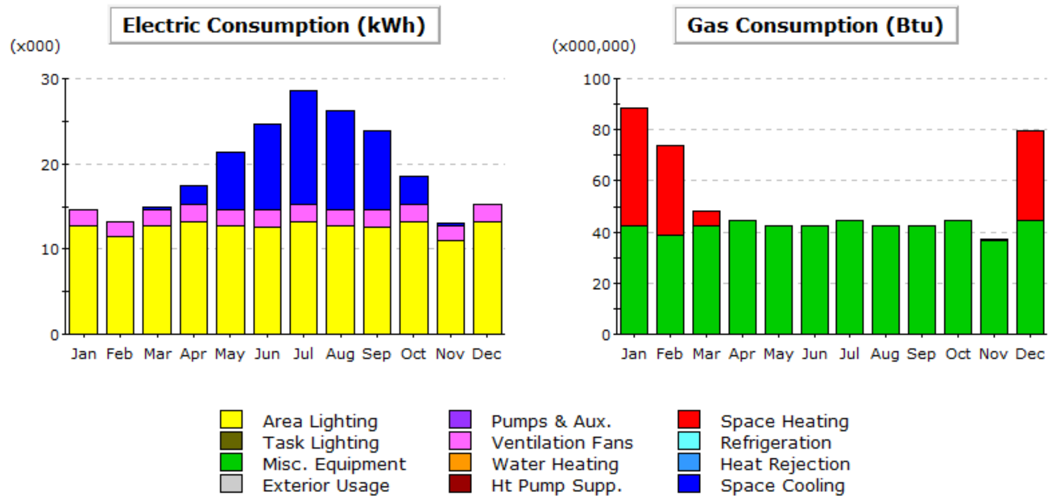
Area	Demand Savings (kW)	Energy Savings (kWh)	Electrical Savings	Maintenance Savings	Total Savings
Conference Room	0.23	912	$73	$11	$84
Main Production Area	3.82	15,264	$1,224	$717	$1,941
Main Production Area	0.25	1,008	$81	$29	$110
Assembly	1.37	5,488	$440	$40	$480
Ovens	0.98	3,920	$314	$29	$343
Cleaning	1.18	4,704	$377	$34	$412
Washing	0.53	2,120	$170	$100	$270
Assembly	0.85	3,392	$272	$159	$431
Paint Booth	0.51	2,052	$165	$25	$189
Testing	0.63	2,520	$202	$73	$275
Hallways/Lobby	1.03	4,104	$329	$49	$378
Breakroom	0.40	1,596	$128	$19	$147
Bathrooms	0.68	2,736	$219	$33	$252
Total	12.45	49,816	$3,995	$1,317	$5,312

In total, annual savings, excluding heating and cooling, from upgrading lighting are $5,312/yr. The total costs for implementing these upgrades are shown below in Table 8.

Table 8: Implementation Costs and Expected Payback for Assembly Manufacturing Facility

Area	Total Annual Savings	Implementation Costs	Payback (Months)
Conference Room	$84	$440	63
Main Production Area	$1,941	$20,171	125
Main Production Area	$110	$629	69
Assembly	$480	$5,030	126
Ovens	$343	$3,593	126
Cleaning	$412	$4,311	126
Washing	$270	$2,802	125
Assembly	$431	$4,482	125
Paint Booth	$189	$989	63
Testing	$275	$1,571	69
Hallways/Lobby	$378	$1,979	63
Breakroom	$147	$770	63
Bathrooms	$252	$1,319	63
Total	$5,312	$48,085	109

The total implementation cost for this lighting upgrade is $48,085 which is expected to payback in 109 months based on the annual savings. This lighting upgrade reduces the average power from 55.82 kW to 43.37 kW. The changes in HVAC energy consumption in the building from this upgrade are shown below in Figure 10.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	0.29	2.24	6.68	10.04	13.35	11.57	9.23	3.28	0.31	-	57.00
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	1.99	1.80	1.99	2.08	1.99	1.99	2.08	1.99	1.99	2.08	1.70	2.08	23.73
Pumps & Aux.	0.03	0.02	0.02	0.01	0.00	-	-	-	-	0.01	0.02	0.03	0.13
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	12.66	11.45	12.66	13.13	12.66	12.61	13.18	12.66	12.61	13.18	11.03	13.18	151.01
Total	14.68	13.27	14.95	17.46	21.33	24.63	28.62	26.21	23.82	18.55	13.05	15.29	231.87

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	45.83	35.06	5.40	-	-	-	-	-	-	-	0.60	34.94	121.82
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	42.64	38.58	42.64	44.54	42.64	42.59	44.59	42.64	42.59	44.59	36.72	44.59	509.36
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	88.47	73.63	48.04	44.54	42.64	42.59	44.59	42.64	42.59	44.59	37.32	79.53	631.18

Figure 10: Heating and Cooling Energy Consumption at Assembly Manufacturing Facility with Proposed Lighting

Like what was seen in the first building, the energy consumption for space cooling goes down with reduced lighting density. However, unlike the first building which did not space heat, the assembly manufacturing building sees its gas consumption increase as the lighting density goes down. While it is anticipated that cooled-only facilities will see a measurable HVAC savings, it seems likely that cooled and heated facilities will see far smaller savings, break even points, or even potential net cost increase as more energy is consumed to make up for decrease heating from light fixtures.

2.4.4 Analysis

According to the simulation, the total annual HAC energy consumption before the lighting upgrade is as follows:

- Space Cooling: 64.64 MWh
- Space Heating: 89.05 MMBTU
- Ventilation: 24.18 MWh
- Pumps & Aux.: 0.13 MWh

After upgrading the lighting, these values become:

- Space Cooling: 57.00 MWh
- Space Heating: 121.82 MMBTU
- Ventilation: 23.73 MWh
- Pumps & Aux.: 0.13 MWh

The net electrical energy savings is shown below:

$$
\begin{aligned}
\text{Elec. HVAC Savings (MWh)} &= \text{Net Cooling + Net Vent. + Net Pumps \& Aux.} \\
&= (64.64\ \text{MWh} - 57.00\ \text{MWh}) \\
&\quad + (24.18\ \text{MWh} - 23.73\ \text{MWh}) \\
&\quad + (0.13\ \text{MWh} - 0.13\ \text{MWh}) \\
&= 7.64\ \text{MWh} - 0.45\ \text{MWh} - 0.00\ \text{MWh} \\
&= 7.19\ \text{MWh}
\end{aligned}
$$

The net natural gas savings is shown below:

$$
\begin{aligned}
\text{NG HVAC Sav. (MMBTU)} &= \text{Net Space Heating} \\
&= 89.05\ \text{MMBTU} - 121.82\ \text{MMBTU} \\
&= -32.77\ \text{MMBTU}
\end{aligned}
$$

Throughout the course of the year, the HVAC system will see a decrease of 7.19 MWh and an increase of 32.77 MMBTU. The cost savings from this is shown below:

$$
\begin{aligned}
\text{Cost Savings (\$/yr.)} &= (\text{Elec. Energy x \$/kWh}) + (\text{NG x \$/MMBTU}) \\
&= (7.19\ \text{MWh x 1,000 kWh/MWh x\$0.0676/kWh}) \\
&\quad + (-32.77\ \text{MMBTU x \$9.14/MMBTU}) \\
&= \$486 + (-\$300) \\
&= \$186/\text{yr.}
\end{aligned}
$$

In total, there is a net decrease in HVAC costs of $186/yr. According to the calculations done using Newer Lighting, the savings directly from the lighting upgrade are $5,312/yr. Therefore, the HVAC savings is 3.5% of lighting savings. Originally, the expected payback was calculated to be 109 months. Including the additional HVAC savings, this payback is reduced to 105 months.

2.5 Plastic Injection Molding

2.5.1 Facility Information

The third manufacturing building studied for this project is a plastic injection molding facility. Located near central North Carolina, this facility produced various plastic products ranging from small parts for cars to larger piece for container using plastic injection molding. The building had a total area of 44,000 ft^2 and, similar to the first facility, cooled throughout the cooled with no space heating due to the large amount of heat released from the process. The utility costs were $0.0421/kWh and $10.88/kW. The production schedule was 24/6 which came to an annual total of 7,200 hours.

At the time of the assessment, the building was lit using a combination of metal halide, T12, and T8 fixtures. While the building did use a 20 hp rotary screen VFD compressor, it was not logged during the assessment. This building has a similar lighting issue as the assembly manufacturing building. As seen in Table 9 below as calculated by Newer Lighting, the building had upgraded some of the fixtures to T8 fluorescents but the majority of the fixtures were older style metal halides and T12s.

Table 9: Current Fixtures Installed in Plastic Injection Molding Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Offices (5)	4xF34-T12	18	2,250	2.95	6,642	$720
Conference Room	4xF34-T12	4	2,250	0.66	1,476	$160
Material Room	4xF32-T8	10	7,200	1.07	7,704	$517
Material Room	4xF54-T5	8	7,200	1.92	13,824	$914
Maintenance	400W-MH	8	7,200	3.66	26,381	$1,747
Maintenance	6xF54-T5	4	7,200	1.44	10,368	$685
Main Floor	400W-MH	109	7,200	49.92	359,438	$23,805
Main Floor	6xF54-T5	13	7,200	4.68	33,696	$2,228
Main Floor	4xF32-T8	37	7,200	3.96	28,505	$1,912
Main Floor	4xF54-T5	5	7,200	1.20	8,640	$571
Quality	4xF34-T12	24	2,250	3.94	8,856	$960
Receiving Bay	4xF32-T8	3	7,200	0.32	2,311	$155
Hallway/Cubicles	4xF34-T12	32	2,250	5.25	11,808	$1,280
Breakroom	4xF34-T12	11	7,200	1.80	12,989	$890
Breakroom	2xF32-T8	6	7,200	0.33	2,376	$159
Bathrooms	2xF32-T8	5	7,200	0.28	1,980	$132
Total		297		83.38	536,994	$36,836

Based on a yearly consumption of 536,944 kWh and 7,200 production times, the average lighting power is 74.58 kW. Rolling back the current fixtures to use only metal halides and T12s as was done for the assembly manufacturing facility, the historical lighting list is shown in Table 10.

Table 10: Historical Fixtures Installed in Plastic Injection Molding Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Offices (5)	4xF34-T12	18	2,250	2.95	6,642	$720
Conference Room	4xF34-T12	4	2,250	0.66	1,476	$160
Material Room	4xF34-T12	10	7,200	1.64	11,808	$809
Material Room	250W-MH	8	7,200	2.34	16,877	$1,232
Maintenance	400W-MH	8	7,200	3.66	26,381	$1,747
Maintenance	400W-MH	4	7,200	1.83	13,190	$874
Main Floor	400W-MH	109	7,200	49.92	359,438	$23,805
Main Floor	400W-MH	13	7,200	5.95	42,869	$2,839
Main Floor	4xF34-T12	37	7,200	6.07	43,690	$2,994
Main Floor	250W-MH	5	7,200	1.47	10,548	$769
Quality	4xF34-T12	24	2,250	3.94	8,856	$960
Receiving Bay	4xF34-T12	3	7,200	0.49	3,542	$242
Hallway/Cubicles	4xF34-T12	32	2,250	5.25	11,808	$1,280
Breakroom	2xF34-T12	11	7,200	0.90	6,494	$445
Breakroom	2xF34-T12	6	7,200	0.49	3,542	$242
Bathrooms	2xF34-T12	5	7,200	0.41	2,952	$202
Total		297		87.98	570,114	$39,321

The average power consumption of this lighting configuration is 79.18 kW. The proposed lighting list, created by upgrading all of the lighting to what is typically recommended, is shown below in Table 11.

Table 11: Proposed Fixtures Installed in Plastic Injection Molding Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Offices (5)	4xF32-T8	18	2,250	1.93	4,334	$464
Conference Room	4xF32-T8	4	2,250	0.43	963	$103
Material Room	4xF32-T8	10	7,200	1.07	7,704	$517
Material Room	4xF54-T5	8	7,200	1.92	13,824	$914
Maintenance	6xF32-T8	8	7,200	1.76	12,672	$944
Maintenance	6xF54-T5	4	7,200	1.44	10,368	$685
Main Floor	6xF32-T8	109	7,200	23.98	172,656	$12,871
Main Floor	6xF54-T5	13	7,200	4.68	33,696	$2,228
Main Floor	4xF32-T8	37	7,200	3.96	28,505	$1,912
Main Floor	4xF54-T5	5	7,200	1.20	8,640	$571
Quality	4xF32-T8	24	2,250	2.57	5,778	$619
Receiving Bay	4xF32-T8	3	7,200	0.32	2,311	$155
Hallway/Cubicles	4xF32-T8	32	2,250	3.42	7,704	$824
Breakroom	2xF32-T8	11	7,200	0.61	4,356	$291
Breakroom	2xF32-T8	6	7,200	0.33	2,376	$159
Bathrooms	2xF32-T8	5	7,200	0.28	1,980	$132
Total		297		49.89	317,867	$23,389

The average power consumption of the lighting in this configuration is 44.15 kW.

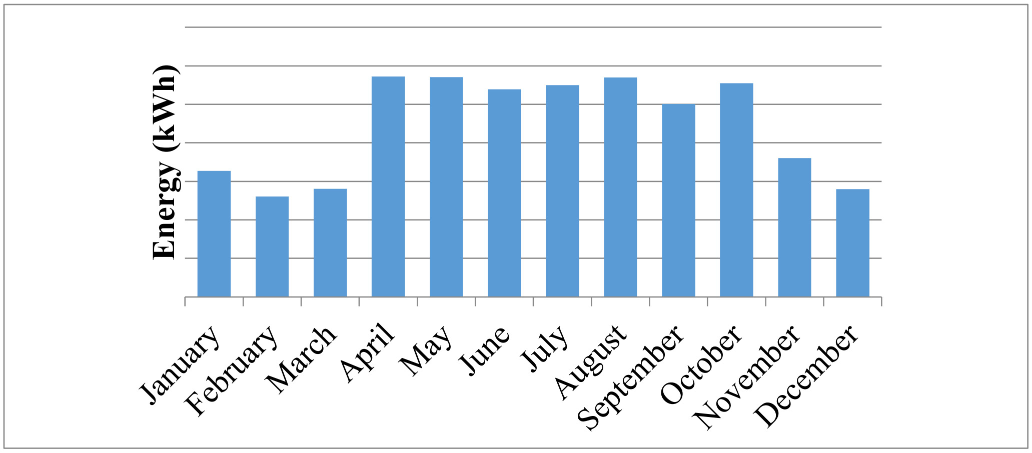


Figure 11: Electric Utility Bills for Plastic Injection Molding Facility

As no there is no space heating, the electrical usage shows that energy use increased during the warmer months as cooling loads increase. Interestingly, the cooling loads are nearly the same throughout the year with except for the winter. This indicates that the process emits a significant amount of heat which is to be expected when the primary activity is melting plastic 24 hours per day, 6 days per week. Like the previous buildings, December will be used as the baseline to estimate the process load. December had a total usage of 191,214 kWh. Based on 24 production days, the average power is calculated below:

$$\text{Average Power (kW)} = 191{,}214 \text{ kWh} / (24 \text{ days/month} \times 24 \text{ hours/day})$$
$$= 331.97 \text{ kW}$$

Subtracting the average lighting power based on the current lighting configuration.

$$\text{Process Heating (kW)} = 331.97 \text{ kW} - 74.58 \text{ kW}$$
$$= 257.39 \text{ kW}$$

Converting this value to BTUh:

$$\text{Process Heating (BTUh)} = 257.39 \text{ kW} \times 3{,}412 \text{ BTUh/kW}$$
$$= 878{,}214.7 \text{ BTUh}$$

On average, 878,214.7 BTUh of heating is done by the process. With this information, the model is built using eQuest.

2.5.2 eQuest Model

Like the buildings before, the construction of the model is kept the same with the exception of the square footage. This is done even though it is know that the walls of this building are brick because it eliminates an extra variable which could confuse the results of this project. The building operation schedule was set to be 24 hours per day on all days of the week except on Sunday and closed on holidays.

The lighting density is calculated by dividing the lighting power by the square footage of the building. For this first simulation run, the historical lighting power will be used:

$$\text{Lighting Density (W/ft}^2\text{)} = 79.18 \text{ kW} / 44{,}341 \text{ ft}^2$$

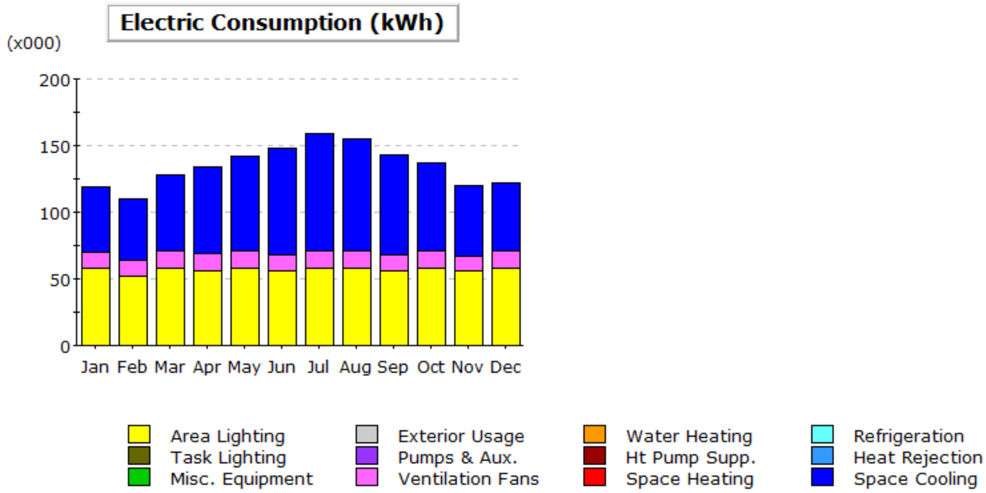
$$= 1.79 \text{ W/ft}^2$$

The process load is then divided by the building area as well to get the Process Density:

$$\text{Process Density (BTUh/ft}^2\text{)} = 878{,}214.7\text{BTUh} / 44{,}341 \text{ ft}^2$$

$$= 19.81 \text{ BTUh/ft}^2$$

Keeping the set point the same, 75°F for cooling and 65° for heating, no humidity control, and direct expansion refrigerant coils for cooling with no heating, the simulation is run and the results are shown below in Figure 12.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	48.8	46.2	56.7	64.5	71.3	79.5	88.1	84.5	75.0	66.1	52.9	51.7	785.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	12.5	11.5	13.0	13.0	13.0	12.5	13.0	13.0	12.5	13.0	11.5	13.0	151.6
Pumps & Aux.	0.0	0.0	0.0	0.0	-	0.0	-	-	-	0.0	0.0	0.0	0.0
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	57.7	52.1	57.8	56.0	57.8	55.9	57.8	57.8	55.9	57.8	55.7	57.8	679.9
Total	119.0	109.8	127.5	133.5	142.1	147.9	158.9	155.2	143.4	136.9	120.1	122.5	1,616.8

Figure 12: Cooling Energy Consumption with Historical Fixtures at the Plastic Injection Molding Facility

As expected from the simulating the paperboard packaging facility, cooling is required year-round due to the large amount of heating from the process. While cooling loads do increase in the summer, the cooling load throughout the year in general is quite high.

2.5.3 Lighting Upgrade

The estimated savings of upgrading all of the lighting in the building from the historical to the proposed fixtures is shown below in Table 12.

Table 12: Savings from Upgrading Lighting at Plastic Injection Molding Facility

Area	Demand Savings (kW)	Energy Savings (kWh)	Electrical Savings	Maintenance Savings	Total Savings
Offices (5)	1.03	2,309	$231	$25	$256
Conference Room	0.23	513	$51	$6	$57
Material Room	0.57	4,104	$247	$45	$292
Material Room	0.42	3,053	$184	$134	$318
Maintenance	1.90	13,709	$826	-$23	$802
Maintenance	0.39	2,822	$170	$18	$188
Main Floor	25.94	186,782	$11,251	-$316	$10,934
Main Floor	1.27	9,173	$553	$59	$612
Main Floor	2.11	15,185	$915	$167	$1,081
Main Floor	0.27	1,908	$115	$84	$199
Quality	1.37	3,078	$308	$34	$342
Receiving Bay	0.17	1,231	$74	$14	$88
Hallway/Cubicles	1.82	4,104	$411	$45	$456
Breakroom	0.30	2,138	$129	$25	$154
Breakroom	0.16	1,166	$70	$14	$84
Bathrooms	0.14	972	$59	$11	$70
Total	38.09	252,248	$15,593	$340	$15,932

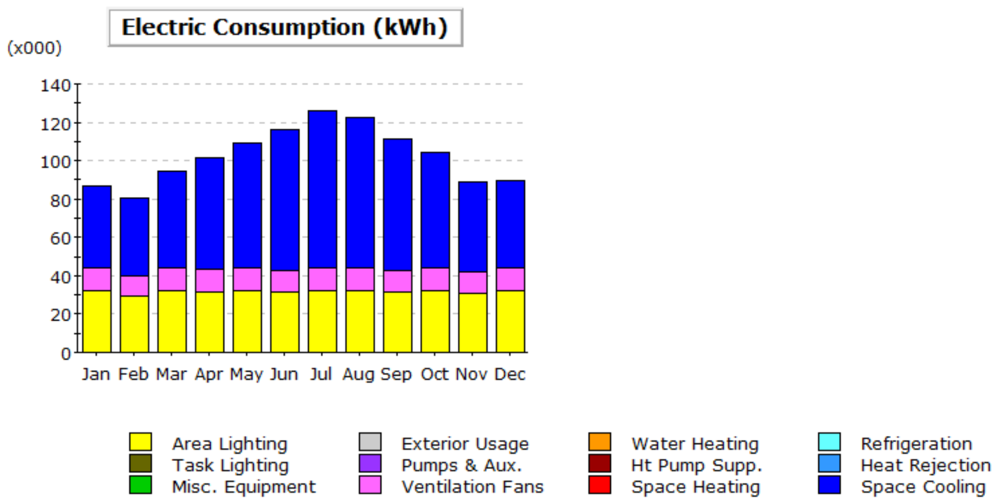
In total, annual savings, excluding heating and cooling, from upgrading the lighting are $15,932/yr. The total costs for implementing these upgrades are shown below in Table 13.

Table 13: Implementation Costs and Expected Payback for Plastic Injection Molding Facility

Area	Total Annual Savings	Implementation Costs	Payback (Months)
Offices (5)	$256	$1,869	87
Conference Room	$57	$415	87
Material Room	$292	$1,039	43
Material Room	$318	$2,165	82
Maintenance	$802	$1,804	27
Maintenance	$188	$1,382	88
Main Floor	$10,934	$24,578	27
Main Floor	$612	$4,491	88
Main Floor	$1,081	$3,843	43
Main Floor	$199	$1,353	82
Quality	$342	$2,492	87
Receiving Bay	$88	$312	43
Hallway/Cubicles	$456	$3,323	87
Breakroom	$154	$1,055	82
Breakroom	$84	$576	82
Bathrooms	$70	$480	82
Total	$15,932	$51,177	39

The total implementation cost for this lighting upgrade is $51,177 which is expected to payback in 39 months based on the annual savings. This lighting upgrade reduces the average power from 79.18 kW to 44.15 kW. The changes in HVAC energy consumption in the building from this upgrade are shown below in Figure 13.

Project/Run: Plastic Injection Molding - Baseline Design Run Date/Time: 04/02/15 @ 14:38



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	43.0	40.7	50.5	58.3	65.1	73.3	81.4	78.0	68.8	59.9	47.2	45.3	711.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	11.5	10.6	12.0	12.0	12.0	11.6	12.0	12.0	11.6	12.0	10.6	12.0	139.8
Pumps & Aux.	0.0	0.0	0.0	0.0	-	0.0	-	-	-	0.0	0.0	0.0	0.0
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	32.2	29.1	32.3	31.3	32.3	31.2	32.3	32.3	31.2	32.3	31.1	32.3	379.8
Total	86.8	80.4	94.8	101.6	109.3	116.0	125.7	122.2	111.6	104.1	88.9	89.6	1,231.0

Figure 13: Cooling Energy Consumption with Proposed Fixtures at the Plastic Injection Molding Facility

Similar to the paperboard packaging facility, the decrease in lighting density resulted in a decrease in both space cooling and ventilation fan energy consumption. Space cooling saw a decrease of 74,000 kWh, from 785.4 MWh to 711.4 MWh, and ventilation fans used 11,800 kWh less energy, from 151.6 MWh to 139.8 MWh. As there was no heating done in the building, heating costs did not increase resulting in a significant net decrease in HVAC costs.

2.5.4 Analysis

According to the simulation, the total annual HVAC energy consumption before the lighting upgrade is as follows:

- Space Cooling: 785.4 MWh
- Ventilation: 151.6 MWh

After upgrading the lighting, these values become:

- Space Cooling: 711.4 MWh
- Ventilation: 139.8 MWh

The net energy savings is shown below:

$$
\begin{aligned}
\text{HVAC Savings (MWh)} &= \text{Net Cooling + Net Ventilation} \\
&= (785.4\text{ MWh} - 711.4\text{ MWh}) \\
&\quad + (151.6\text{ MWh} - 139.8\text{ MWh}) \\
&= 74\text{ MWh} + 11.8\text{ MWh} \\
&= 85.8\text{ MWh}
\end{aligned}
$$

Throughout the course of the year, the HVAC system will see a decrease of 85.8 MWh. The cost savings from this is shown below:

$$
\begin{aligned}
\text{Cost Savings (\$/yr.)} &= \text{Electrical Energy x \$/kWh} \\
&= 85.8\text{ MWh x 1,000 kWh/MWh x \$0.0421/kWh} \\
&= \$3{,}612\text{/yr.}
\end{aligned}
$$

In total, there is a net decrease in HVAC costs of \$3,612/yr. According to the calculations done using Newer Lighting, the savings directly from the lighting upgrade are \$15,932/yr.

Therefore, the HVAC savings are an additional 22.7% of lighting savings. Originally, the expected payback was calculated to be 39 months. Including the additional HVAC savings, this payback is reduced to 32 months.

2.6 Vehicle Manufacturing

2.6.1 Facility Information

The fourth manufacturing building for this project is a facility which manufactures large vehicles. Located in central North Carolina. The building had a total area of 535,738 ft^2 which was heated during the winter months but had no cooling. For utilities, the facility paid $0.057/kWh, $4.43/kW, and $7.13/MMBTU of natural gas. Manufacturing was on an 18/6 schedule for a total of 5,400 hrs/yr.

At the time of the assessment, the building was lit using a combination of fluorescent T12 and metal halide fixtures. The facility also employed three air compressors: one 200 hp Variable Speed Drive (VSD), one 200 hp modulating, and one 250 hp modulating. These compressors were logged during the assessment.

Using Newer Lighting, the current lighting list, energy use, and electrical and maintenance costs were calculated and shown below in Table 14.

Table 14: Current Fixtures Installed in Vehicle Manufacturing Facility

Area	Fixture Type	Number of Fixtures	Operating Hours	Power (kW)	Energy (kWh)	Electrical and Maintenance Cost
Fabrication Shop	2xF96-T12	5	5,400	0.87	4,671	$371
Warehouse	250W-MH	220	5,400	64.46	348,084	$27,794
Warehouse	2xF96-T12	20	5,400	3.46	18,684	$1,484
Manufacturing	250W-MH	197	5,400	57.72	311,693	$24,889
Prefabrication	400W-MH	45	5,400	20.61	111,294	$8,116
Manufacturing	2xF96-T12	15	5,400	2.60	14,013	$1,113
Manufacturing	2xF34-T12	5	5,400	0.41	2,214	$166
Manufacturing	2xF96-T12	9	5,400	1.56	8,408	$668
Manufacturing	400W-MH	20	5,400	9.16	49,464	$3,607
Manufacturing	2xF96-T12	10	5,400	1.73	9,342	$741
Manufacturing	2xF96-T12	36	5,400	6.23	33,631	$2,670
Manufacturing	250W-MH	316	5,400	92.59	499,975	$39,924
Manufacturing	400W-MH	39	5,400	17.86	96,455	$7,034
Manufacturing	250W-MH	148	5,400	43.36	234,166	$18,699
Manufacturing	250W-MH	25	5,400	7.33	39,555	$3,158
Manufacturing	2xF96-T12	3	5,400	0.52	2,803	$222
Manufacturing	400W-MH	42	5,400	19.24	103,874	$7,575
Parts Warehouse	250W-MH	84	5,400	24.61	132,905	$10,613
Manufacturing	2xF96-T12	24	5,400	4.15	22,421	$1,780
Boiler Room	2xF96-T12	3	5,400	0.52	2,803	$222
Boiler Room	2xF34-T12	1	5,400	0.08	443	$34
Manufacturing	250W-MH	16	5,400	4.69	25,315	$2,021
Total		1,283		383.74	2,072,212	$162,902

With a yearly energy consumption of 2,072,212 kWh and 5,400hrs/yr. of production time, the average lighting power is determined to be 383.74 kW. The utility bills are shown below.

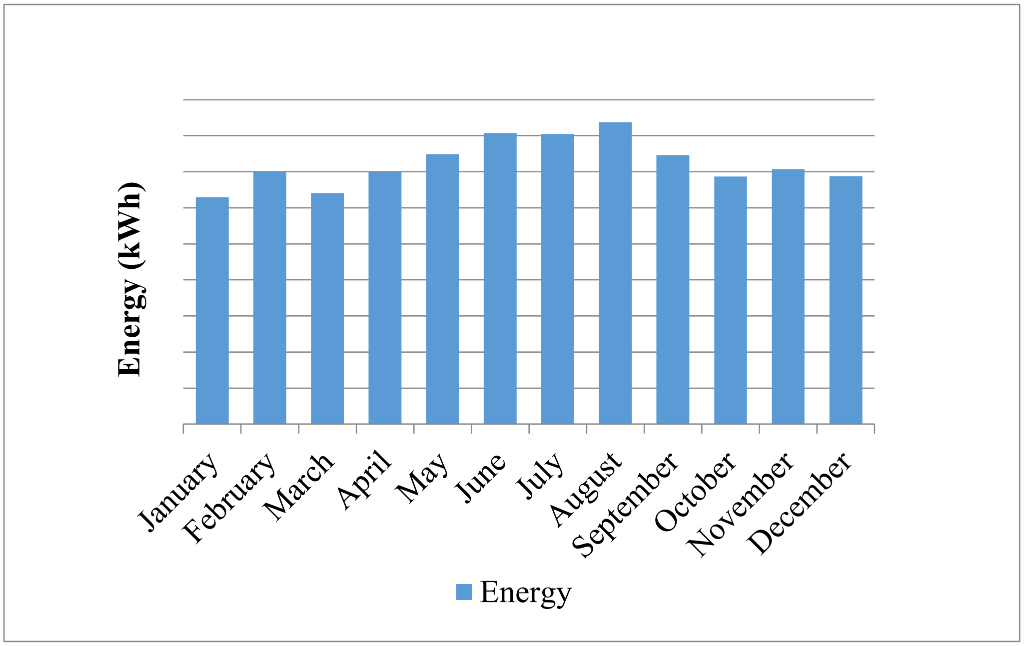


Figure 14: Electric Utility Bills for Vehicle Manufacturing Facility

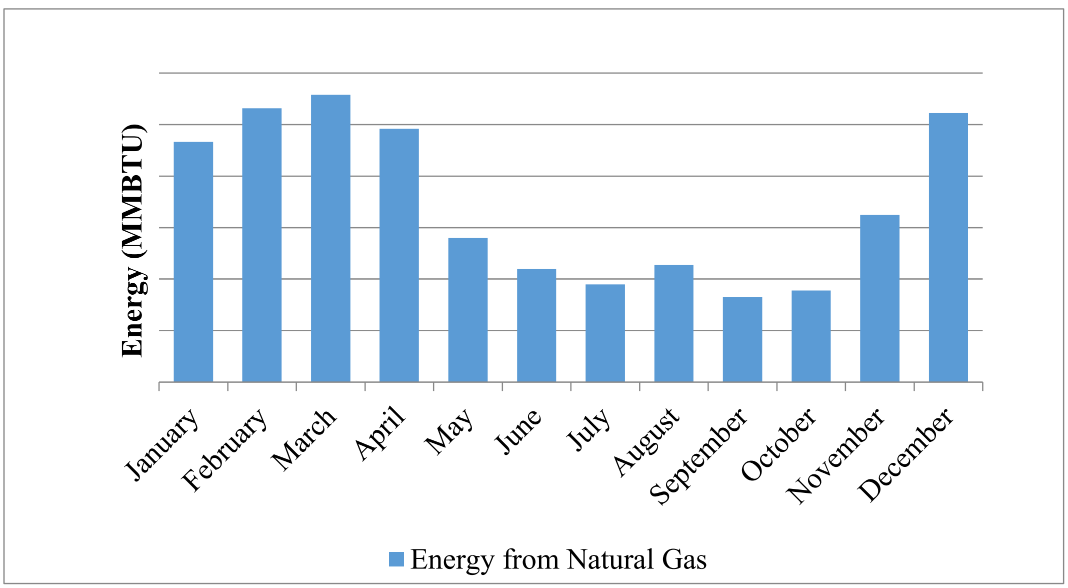


Figure 15: Natural Gas Utility Bills for Vehicle Manufacturing Facility

Examining the electric utility bills shows that while usage does increase during the summer months, the increase is not nearly as dramatic as seen in other buildings as the production floor is not air conditioned. While natural gas is used year-round for various process related tasks such as parts washing, there is a large increase during the colder months of the year as space heating is employed.

Like the facilities modeled before, December is the month that will be used for setting the baseline for average power consumption in the facility. December saw a total usage of 1,375,000 kWh. The average power calculation is shown below:

$$\text{Average Power (kW)} = 1{,}375{,}000 \text{ kWh/month} / (24 \text{ days/month} \times 18 \text{ hours/day})$$

$$= 3{,}182.87 \text{ kW}$$

On average, 3,182.87 kW of electricity are being consumed in the facility. This includes lighting and compressors, both of which must be removed before actual process heating is determined. During the assessment, all three of the running compressors were logged and the data collected is shown in Figure 16 below.

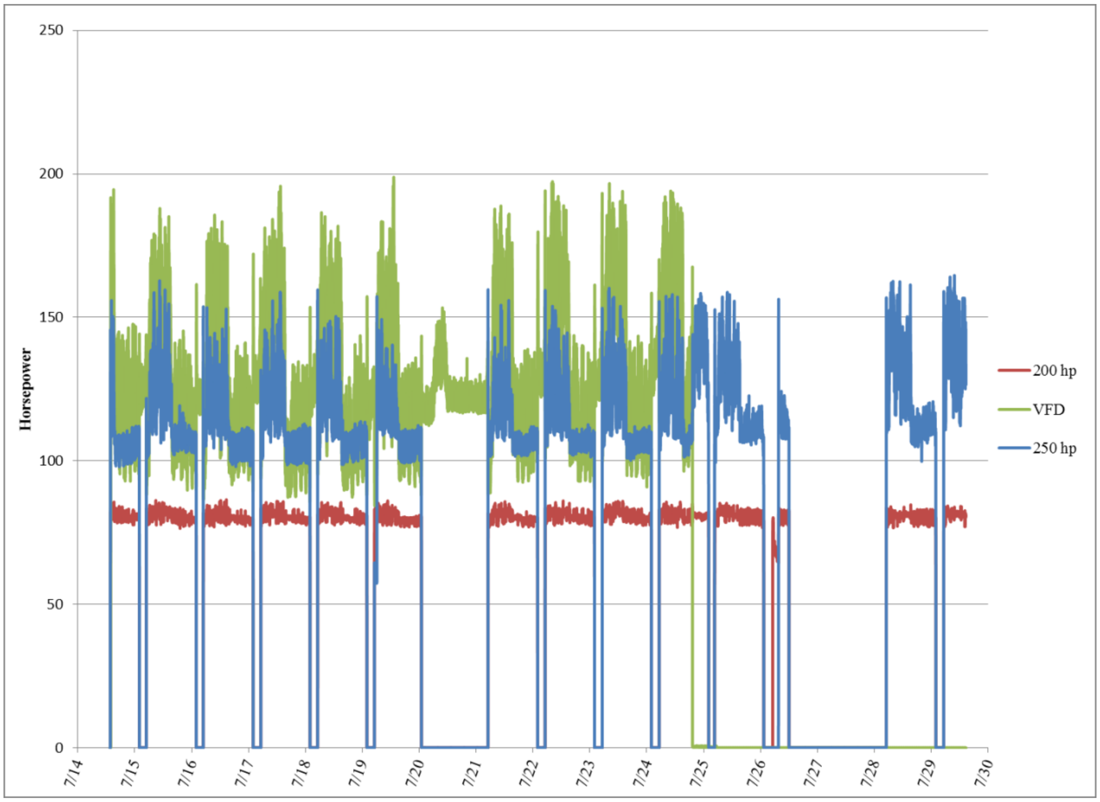


Figure 16: Compressor Power at Vehicle Manufacturing Facility

From the data, it is determined that the average combined horsepower of the compressors is 261.5 hp. This value is converted to kilowatts below:

Compressor Power	=	261.5 hp x 0.75 kW/hp
	=	196.13 kW

On average, 196.13 kW of power are used by the compressors in the building. Removing this and the lighting power allows for the power that contributes to heating to be calculated as shown below:

Process Heating	=	3,182.87 kW - 383.74 kW – 196.13 kW
	=	2,603 kW

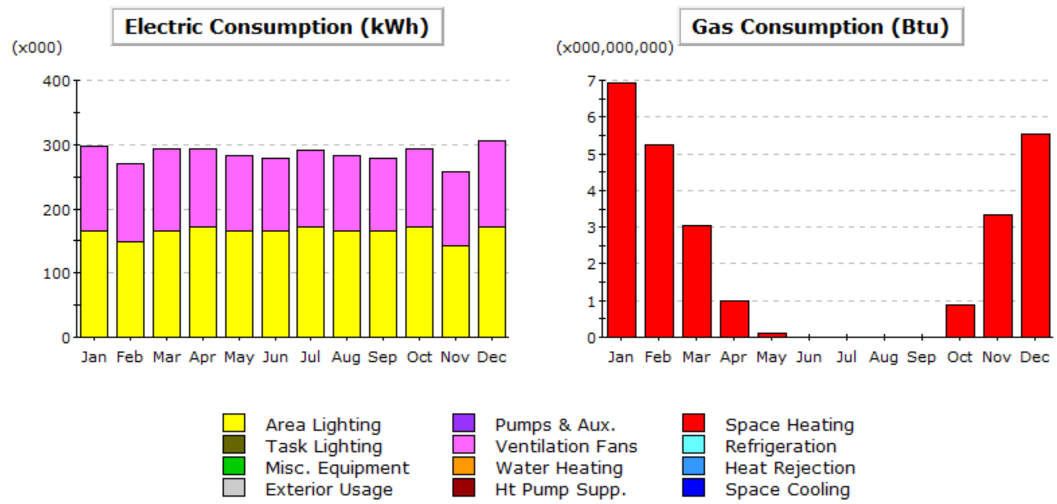
Converting this to BTUh:

$$\text{Process Heating (BTUh)} = 2{,}603 \text{ kW} \times 3{,}412 \text{ BTUh/kW}$$
$$= 8{,}881{,}436 \text{ BTUh}$$

On average, 8,881,436 BTUh of heating is done by the process inside the building. With this information, the model is built using eQuest.

2.6.2 eQuest Model

Still using the same model in terms of construction, the square footage is set to 535,738 ft^2, the hours were set to 6 AM to 12 AM, the square footage per person to 143 ft^2, and the CFM per person to 10. The lighting density and process heating density both are calculated by dividing the lighting power and process heating density. Respectively, the values are 0.72 W/ft^2 and 16.58 $BTUh/ft^2$. With no cooling, the building is modeled to natural gas for space heating and 65°F is used as the heating set point. There are no economizers and the building is not humidity controlled. One additional variable for this simulation is a manually entered infiltration CFM/ft^2 value. The previous buildings had the majority of their manufacturing occurring inside with no significant traffic going into or out of the building. In this building, large bay doors are nearly constantly open with large amount of material moving into the building and completed vehicles moving out as well as multiple paint booths and a large amount of welding. As a result, the actual CFM of air movement through the building is far larger. In eQuest, this value is set to 4 CFM/ft2 of exterior wall area to account for this large amount of air exchange. With this variable set, the simulation is run and the results are shown in Figure 17 below.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	132.6	120.0	127.2	121.4	118.4	114.0	118.3	118.0	114.0	120.6	114.9	133.5	1,452.9
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	165.4	149.6	165.7	172.1	165.1	165.2	172.6	165.1	165.2	172.3	143.3	172.6	1,974.1
Total	298.0	269.6	292.9	293.5	283.5	279.2	290.8	283.1	279.2	292.9	258.2	306.1	3,426.9

Gas Consumption (Btu x000,000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	6.93	5.23	3.04	0.97	0.12	0.01	-	-	0.01	0.88	3.32	5.55	26.05
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	6.93	5.23	3.04	0.97	0.12	0.01	-	-	0.01	0.88	3.32	5.55	26.05

Figure 17: Heating Energy Consumption at Vehicle Manufacturing Facility

With no cooling occurring on the production floor, the electric consumption is fairly consistent throughout the year. Gas consumption shown in the plot is for heating only and goes from no heating during the summer months to a large amount of heating during the winter. Comparing the simulation utility bills and the actual, December has a simulated usage of 5,500 MMBTU. For the actual bills, the gas usage for process related usage needs to be removed from the heating usage. In July, approximately 4,000 MMBTU was used. It is assumed that none of this was used for heating purposed. In December, approximately 10,500 MMBTU were used. Therefore, approximately 7,500 MMBTU were used for heating. This matches relatively well with the simulation results.

2.6.3 Lighting Upgrade

The estimated savings of upgrading all of the lighting in the building from the current to proposed fixtures is shown below in Table 15.

Table 15: Savings from Upgrading Lighting at Vehicle Manufacturing Facility

Area	Demand Savings (kW)	Energy Savings (kWh)	Electrical Savings	Maintenance Savings	Total Savings
Fabrication Shop	0.32	1,701	$114	$46	$160
Warehouse	40.92	220,968	$14,770	$3,656	$18,426
Warehouse	1.26	6,804	$455	$183	$638
Manufacturing	36.64	197,867	$13,226	$3,273	$16,500
Prefabrication	10.71	57,834	$3,866	-$137	$3,729
Manufacturing	0.95	5,103	$341	$138	$479
Manufacturing	0.14	729	$49	$8	$57
Manufacturing	0.57	3,062	$205	$83	$287
Manufacturing	4.76	25,704	$1,718	-$61	$1,657
Manufacturing	0.63	3,402	$227	$92	$319
Manufacturing	2.27	12,247	$819	$330	$1,149
Manufacturing	58.78	317,390	$21,216	$5,251	$26,467
Manufacturing	9.28	50,123	$3,350	-$119	$3,231
Manufacturing	27.53	148,651	$9,937	$2,459	$12,396
Manufacturing	4.65	25,110	$1,678	$415	$2,094
Manufacturing	0.19	1,021	$68	$28	$96
Manufacturing	10.00	53,978	$3,608	-$128	$3,480
Parts Warehouse	15.62	84,370	$5,640	$1,396	$7,035
Manufacturing	1.51	8,165	$546	$220	$766
Boiler Room	0.19	1,021	$68	$28	$96
Boiler Room	0.03	146	$10	$2	$11
Manufacturing	2.98	16,070	$1,074	$266	$1,340
Total	229.90	1,241,465	$82,985	$17,428	$100,413

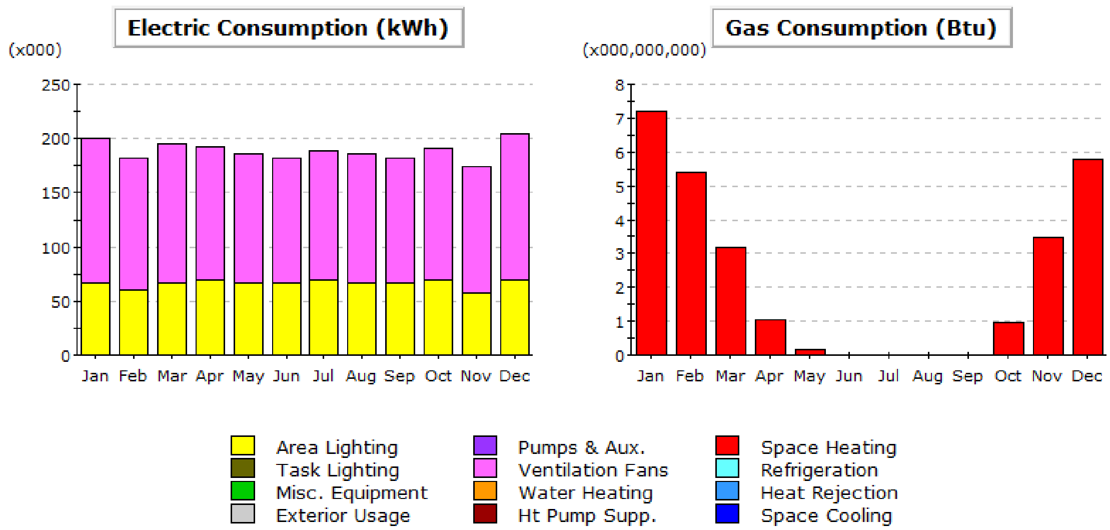
In total, annual savings, excluding heating, from upgrading lighting are $100,413/yr. The total costs for implementing these upgrades are shown below in Table 16.

Table 16: Implementation Costs and Expected Payback for Vehicle Manufacturing Facility

Area	Total Annual Savings	Implementation Costs	Payback (Months)
Fabrication Shop	$160	$741	56
Warehouse	$18,426	$22,848	15
Warehouse	$638	$2,966	56
Manufacturing	$16,500	$20,459	15
Prefabrication	$3,729	$10,018	32
Manufacturing	$479	$2,224	56
Manufacturing	$57	$480	101
Manufacturing	$287	$1,334	56
Manufacturing	$1,657	$4,452	32
Manufacturing	$319	$1,483	56
Manufacturing	$1,149	$5,338	56
Manufacturing	$26,467	$32,817	15
Manufacturing	$3,231	$8,682	32
Manufacturing	$12,396	$15,370	15
Manufacturing	$2,094	$2,596	15
Manufacturing	$96	$445	56
Manufacturing	$3,480	$9,350	32
Parts Warehouse	$7,035	$8,724	15
Manufacturing	$766	$3,559	56
Boiler Room	$96	$445	56
Boiler Room	$11	$96	101
Manufacturing	$1,340	$1,662	15
Total	$100,413	$156,088	19

The total implementation cost for this lighting upgrade is $156,088 which is expected to payback in 19 months based on the annual savings. The lighting upgrade reduces the average power from 383.74 kW to 153.84 kW. This reduces the lighting density from 0.72 W/ft^2 to

0.29 W/ft^2. The changes in heating energy consumption in the building form this upgrade is shown below in Figure 18: Heating Energy Consumption at Vehicle Manufacturing Facility.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	133.9	121.2	128.5	122.7	119.6	115.1	119.4	119.1	115.1	121.9	116.2	134.9	1,467.6
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	66.6	60.3	66.7	69.3	66.5	66.5	69.5	66.5	66.5	69.4	57.7	69.5	795.1
Total	200.5	181.4	195.3	192.0	186.1	181.6	188.9	185.6	181.6	191.3	173.9	204.4	2,262.7

Gas Consumption (Btu x000,000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	7.19	5.42	3.20	1.07	0.15	0.01	-	-	0.01	0.95	3.47	5.77	27.24
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	7.19	5.42	3.20	1.07	0.15	0.01	-	-	0.01	0.95	3.47	5.77	27.24

Figure 18: Heating Energy Consumption at Vehicle Manufacturing Facility

As expected, reducing the lighting density caused the natural gas consumption for heating to increase from 26,050 MMBTU to 27,240 MMBTU.

2.6.4 Analysis

According to the simulation, the total annual HVAC energy consumption before the lighting upgrade is as follows:

- Space Heating: 26,050 MMBTU
- Ventilation: 1,452.9 MWh

After upgrading the lighting, these values become:

- Space Heating: 27,240 MMBTU
- Ventilation: 1,467.6 MWh

The net electrical savings is shown below:

Elec. HVAC Savings (MWh)	=	Net Cooling + Net Ventilation
	=	(1,452.9 MWh – 1,467.6 MWh)
	=	(-14.7 MWh)

The net natural gas savings is shown below:

NG HVAC Sav. (MMBTU)	=	Net Space Heating
	=	(26,050 MMBTU – 27,240 MMBTU)
	=	(-1,190 MMBTU)

Throughout the course of the year, the HVAC system will see an increase of 14.7 MWh and an increase of 1,190 MMBTU. The additional cost from this is shown below:

$$
\begin{aligned}
\text{Additional Cost (\$/yr.)} &= (\text{Elec. Energy x \$/kWh}) + (\text{NG x \$/MMBTU}) \\
&= (-14.7 \text{ MWh x } 1{,}000 \text{ kWh/MWh x } \$0.057/\text{kWh}) \\
&\quad + (-1{,}190 \text{ MMBTU x } \$7.13/\text{MMBTU}) \\
&= (-\$838) + (-\$8{,}485) \\
&= (-\$9{,}323/\text{yr.})
\end{aligned}
$$

In total, there is a net increase in HVAC costs of -\$9,323/yr. According to the calculations done using Newer Lighting, the savings directly from the lighting upgrade are \$100,413/yr. Therefore, the HVAC cost increase is 9.3% of lighting savings. Originally, the expected payback was calculated to be 19 months. Including the HVAC cost increase, this payback is increased to 21 months.

3 DISCUSSION OF RESULTS

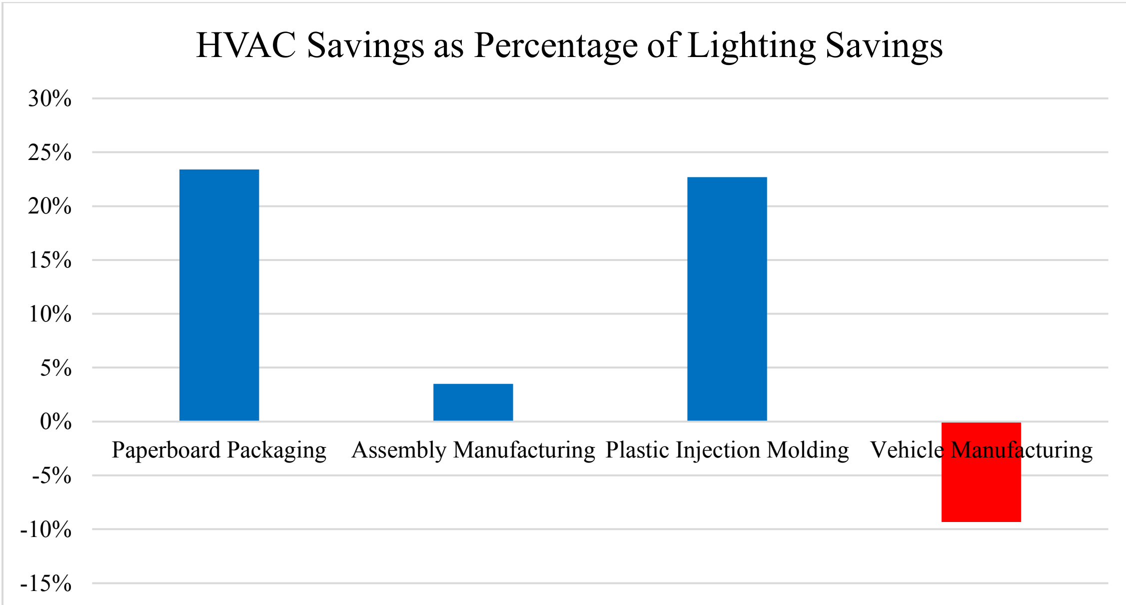


Figure 19: Comparison of HVAC Savings and Penalties for the Buildings Studied

A comparison of all of the buildings' HVAC savings/penalties is shown below. It is clear that based on the results, the heating and cooling strategies of the building are what decide if a lighting upgrade results in savings or penalties. Both the paperboard packaging and the plastic injection molding facilities were essentially only cooled and both buildings showed the highest HVAC savings as percentage of lighting savings. The vehicle manufacturing building, which was only heated, experienced a HVAC penalty. The assembly manufacturing building showed a net HVAC savings but it was a very small percentage and was the only building which both heated and cooled.

3.1.1 Comparison of Results

In order to see why the results of this project are so important, they will be compared to an already established estimation. Comparing how the results are similar and how they are different highlights the significance of this projects findings. From the November 1993 ASHRAE Journal, Robert A Rundquist, Karl F. Johnson, and Donald J. Aumann developed an easy to use to formula to estimate the lighting effect on HVAC [6].

3.1.1.1 Paperboard Packaging

Lighting Energy (LkWh)	=	LkW x Diversity x hours/week x weeks/year
	=	86.62 LkW x 0.9 x 168 hrs/wk x 50 wks/yr.
	=	654,847 LkWh
Lighting Demand (LkW)	=	LkW x Diversity
	=	86.62 kW x 0.9
	=	78.0 LkW

The method for calculating the cooling energy and demand savings is shown below:

Cooling Savings (CkWh)	=	LkWh x Cooling Fraction / System MCOP
	=	654,847 x 0.49 / 2.4
	=	133,698 CkWh
Cooling Savings (CkW)	=	LkW / System MCOP
	=	78.0 kW / 2.4
	=	32.5 CkW

Cooling Savings ($)	=	(133,698 CkWh x $0.04/kWh)
		+ (32.5 CkW x $10.42/kW)
	=	$5,348 + $339
	=	$5,687

The net savings from the lighting reduction is therefore:

Net Savings ($)	=	Cooling Savings ($) – Heating Penalty ($)
	=	$5,687 - $0
	=	$5,687

Based on the ASHRAE method, the net savings from upgrading the lighting is $5,687/yr. This result is 46% lower than the $10,504/yr. calculated using the eQuest modeling method. The manufacturing process of producing the paperboard packaging resulting in enough heating being done that very little space heating was required even during the winter. In fact, active cooling is required throughout the year due to the process heating. Reducing the power consumption and therefore the heating effect of the lighting reduces the cooling load year round which results in the much larger savings seen in the eQuest method. The Rundquist method was not made with this type of building in mind and therefore is unable to properly account for how a large internal heat generation will favor cooling savings.

3.1.1.2 Assembly Manufacturing

To begin, the lighting energy consumption and demand is determined using the following formulae:

Lighting Energy (LkWh)	=	LkW x Diversity x hours/week x weeks/year
	=	12.45 LkW x 0.9 x 80 hrs/wk x 50 wks/yr.
	=	44,820 LkWh
Lighting Demand (LkW)	=	LkW x Diversity
	=	12.45 kW x 0.9
	=	11.21 LkW

The method for calculating the cooling energy and demand savings is shown below:

Cooling Savings (CkWh)	=	LkWh x Cooling Fraction / System MCOP
	=	44,820 x 0.49 / 2.4
	=	9,151 CkWh
Cooling Savings (CkW)	=	LkW / System MCOP
	=	11.21 kW / 2.4
	=	4.67 CkW
Cooling Savings ($)	=	(9,151 CkWh x $0.0676/kWh)
		+ (4.67 CkW x $4.20/kW)
	=	$619 + $20
	=	$639

The method for calculating the heating penalty is shown below:

Heating Penalty (MMBTU)	=	LkWh x Heating Fraction x Per. Fraction
		x kWh/Therm*
		* Including seasonal efficiency = 75%
	=	44,820 LkWh x 0.16 x 0.9 x 0.046
	=	297 Therms = 29.7 MMBTU
Heating Penalty ($)	=	29.7 MMBTU x $9.14/MMTBU
	=	$271

The net savings from the lighting reduction is therefore:

Net Savings ($)	=	Cooling Savings ($) – Heating Penalty ($)
	=	$639 - $271
	=	$368

Based on the ASHRAE method, the net savings from upgrading the lighting is $368/yr. Rundquist's method overestimates both the cooling savings and, to a less extent, the heating penalty, compared to the eQuest modeling results of $186/yr. Overall, this method results in savings which are 98% too high. This large percent difference is potentially misleading as the actual difference in dollar is quite small. This method actually resulted in a similar yearly savings price as the eQuest method which is expected as the building is both heated and cooled which is the type of building the Rundquist model was developed for.

3.1.1.3 Plastic Injection Molding

Lighting Energy (LkWh)	=	LkW x Diversity x hours/week x weeks/year
	=	35.03 LkW x 0.9 x 144 hrs/wk x 50 wks/yr.
	=	226,994 LkWh
Lighting Demand (LkW)	=	LkW x Diversity
	=	35.03 kW x 0.9
	=	31.53 LkW

The method for calculating the cooling energy and demand savings is shown below:

Cooling Savings (CkWh)	=	LkWh x Cooling Fraction / System MCOP
	=	226,994 x 0.49 / 2.4
	=	46,344 CkWh
Cooling Savings (CkW)	=	LkW / System MCOP
	=	31.53 kW / 2.4
	=	13.14 CkW
Cooling Savings ($)	=	(46,344 CkWh x $0.0421/kWh)
		+ (13.14 CkW x $10.88/kW)
	=	$1,951 + $143
	=	$2,094

The net savings from the lighting reduction is therefore:

Net Savings ($)	=	Cooling Savings ($) – Heating Penalty ($)
	=	$2,094 - $0
	=	$2,094

Based on the ASHRAE method, the net savings from upgrading the lighting is $2,094/yr. This is 42% lower than the eQuest modeling results of $3,612/yr. Plastic injection molding is a process which produces a large amount of heat. Similar to the paperboard packaging but to an even greater extent, cooling is

3.1.1.4 Vehicle Manufacturing

Lighting Energy (LkWh)	=	LkW x Diversity x hours/week x weeks/year
	=	229.9 LkW x 0.9 x 108 hrs/wk x 50 wks/yr.
	=	1,117,314 LkWh
Lighting Demand (LkW)	=	LkW x Diversity
	=	229.9 kW x 0.9
	=	206.91 LkW
Heating Penalty (MMBTU)	=	LkWh x Heating Fraction x Per. Fraction x kWh/Therm*
		* Including seasonal efficiency = 75%
	=	1,117,314 LkWh x 0.16 x 0.4 x 0.046
	=	3,289 Therms = 328.9 MMBTU
Heating Penalty ($)	=	328.9 MMBTU x $7.13/MMTBU
	=	$2,345

Based on the ASHRAE method, the net cost increase from upgrading the lighting is $2,345/yr. This is 75% lower than the modeling result of $9,323/yr. This large difference is due to the fact that the building is not climate controlled throughout the year as the Rundquist method assumes but rather is only heated during the winter. Additionally, the Rundquist method is based on a commercial building with normal ventilation and infiltration. The vehicle manufacturing building has multiple paint booths, welding, and materials moving into and out of the building constantly. Due to this, the amount of air movement is enormous and far larger than the estimations made by the Rundquist method.

3.1.1.5 eQuest vs. Rundquist Method

In an attempt to quantify the difference between commercial office buildings and manufacturing buildings, internal heat generation was examined to see if there was a correlation between its magnitude and the difference between Rundquist's estimation and that produced using the eQuest building modeling technique. The plot of this is shown below in Figure 20.

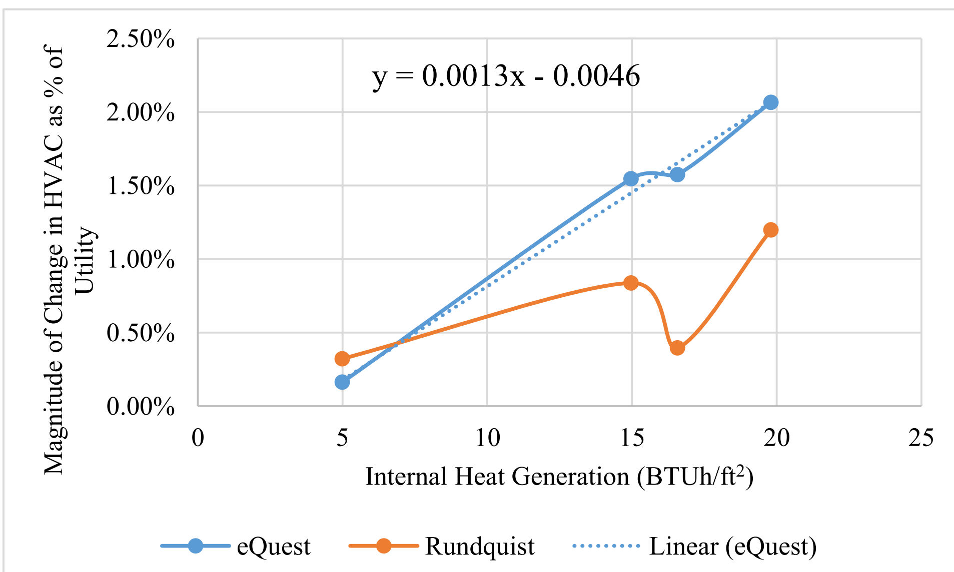


Figure 20: Internal Heat Generation compared to Percent HVAC Change from eQuest Model and the Rundquist Method

Dividing the change in HVAC by the total utility allows for a percentage to be determined of overall change. This is done to compensate for the fact that the various facilities have very different energy consumptions. Additionally, magnitude of the change is analyzed rather than the actual change to account for the fact that some buildings have increased cost rather than savings depending on cooling and heating practices. Comparing this to the internal heat generation rate per square foot shows that as the heating density increases, the change in HVAC due to lighting upgrades changes as well with a nearly linear relationship for the eQuest data. Therefore, for buildings which mostly cool, the higher the internal heat generation, the higher the potential for increased cooling savings. Additionally, for buildings which mostly heat, the higher the internal heat generation, the higher potential for increased heating penalty.

Fitting the data with a linear trend line results in the following equation:

$$y = 0.0013x - 0.0046$$

where "y" is the magnitude of change in HVAC as a percentage of total utility and "x" is the density of internal heat generation. This equation can be used to estimate the potential savings or additional cost of HVAC due to a lighting upgrade based on a individual building's heating density. Specifically, the lighting upgrade associated is moving from T12 and metal halide fixtures to T8 and T5 fixtures. The interplay of the magnitude of change of HVAC costs as a percentage of overall lighting savings was also explored as seen in Figure 22. There did not appear to be any observable trends in this relationship.

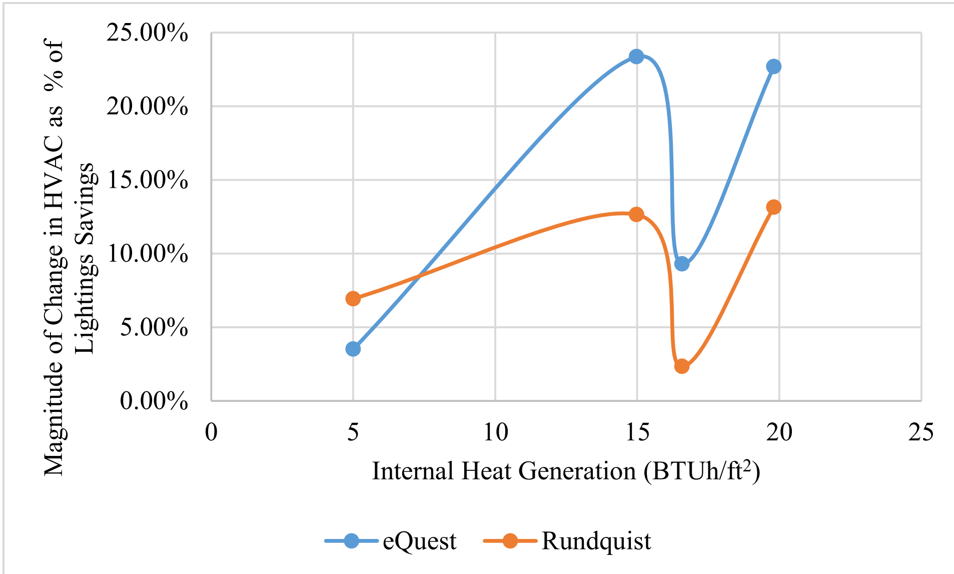


Figure 22: Internal Heat Generation compared to HVAC Cost Change as a Percentage of Lighting Savings from eQuest Modeling and the Rundquist Method

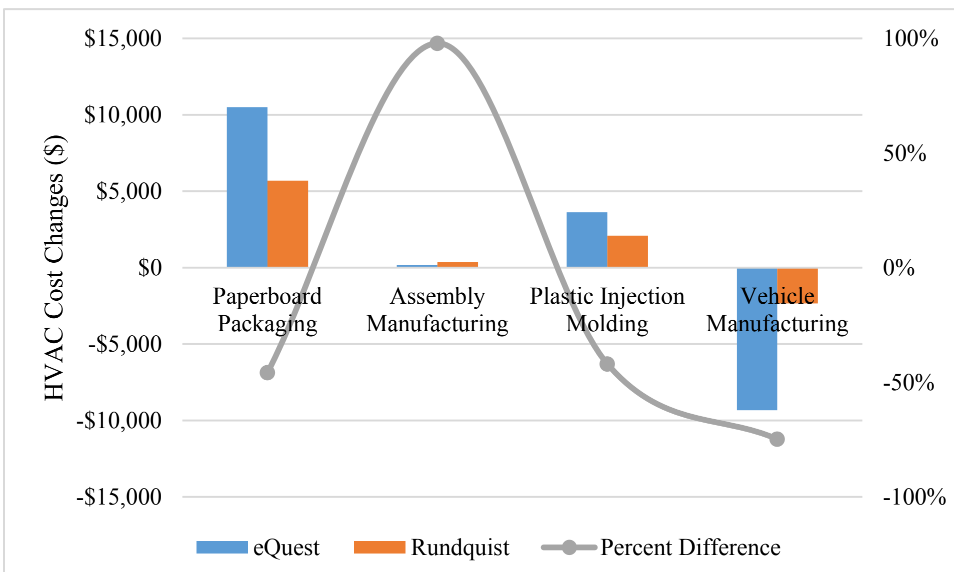


Figure 21: Comparison of Savings from eQuest Modeling and the Rundquist Method

Comparing the eQuest and Rundquist methods, it can be seen that Rundquist's method consistently underestimated the magnitude of the HVAC cost change when the building is not both heated and cooled rather than one or the other. This is more clearly seen in Figure 21. When a building is only either heated or cooled, the Rundquist estimate was between 42% and 75% lower than the eQuest results. When a building is both heated and cooled, the Rundquist estimate was 98% too high. The large percentage difference between the HVAC cost changes of the assembly manufacturing facility can be misleading because though because the Rundquist estimate is nearly double the eQuest, the actual difference is only $182 where the differences between the other buildings is thousands of dollars. What this implies is that the problem with the Rundquist model is not exclusively dependent on the internal heat generation value but also on the heating and cooling practices. This is reasonable because the Rundquist model was developed to be used for spaces which require both heating and cooling. When a space only does one or the other, it is no longer a valid candidate and the accuracy of the method falls off. This is because of internal heat generation and ventilation of the building.

3.1.2 Normalization of Results

Using percentage of lighting savings for measuring additional HVAC savings is a valuable tool when examining buildings on an individual basis. However, the goal of this project is to find the trends between multiple buildings studied and can then be applied to others. Additionally, different facilities can have wildly different utility rates. By removing the cost and only looking at power and energy, the results are valid regardless of the utility rates. To do this, the power savings will be examined based on HVAC kW changes compared to lighting upgrade kW saved.

3.1.2.1 Paperboard Packaging

The lighting upgrade reduced the average lighting consumption by 86.62 kW, space cooling by 194.3 MWh/yr., and ventilation by 68.4 MWh/yr. and increased space heating by 0.1 MWh/yr. Overall, this results in a net savings of 262.6 MWh/yr. which is equal to 262,600 kWh/yr. Dividing this value by the operation hours, 8,400 hrs/yr., gives an average power reduction of 31.26 kW. Finally, dividing the average HVAC power reduction by the average lighting power reduction gives the ratio of HVAC savings to lighting savings. This value is 0.36. This means that for every 1 kW reduction in lighting power, the building will also see an addition 0.36 kW reduction in HVAC power consumption. It is important to note that because this is an average power reduction, it is only valid when being used to determine cost savings from energy reductions, not demand savings. This is due to the fact that demand costs are set by peak usage. Peak usages for HVAC equipment may remain the save even after a lighting upgrade depending on the conditions both inside and outside of the building.

3.1.2.2 Assembly Manufacturing

The lighting upgrade reduced the average lighting consumption by 12.45 kW, space cooling by 7.64 MWh/yr., and ventilation by 0.45 MWh/yr. and increased space heating by 32.77 MMBTU of natural gas. In order to compare both heating and cooling effects, the natural gas usage will be converted into an equivalent electrical energy usage. This must take into account the number of BTU/kWh as well as a seasonal efficiency value which will be set at 75%. The calculation is shown below:

$$\text{Space Heating (kWh)} = \text{Space Heat (MMBTU)} \times (1\times10^6 \text{ BTU/MMBTU}) \div (3{,}412 \text{ BTU/kWh} \times 75\% \text{ Seasonal Efficiency})$$

$$= 32.77 \text{ MMBTU} \times (1\times10^6 \text{ BTU/MMBTU}) \div (3{,}412 \text{ BTU/kWh} \times 75\%)$$

$$= 12{,}806 \text{ kWh}$$

Space heating increased by the equivalent of 12,806 kWh/yr. Therefore, the net change in HVAC is an increase of 4,716 kWh/yr. When looking at the change on a cost basis, there was a net savings due to the relatively high prices of electricity and lower prices of natural gas. This disguised the fact that there is actually a net increase in equivalent electrical HVAC energy consumption. The average cooling reduction is 2.0 kW and the average heating increase is 3.2 kW, based on 4,000 hrs/yr. Dividing these values by the lighting power savings, the ratios are 0.16 for cooling and 0.26 for heating.

3.1.2.3 Plastic Injection Molding

The lighting upgrade reduced the average lighting consumption by 35.03 kW, space cooling by 74 MWh/yr., and ventilation by 11.8 MWh/yr. The average cooling power decrease is 11.92 kW based on 7,200 hrs/yr. Therefore, for every 1 kW reduction in lighting power, there is 0.34 kW decrease in HVAC power consumption.

3.1.2.4 Vehicle Manufacturing

The lighting upgrade reduced the average lighting consumption by 229.9 kW, increased space heating by 1,190 MMBTU/yr., and increased ventilation by 14.7 MWh. Using the same method as earlier, the equivalent electrical space heating energy use is 465 MWh. The total average power increase is therefore 88.83 kW based on 5,400 hrs/yr. Therefore, for every 1 kW reduction in lighting power, there is a 0.39 kW increase in space heating average power.

3.1.2.5 Normalization Summary

The results of the normalization are shown below in Figure 23 where green represents cooling savings, red represents heating penalty, and yellow represents the net results, where applicable.

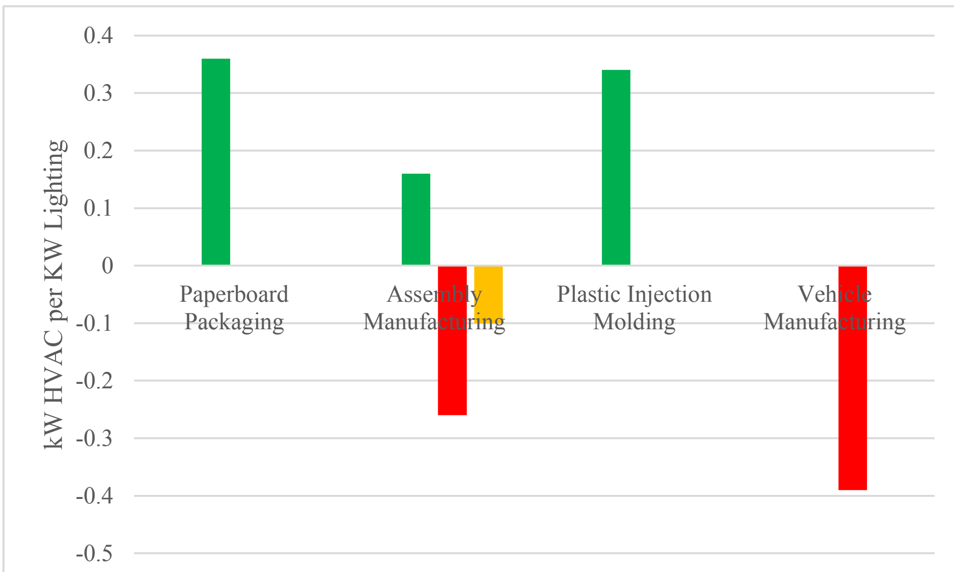


Figure 23: Results of Buildings Being Normalized based on HVAC kW Change per Lighting kW Reduction

On average, buildings which either nearly or entirely space cooling exclusively saw an average HVAC power reduction of 0.35 kW per 1 kW of lighting power reduced. For buildings which evenly cooled and heated throughout the year, average cooling power consumption was decreased by 0.16 kW per 1 kW of lighting power reduction while heating increased 0.26 kW per 1 kW for a net of 0.1 kW average HVAC power consumption per 1 kW of lighting power reduction. For buildings which exclusively heated, an average HVAC increase of 0.39 kW per 1 kW of lighting power reduction was seen.

These ratios between HVAC power reductions and lighting power reduction are essentially correction factors which can be applied to future lighting savings calculations. For buildings which are only cooled, when lighting savings are being calculated, a correction factor of 0.35 can be applied to the final power savings which would include for HVAC energy savings. For buildings which are only heated, multiplying the lighting power reduction by 0.39 will account for the energy increase due to increased heating requirements. To be more conservative, this correction factor can be reduced but regardless of its magnitude, there is a significant savings or penalty which should not be ignored as it can change the payback length substantially.

For buildings which are both heated and cooled, more data needs to be collected and analyzed before a correction factor can be confidently applied. It appears that there are potential savings available but that it depends very heavily on the individual building with a potential net heating penalty possible. Additionally, it is possible that more data would show a near zero net affect overall. Until then, it would be more conservative to not apply a correction factor in this case especially because its effect would be much smaller than the buildings with only heating or cooling.

4 CONCLUSION

The goal of this project was to develop a method to understand and quantify the interaction between lighting and HVAC. By simulating these buildings before and after lighting upgrades, the changes in heating and cooling energy usage could be examined. This project has shown that current conventional methods for estimating lighting and HVAC interactions are suitable for using in manufacturing buildings as they are substantially different than the commercial buildings that estimations were based upon.

The work done in this project as shown that in some cases, HVAC savings or penalties can significantly change the estimated savings from upgrading light fixtures and therefore the amount of time required for it to pay back. More importantly, ratios between average lighting power changes and average HVAC power changes have been quantified for three types of buildings: cooled only, cooled and heated, and heated only. These ratios can be used to estimate the interaction in future buildings between lighting and HVAC and allow for more accurate savings and payback periods to be calculated.

Another result of this project is that there is a relationship between the heating density of a building and the changes in HVAC cost as a percentage of total utility cost. As the heating density increases, expected changes in the magnitude HVAC expenditures also increases. Therefore, buildings which have large amount of internal heating per square foot of building area have the largest potential for both cooling savings and heating penalties depending on heating and cooling practices. A linear fit was applied which resulting in an equation which can be used to estimate potential HVAC cost changes based on heating density values. This is an important consideration when determining candidates for this analysis.

Future work in this area can be done in two different ways. First, increasing the sample size can help to increase the accuracy of the findings of this project. By performing this modeling technique on more buildings of the same type, potential outliers can be identified and removed and more accurate averages can be determined. As it is one of the most common types, more buildings which are both heated and cooled should be explored and modeled. The second avenue of future work would be real world results. In the IAC, nearly all of the facilities assessed receive some kind of lighting upgrade recommendation. By logging various HVAC equipment before and after the upgrade, the actual interaction between the HVAC and lighting systems could be observed and used to further validate the findings of this paper.

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